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Energy Price Distortions and Urban Carbon Emission Efficiency: Evidence from China's Energy-Intensive Sectors

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Abstract: With a primary focus of achieving carbon neutrality, the energy-intensive industrial sectors (EIIs) contribute to more than half of China's carbon dioxide (CO_2) emissions. During the process of China's rapid economic development, distorted energy prices gradually became the main obstacle to energy conservation and emission reductions in the EIIs. Therefore, this study focused on determining the mechanisms affecting the energy price distortions of carbon emission efficiency (CEE) in China's EIIs. Based on a stochastic frontier analysis, the changing trend of CEE in China's EIIs was evaluated. The channels impacting the energy price distortions of CEE were further analyzed by a mediating effect and moderated mediating effect model. The main contributions and findings include the following: energy price distortions have a significant negative impact on CEE by suppressing technological innovations and hindering the restructuring of energy consumption; governmental environmental regulatory policies mitigate their suppressing effect on technological innovations and reduce the preventing effect by improving the energy consumption structure. The results suggest that market-based price reforms and moderate environmental regulation by the government could help to improve CEE in China's EIIs. These findings are of great significance for promoting the sustainable development of the energy-intensive industrial sectors and achieving carbon neutrality.

Keywords: energy price distortion; urban carbon emission efficiency; technical innovation; energy consumption structure

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1. Introduction

Along with the rapid process of industrialization and urbanization in China, fossil energy consumption and its resulting carbon dioxide (CO_2) emissions are becoming severe constraints on China's sustainable development. As important production sectors within urban infrastructure construction, the development of energy-intensive sectors was accompanied by the urgent task of cutting emissions. According to the China Statistical Yearbook published by the National Bureau of Statistics (NBS), in 2017, the input of fossil energy into China's EIIs was 2185.959 million tons of coal equivalent (Mtce), which accounted for 47.96% of the total energy consumption in China; the energy-related carbon emissions contributed 4952.177 million tons (MT), accounting for 49.896% of the total carbon emissions in China. How can we control the energy input and improve carbon emission efficiency (CEE) without affecting the growth target? What is the fundamental economic channel with which to improve CEE?

There have been many constraint factors on CEE. Existing studies have shown that the constraints on improving CEE can be summarized as technical factors and institutional factors [1,2]. The constraints from technical factors have mainly manifested themselves through the independent research and development of low-carbon technical innovations, the digestion and absorption of foreign technology introduced into the country, etc. The institutional factors have been more complex and diverse, including the factor pricing mechanism, environmental compensation mechanism, promotion and assessment mechanism of

government officials, and social supervision mechanism. Among the complex mechanisms affecting a low-carbon transition, the constraint from the factor pricing mechanism refers to the price distortion caused by non-market pricing means, especially the price distortion of fossil energy products, which hinders the role of market price signals and further restricts improvements in CEE, the green transition, and the upgrading of industries.

For China's EIIs, the price distortion caused by the lagging energy market reform was the fundamental economic obstacle to green development. As important input factors for industrial production, the marketization of energy products lagged far behind the product market, and so the price signal could not reflect the real demand. In fact, the distorted price of energy inhibited the improvement in CEE by two channels: firstly, the low cost of fossil energy encouraged the EIIs to gain profits by increasing the fossil fuel input and inhibiting green R&D investment and technical innovation; secondly, the low fossil fuel costs encouraged the EIIs to make profits by adopting traditional fossil energy and hindering the substitution of clean energy. Furthermore, in order to control carbon emissions, the government introduced a series of environmental regulation policies to mitigation carbon emissions. The question is whether the current environmental regulations can moderate technical innovation and energy substitution channels.

Although there are many existing studies on carbon emission efficiency, there are still shortcomings in the explorations of the impact of China's distorted energy prices on the efficiency of urban carbon emissions. The main objective of this study was to evaluate the possible energy price distortion and the level of CEE in China's EIIs, and to further analyze the mechanism affecting energy price distortion on CEE. The main research questions are the following: (1) How do energy price distortions impact the production process of the EIIs in different cities? (2) What are the channels affecting CEE? (3) Do the existing environmental regulation policies show different moderating effects on the negative impacts of energy price distortions on CEE? To answer these questions, we first estimated the total factor carbon emission efficiency and the degree of energy price distortion at the city level; second, we analyzed the blocking mechanism of energy price distortions on the improvements in carbon emission efficiency from theoretical perspectives; and, third, we empirically evaluated the preventing effect of energy price distortions on improving carbon emission efficiency by the moderated mediating effect model.

2. Literature Review and Theoretical Background

As the major sectors of energy consumption and carbon emissions, EIIs account for half of the energy-related CO_2 emissions in China [3]. The literature includes studies of the factors impacting carbon emissions in China's EIIs from various perspectives. Adopting the Logarithmic Mean Divisia Index (LMDI) method, Lin and Ouyang [4], Lin and Tan [5], and Du et al. [6] studied CO_2 emissions in different energy-intensive sectors in different periods but mainly found that the industrial scale, energy intensity, energy structure, and carbon intensity were the important factors for CO_2 emissions. Based on production and consumption accounting principles, Yuan and Zhao [7] adopted an input–output model to study the drivers of CO_2 reduction and found that the emission intensity effect, technology effect, and demand effect were the important drivers for cutting carbon emissions. From the perspective of technical utilization, Wang et al. [8] explored the impact of market power, imperfect competition, and carbon emission trade on the carbon emission efficiency of heterogeneous enterprises; Yang [9] explored the Nash equilibrium strategy of energy-intensive enterprises in carbon dioxide emissions reduction, adopting an integrated evaluation model. Based on fuel and factor substitution, Tan and Lin [10] found that carbon tax was conducive to a reduction in CO_2 emissions in EIIs but cannot promote improvements in CEE. Tong et al. [11] decomposed the factors affecting carbon emissions into economic structure, energy intensity, and energy structure effect, which significantly promoted the growth of carbon emissions in China's EIIs.

At the same time, CEE in China was also characterized with spatial heterogeneity. Choi et al. [12] analyzed the CEE based on SBM-DEA at the provincial level, and the results

showed a phenomenon of decreasing efficiency from the east to west regions, which was further verified by the results of Dong et al. [13] (trans-log SFA model), Wang et al. [14] (directional distance function), Lin and Du [15] (fixed-effect panel SFA), and Wang et al. [16] (SBM model). Wang et al. [8] focused on the regional convergent effect in China's EIIs and provided larger potential for CO_2 emission reductions. Fang et al. [17] focused on the spatial spillover effects of urban CEE and found that industrial agglomeration showed adverse effects on CEE. Therefore, spatial heterogeneity was an important dimension of analysis when studying CEE in China.

The prices of fossil energy in China have been subsidized by the government and kept at a relatively low level, and the resulting price distortion affects resource allocation efficiency and brings a series of economic and environmental effects [18,19]. Considering the phenomenon of energy price distortions in China, Shi and Sun [20] focused on the economic growth effect of regulated energy prices and found a negative effect on output growth in China; Li et al. [21] studied the environmental effect of energy prices and found that increasing energy prices could alleviate environmental pollution in China. Xu and Lin [22] studied the impact of energy price distortion on energy efficiency and found a positive effect of eliminating relative price distortions.

Energy prices can also indirectly influence carbon emissions and carbon intensity through other factors, such as economic development, industrial structure, energy efficiency, and energy investment [23,24]. The study of Wang et al. [25] on China's transport sector showed that oil price distortions had a negative effect on CEE, and eliminating distortions could promote clean energy substitutions and so reduce CO_2 emissions. Sun et al. [26] concluded that factor price distortion depressed CEE through restricted industrial production and technical investment. Tan et al. [27] focused on energy allocation distortion in China's tertiary industries and showed that removing the distortion can promote production growth and reduce CO_2 emissions.

Considering the impact mechanism of distorted prices on CEE, firstly, we recalled the reasons for energy price distortion. As import input factors of industrial production, the cost paid by energy production enterprises relates to administrative fees, and the price of energy products in China was kept lower than the market equilibrium price, leading to imperfection in the price structure of energy products and so negative price distortion [28,29]. The low price of fossil energy made a large amount of backward production capacity, that should be eliminated, profitable, increasing carbon emissions in China's EIIs and inhibiting improvements in CEE from two mediating channels.

The first channel is technical innovation. When fossil energy costs are low due to price distortions, enterprises in EIIs are incentivized to maximize profits by increasing fossil energy inputs rather than investing in efficiency improvements. This dynamic significantly suppresses the industry's motivation for R&D investment in clean technologies, ultimately decreasing innovation efficiency [30–32]. Murad et al. [33] found that energy prices have a significant negative impact on energy consumption. When energy prices are low, the motivation for companies to invest in energy-saving technologies decreases. Therefore, they proposed that policy settings should incentivize companies to invest in green technologies. Calì [34] used emerging-country companies as an example to empirically demonstrate that energy prices are positively correlated with economic performance in certain situations. In such cases, companies naturally use more energy rather than innovation to increase profits. R&D investment in green technologies is crucial for promoting technical progress, which has a demonstrably positive effect on improving CEE [35]. By discouraging such investments, energy price distortions indirectly hinder CEE improvements. Moreover, distorted energy prices will affect factor allocation and total factor productivity [36,37], which influence the cultivation of human resources and technical progress overall.

The second channel is the energy consumption structure. The distortion of energy prices led to the excessive dependence on and usage of fossil energy in EIIs, which suppressed the inputs of clean and low-carbon energy, thus triggering the fossil substitution effect and inhibiting improvements in CEE [38]. The enterprises input more coal-related

and oil-related fossil energy, keeping old production equipment and processes and leading to more carbon emissions. Furthermore, the imperfect energy market brings erroneous price signals to the local government, provides more policy support to industrial enterprises [39], and hinders the transformation of the energy consumption structure, which further decreases CEE in EIIs. We propose Hypothesis 1 as follows.

Hypothesis 1. *The null hypothesis is that distorted energy prices do not negatively affect carbon emission efficiency (CEE) through hindering technical innovation or by increasing the proportion of fossil energy in the energy consumption structure.*

The alternative hypothesis is that distorted energy prices might negatively affect CEE through hindering technical innovation and increasing the proportion of distorted fossil energy in the energy consumption structure.

Both channels of technical progress and the energy consumption structure will be moderated by government environmental regulation. Although traditional theories conclude that environmental regulation requires enterprises to install pollution control equipment and increase the costs of enterprises [40], based on the "Porter Hypothesis" proposed by Porter and Linde [41], environmental regulation would force enterprises to invest in R&D, carry out innovation activities, and bring about technical progress [42–44]. Therefore, environmental regulation might mitigate the negative effect of distorted energy prices on technical progress. On the other hand, government environmental regulation policies contain direct commands of reducing fossil fuel consumption and increasing the proportion of clean energy. Therefore, Hypothesis 2 is further proposed.

Hypothesis 2. *The null hypothesis is that increased environmental regulation does not moderate the inhibitory effect of energy price distortions on technical progress or the energy consumption structure.*

The alternative hypothesis is that, with an increase in environmental regulation, the inhibitory effect of energy price distortions on technical progress and the energy consumption structure can be moderated.

3. Methodologies and Data Description

3.1. Methodology of Evaluating Fossil Price Distortion

Mitigating energy price distortion was beneficial to improving CEE [8]. The higher the energy price, the higher the cost of energy input by the producer, thus increasing the input of alternative elements (capital, labor, or clean energy) and reducing the input of fossil energy. However, due to government subsidies, the price of fossil energy in China was controlled at levels lower than the equilibrium price, leading to mass abuse in EIIs. In order to evaluate the distorted level of energy products at the city level, the direct distortion was calculated with the following equations.

$$EPD = \sum_{i=1}^{3} \frac{(P_i - P_{bi})}{P_{bi}} \times \omega_i \quad (1)$$

Like Shi and Sun [20], the price of mature coal, oil, and electricity markets in the world was taken as the benchmark price (P_{bi}), ω_i was calculated by the input proportion of ith energy in China's EIIs, and the differences of domestic and international energy prices were taken as the price gap. In this study, the prices of the American coal market and the American oil and electricity markets were selected as the benchmark prices. The data of prices in the American energy market and domestic market were obtained from the CEIC database.

3.2. Methodology of Evaluating CEE

As the distorted prices affect the relationship of production inputs and outputs, the method of SFA with a directional distance function was adopted to estimate CEE in China's

EII sectors. Referring to Lin and Du [15], CO_2 emissions were taken as the undesirable output, and the directional distance function of multiple outputs and multiple inputs was defined as follows to reflect the opposite direction of increasing industrial output and reducing carbon emissions.

$$D_I(K_{it}, L_{it}, E_{it}, Y_{it}, C_{it}) = sup\{(Y_{it} + \beta G_y, C_{it} - \beta G_c) \in P(K_{it}, L_{it}, E_{it})\} \quad (2)$$

where K represents capital input, L represents labor input, E is energy input, Y is desirable output (gross industrial value), and C represents undesirable output (CO_2 emissions). G_y represents the expansion direction of industrial output and G_c represents the reduction direction of CO_2 emissions. Adopting trans-log production function and considering the time trend, Equation (2) can be converted into:

$$\begin{gathered} LnD_I = \beta_0 + \beta_1 LnK_{it} + \beta_2 LnL_{it} + \beta_3 LnE_{it} + \beta_4 LnY_{it} + \beta_5 LnC_{it} + \beta_6 LnK_{it} \times \\ LnL_{it} + \beta_7 LnK_{it} \times LnE_{it} + \beta_8 LnK_{it} \times LnY_{it} + \beta_9 LnK_{it} \times LnC_{it} + \beta_{10} LnL_{it} \times LnE_{it} + \\ \beta_{11} LnL_{it} \times LnY_{it} + \beta_{12} LnL_{it} \times LnC_{it} + \beta_{13} LnE_{it} \times LnY_{it} + \beta_{14} LnE_{it} \times LnC_{it} + \\ \beta_{15} LnY_{it} \times LnC_{it} + \frac{1}{2}\beta_{16}(LnK_{it})^2 + \frac{1}{2}\beta_{17}(LnL_{it})^2 + \frac{1}{2}\beta_{18}(LnE_{it})^2 + \frac{1}{2}\beta_{19}(LnY_{it})^2 + \\ \frac{1}{2}\beta_{20}(LnC_{it})^2 + \beta_{21} TLnK_{it} + \beta_{22} TLnL_{it} + \beta_{23} TLnE_{it} + \beta_{24} TLnY_{it} + \beta_{25} TLnC_{it} + \beta_{26} T + \\ \frac{1}{2}\beta_{27} T^2 + \nu_{it} \end{gathered} \quad (3)$$

Since the distance function shows translational property, which indicated that GDP increased in the direction of G_y and CO_2 decreased by the same amount in the direction of G_c, if we increase or decrease G_{it} at the same amount, the following distance functions should be satisfied:

$$D_I(K_{it}, L_{it}, E_{it}, Y_{it} + \alpha G_y, C_{it} - \alpha G_c) = D_I(K_{it}, L_{it}, E_{it}, Y_{it}, C_{it}) - \alpha \quad (4)$$

$$D_I(K_{it}, L_{it}, E_{it}, Y_{it} + C_{it}, 0) = D_I(K_{it}, L_{it}, E_{it}, Y_{it}, C_{it}) - C_{it} \quad (5)$$

Convert Equation (5) into trans-log production function mode:

$$\begin{gathered} LnD_I = \beta_0 + \beta_1 LnK_{it} + \beta_2 LnL_{it} + \beta_3 LnE_{it} + \beta_4 (LnY_{it} + LnC_{it}) + \beta_5 LnK_{it} \times LnL_{it} + \\ \beta_6 LnK_{it} \times LnE_{it} + \beta_7 LnK_{it} \times (LnY_{it} + LnC_{it}) + \beta_8 LnL_{it} \times LnE_{it} + \beta_9 LnL_{it} \times (LnY_{it} + LnC_{it}) + \\ \beta_{10} LnE_{it} \times (LnY_{it} + LnC_{it}) + \frac{1}{2}\beta_{11}(LnK_{it})^2 + \frac{1}{2}\beta_{12}(LnL_{it})^2 + \frac{1}{2}\beta_{13}(LnE_{it})^2 + \\ \frac{1}{2}\beta_{14}(LnY_{it} + LnC_{it})^2 + \beta_{15} TLnK_{it} + \beta_{16} TLnL_{it} + \beta_{17} TLnE_{it} + \beta_{18} T(LnY_{it} + LnC_{it}) + \\ \beta_{19} T + \frac{1}{2}\beta_{20} T^2 + \nu_{it} \end{gathered} \quad (6)$$

Further substitute Equation (5) into Equation (4) and obtain the following:

$$\begin{gathered} -LnC_{it} = \beta_0 + \beta_1 LnK_{it} + \beta_2 LnL_{it} + \beta_3 LnE_{it} + \beta_4 (LnY_{it} + LnC_{it}) + \\ \beta_5 LnK_{it} \times LnL_{it} + \beta_6 LnK_{it} \times LnE_{it} + \beta_7 LnK_{it} \times (LnY_{it} + LnC_{it}) + \beta_8 LnL_{it} \times LnE_{it} + \\ \beta_9 LnL_{it} \times (LnY_{it} + LnC_{it}) + \beta_{10} LnE_{it} \times (LnY_{it} + LnC_{it}) + \frac{1}{2}\beta_{11}(LnK_{it})^2 + \\ \frac{1}{2}\beta_{12}(LnL_{it})^2 + \frac{1}{2}\beta_{13}(LnE_{it})^2 + \frac{1}{2}\beta_{14}(LnY_{it} + LnC_{it})^2 + \beta_{15} TLnK_{it} + \beta_{16} TLnL_{it} + \\ \beta_{17} TLnE_{it} + \beta_{18} T(LnY_{it} + LnC_{it}) + \beta_{19} T + \frac{1}{2}\beta_{20} T^2 + \nu_{it} - \mu_{it} \end{gathered} \quad (7)$$

Based on Equation (7), the total factor CEE can be calculated by the following equation.

$$CEE = 1 - \mu_{it} \quad (8)$$

It should be pointed out that the models and methods used in this study have certain assumptions:

Firstly, in terms of research methodology, the assumptions of stochastic frontier modelling (SFA) include the following three main points: (1) distributional assumptions: SFA requires specific assumptions about the distribution of the stochastic error term and the efficiency term, which may not always match the actual data, and there may be other factors in the actual process that are not included in the analysis, such as political factors or

sudden policy changes; (2) single-output assumptions: SFAs are usually better designed for single-output scenarios and may require more complex modelling for multi-output scenarios; (3) static models: most SFA models are static, making it difficult to capture changes in efficiency over time horizons.

For mediated and moderated mediated effects models, the assumptions that the mediating variables are accurately measured and that there are no unobserved confounders affecting the relationship between the variables are not always met. In real-world studies, measurement errors and potential unaccounted-for confounders may have an impact on the results.

Secondly, in terms of research content, this study hypothesizes that the impact of energy price distortions works mainly through two channels: technological innovation and energy consumption structure. The applicability of this hypothesis is limited to energy-intensive industries in China, where energy price distortions are more pronounced, and carbon emissions are particularly problematic.

Finally, in terms of the data, this study uses city-level data for China, and there may be a selection bias because only cities with complete data were selected, failing to cover all regions. Meanwhile, during the data cleaning process, missing values were added by estimation and interpolation, which may lead to some errors. By acknowledging and addressing these limitations and assumptions, we are able to more fully appreciate the limitations of the research methodology, leading to a more in-depth analysis and understanding of the findings and their implications, and avoiding inaccurate or one-sided conclusions.

3.3. Methodology of Evaluating Impacting Mechanism

3.3.1. Mediating Effect Model

To evaluate the impact energy price distortion on CEE, the base regression model can be expressed as Equation (9), where CEE is total factor carbon emission efficiency, ED is energy price distortion, Control reflects the controlled variables, Year is the time fixed effect, Region is the regional fixed effect, and ε is the disturbance.

$$\ln CEE_{it} = \beta_0 + \beta_1 ED_{it} + \beta_2 Control_{it} + Year_i + \mathrm{Re}gion_t + \varepsilon_{it} \quad (9)$$

To further evaluate the mediating effect of technical innovation and energy consumption structure, Equations (10)–(13) were used to test the affected channels, where *TE* is represented as technical innovation and ES is represented as energy consumption structure.

$$\ln TE_{it} = \alpha_0 + \alpha_1 ED_{it} + \alpha_2 Control_{it} + Year_i + \mathrm{Re}gion_t + \varepsilon_{it} \quad (10)$$

$$\ln ES_{it} = \gamma_0 + \gamma_1 ED_{it} + \gamma_2 Control_{it} + Year_i + \mathrm{Re}gion_t + \varepsilon_{it} \quad (11)$$

$$\ln CE_{it} = \eta_0 + \eta_1 ED_{it} + \eta_2 \ln TE_{it} + \eta_3 Control_{it} + Year_i + \mathrm{Re}gion_t + \varepsilon_{it} \quad (12)$$

$$\ln TE_{it} = \tau_0 + \tau_1 ED_{it} + \tau_2 \ln ES_{it} + \tau_3 Control_{it} + Year_i + \mathrm{Re}gion_t + \varepsilon_{it} \quad (13)$$

Taking *TE* as a mediating variable, the procedure of mediation effect test was as follows: Firstly, the significance of coefficients in Equation (9) was tested, and the significant coefficients indicated that energy price distortion showed a significant impact on CEE. Secondly, we estimated the coefficients in Equations (10) and (12). When both the coefficients of α_1 and η_2 were significant, and if the coefficient of η_1 was also significant, it indicated that there was a partial mediating effect; but, if the coefficients of η_1 were not significant, it indicated the existence of a complete mediating effect. If at least one of the coefficients, α_1 and η_2, failed the significant test, the bootstrap method was adopted for further analysis. Similarly, repeating the above steps, we can test the mediating effect of energy consumption structure.

$$\ln TE_{it} = \theta_0 + \theta_1 ED_{it} + \theta_2 \ln ER_{it} + \theta_3 ED_{\mathrm{it}} \times \ln ER_{it} + \theta_4 Control_{it} + Year_i + \mathrm{Re}gion_t + \varepsilon_{it} \quad (14)$$

$$\ln ES_{it} = \omega_0 + \omega_1 ED_{it} + \omega_2 \ln ER_{it} + \omega_3 ED_{\mathrm{it}} \times \ln ER_{it} + \omega_4 Control_{it} + Year_i + \mathrm{Re}gion_t + \varepsilon_{it} \quad (15)$$

$$\ln TE_{it} = \lambda_0 + \lambda_1 ED_{it} + \lambda_2 \ln ER_{it} + \lambda_3 ED_{\mathrm{it}} \times \ln ER_{it} + \lambda_4 \mathrm{lnTE_{it}} + \lambda_5 Control_{it} + Year_i + \mathrm{Re}gion_t + \varepsilon_{it} \quad (16)$$

$$\ln TE_{it} = \delta_0 + \delta_1 ED_{it} + \delta_2 \ln ER_{it} + \delta_3 ED_{\mathrm{it}} \times \ln ER_{it} + \delta_4 \mathrm{lnES_{it}} + \delta_5 Control_{it} + Year_i + \mathrm{Re}gion_t + \varepsilon_{it} \quad (17)$$

3.3.2. Moderated Mediating Effect

Considering environmental regulation as the moderated variable, we further constructed an econometric model and expanded the analysis on the basis of the moderated mediating effect. *ER* was the proxy variable of environmental regulation, and the moderated mediating pathways are shown in Figure 1. Based on Wen and Ye, the significance of the coefficients θ_1 and θ_3 in model (14), ω_1 and ω_3 Equation (15) should be tested, respectively, secondly, evaluating the significance of coefficients λ_4 and δ_4 in Equations (16) and (17). If θ_3 and λ_4 were significant, it indicated that environmental regulations have a significant regulatory effect on path ①; if ω_3 and δ_4 were significant, it indicated that environmental regulations have a moderated effect on path ②.

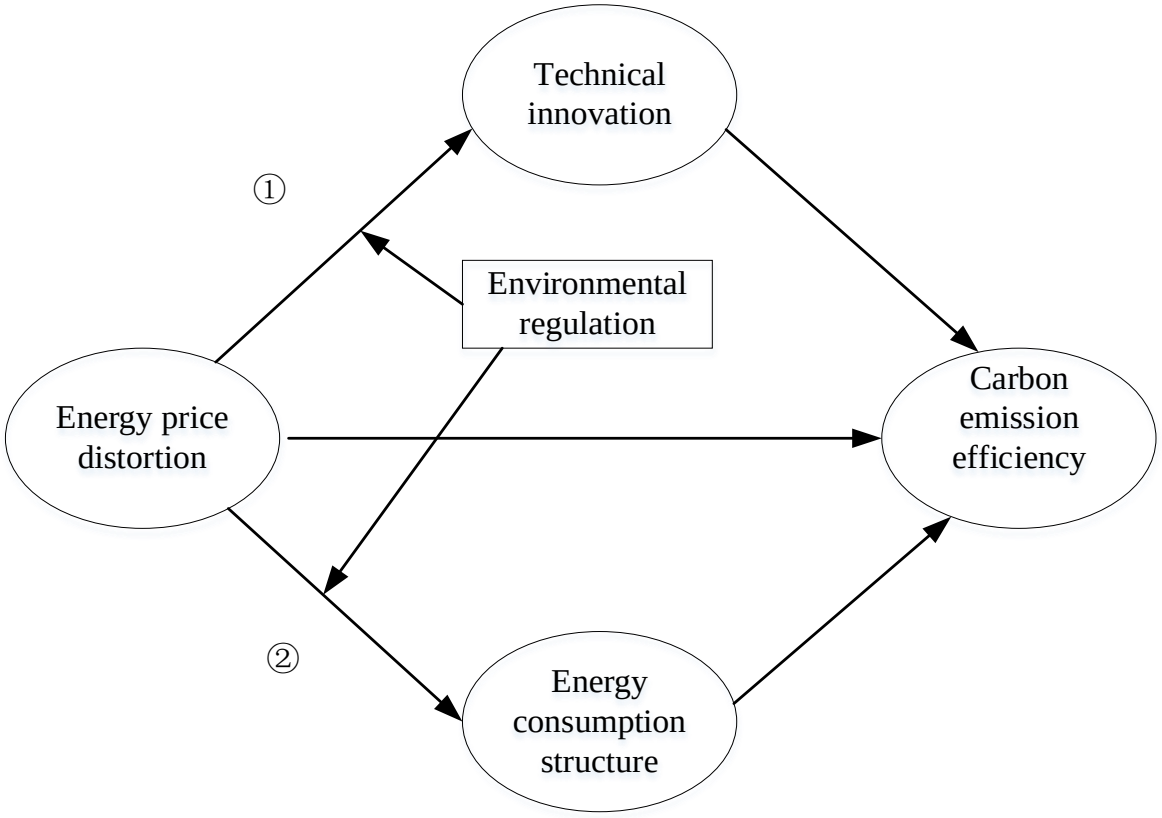


Figure 1. The moderated mediating channels on CEE.

3.4. Variables and Data Description

Based on CEIC database, City Statistical Yearbook (2004–2020), China Statistical Yearbook (2004–2020), China Energy Statistical Yearbook (2004–2020), and China Environmental Statistical Yearbook (2004–2020), the data of China's EIIs in 34 large- and medium-sized cities were compiled during 2003–2019. The EIIs covered in this study included the following: chemical raw materials and chemical product manufacturing, nonmetallic mineral industry, ferrous metal smelting and rolling industry, and nonferrous metal smelting and rolling industry.

Large- and medium-sized cities are often the key implementation areas for energy and environmental regulatory policies. The study of large- and medium-sized cities can

provide a better view of the actual impact of policies on energy price distortions and carbon emission efficiency, as well as the problems and challenges that may arise in the process of policy implementation. And the practical experiences and achievements of large- and medium-sized cities in energy management and environmental protection can serve as a model and reference for other cities. Through the study of large- and medium-sized cities, effective policy models and management experiences can be summarized and expanded to other regions to promote the achievement of the goal of sustainable energy use on the national scale.

As shown in Table 1, variables can be divided into output variables, input variables, and impacting factors of CEE. Desirable output was generally expressed as economic income, which was the ideal output in economic activities. Here, it was expressed as the gross industrial output value of EIIs in each city. Undesired output referred to the output generated by environmental factors in economic activities, which was represented by CO_2 emissions. Due to data deletion on carbon emissions in China, the data were calculated using carbon emission coefficients. The calculation of carbon emissions is described as follows:

$$C_{it} = \sum E_{ijt} \times \rho_j \tag{18}$$

where C_{it} represents carbon emissions of EIIs in city i in year t; E_{it}. represents the consumption of the j^{th} type of energy in the EIIs; ρ_j. represents the carbon emission coefficient (the CO_2 emission coefficient is 2.64 tCO_2/tce for coal, 2.08 tCO_2/tce for petroleum, and 1.63 tCO_2/tce for natural gas (source: the website of the National Development and Reform Commission in China)) of the j^{th} energy resource.

Table 1. Main variables and data descriptions.

Variable	Short	Sample Size	Max	Min	Mean	Standard Deviation
Gross industrial output (CNY 100 million)	Y	578	5726.942	36.101	952.797	961.001
CO_2 emissions (million tons)	C	578	8329.237	16.561	1205.407	1381.439
Capital input (CNY 100 million)	K	578	2309.029	28.734	339.673	362.716
Labor input (person)	L	578	297,400.000	10,416.000	97,986.296	68,439.834
Energy Input 10,000 tce)	E	578	4555.346	9.171	703.6441	795.770
Technical innovation	TP	578	332,652.000	70.000	34,902.282	56,272.387
Environmental regulation (%)	ER	578	0.167	0.008	0.034	0.022
Foreign direct investment (%)	FDI	578	0.139	0.000	0.034	0.025
Energy price distortion	ED	578	0.368	−0.714	−0.372	0.180

Input variables contained capital, labor, and energy factors. Based on Sun et al. [26], capital stock was calculated through deformation using the perpetual inventory method. The calculation formula can be expressed as follows:

$$K_{it} = K_{it_0} + \sum_{t_0+1}^{t} (\triangle K_{it} / I_{it}) \tag{19}$$

where K_{it} represents annual capital stock of city i in year t, K_{it_0}. represents the net fixed assets of EIIs in city i in 2003, $\triangle K_{it}$. represents the difference between the net fixed assets of two adjacent years, and I_{it} represents the fixed asset investment price index.

Labor input was represented by the average amount of labor in EIIs in each city. Energy input included coal, oil, natural gas, and electricity input. Although each energy type, including different thermal power, the total energy input could be added by converting the unit of energy type to standard coal. The converting coefficient was from the China Energy Statistical Yearbook.

The affecting channels of energy price distortion on CEE included the mediating effect and moderated effect. So, the mediating variables are technical innovation and the energy consumption structure. As the core driving force of cutting carbon emissions, technical innovation can promote improvements in CEE by improving total factor productivity [45,46].

The number of patents granted in the province where the city was located was adopted to represent the progress of technical innovation in the region. The energy consumption structure was represented by the proportion of fossil fuels consumed in China's EIIs.

Environmental regulation is an important moderated variable. Carbon emissions showed certain environmental externalities, which required the government to assume certain responsibilities in the process of emission reductions. The empirical results show that the implementation of environmental policies was beneficial to improving the performance of CO_2 emissions [28]. Environmental regulation was expressed by the ratio of pollution control investment in industrial total output.

Controlled variables included the level of economic development, urbanization rate, and foreign direct investment. The level of economic development was expressed as the growth rate of GDP per capita, and the urbanization rate was represented by the number of permanent residents. Foreign direct investment was expressed as the ratio of FDI to urban gross product.

For variables with a small number of missing values, linear interpolation is used to supplement them.

4. Empirical Results

4.1. Estimating Results of Fossil Fuel Price Distortion

As can be shown in Figure 2, although the distortions of fossil energy price were alleviated, the price gaps were still negative. Compared with the US coal price, the coal price China's EIIs faced was, indeed, negatively distorted, and the average distorted value was −0.349. The changing trend of coal price distortion increased from −0.561 in 2003 to 0.010 in 2019, indicating that China's coal pricing mechanism had been greatly improved, and the distortion was alleviated to a certain extent. However, the issue that the coal industry faced was the decentralization of enterprises to form an industrial cluster, which caused significant overcapacity and excessive competition [30], resulting in negative price distortion and unsatisfactory performance in some cities. The cities with the highest coal price distortion were Lanzhou (−0.876), Xi'an (−0.775), and Urumqi (−0.730). The cities are located in the northwest of China, together with backward economic development, weak ability to attract foreign investment, slow progress of energy market-oriented reform, and strong government control, which aggravated the distortion of coal prices. The lowest coal price distortion was in Wuhan (0.035) and Shanghai (0.045), and the prices were highly regulated by the market other than government control.

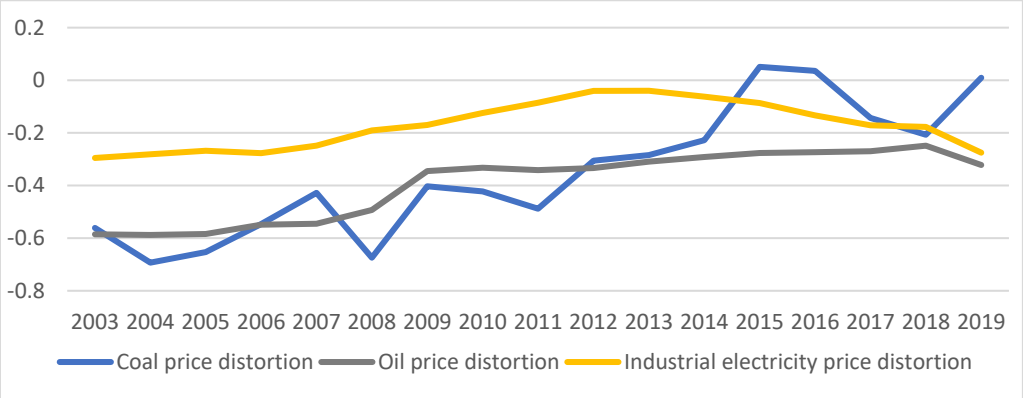


Figure 2. The trend of energy price distortion during 2003–2019.

During the study period, the average distortion oil price was −0.393, and the overall distortion showed a fluctuating increasing trend (from −0.586 in 2003 to −0.322 in 2019). The cities with the highest oil price distortion were Urumqi (−0.421), Zhengzhou (−0.406), and Harbin (−0.404), which are all resource-abundant cities with low economic growth. Therefore, the labor cost and transportation cost are relatively low, and together with

sufficient oil supply, the level of price distortion was relatively higher. The lowest oil price distortion is shown in Shenzhen (−0.378) and Chongqing (−0.378). As a pilot city of China's reform and opening up, Shenzhen has continuously carried out energy market-oriented reform and explored reform experiments for resource-based economic transformation, and the oil market has developed relatively well. As import center city in Southwest China, Chongqing, has actively promoted the market-oriented allocation of energy, optimized the oil storage and transportation system, and, thus, gained an influential price base.

Compared with coal and oil, the distortion of the industrial electricity price presented an inverted "U" shaped trend, which was closely related to the market-based electricity price mechanism implemented by coal power generation, which could fluctuate above and below the benchmark price. In addition, as shown in Figure 3, developing industrial cities like Urumqi (−0.445), Xining (−0.398), and Hohhot (−0.344) showed the highest degree of industrial electricity price distortion, while more developed and international cities such as Guangzhou (−0.040), Shanghai (−0.042), and Shenzhen (−0.050) showed the least distorted level.

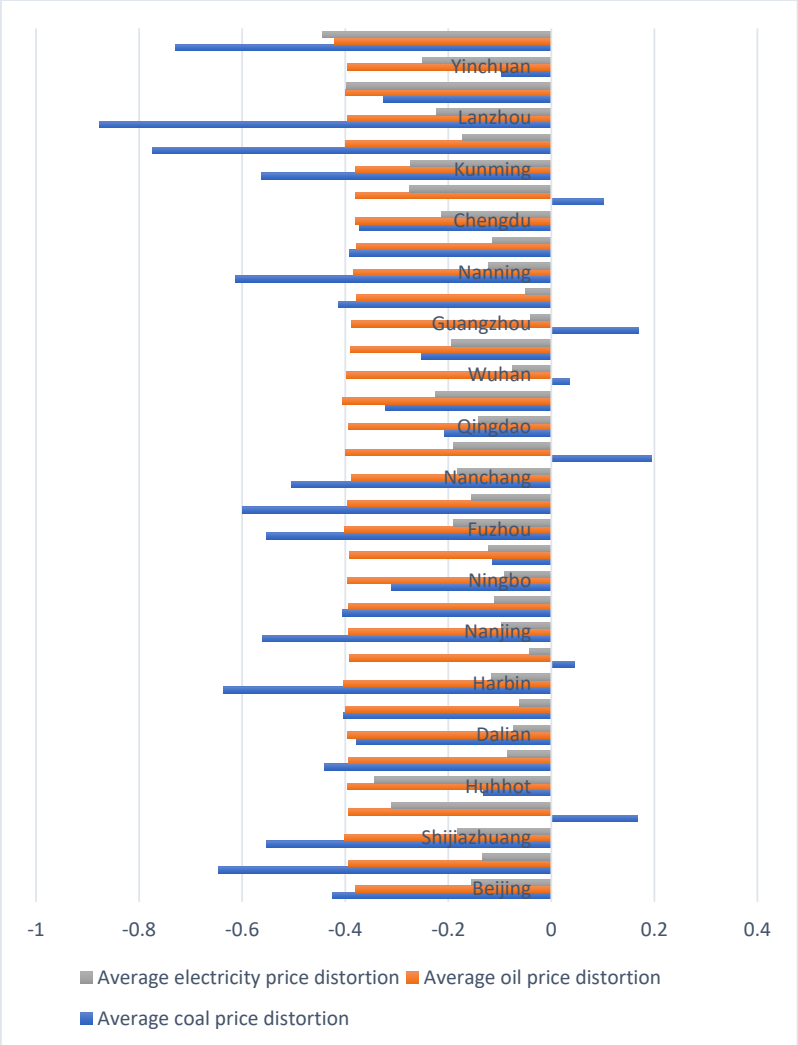


Figure 3. Average energy price distortion in major cities during 2003–2019.

4.2. Estimating Results of CEE

In order to evaluate CEE, the output and input variables and non-efficiency variables were put into Equation (6), and the final regression results are shown in Table 2. As the coefficients of most variables were statically significant at the 1% significance level, the regression results were reliable and can be used to estimate CEE further. As shown in

Figure 4, the average CEE of China's EIIs rose slowly (from 0.484 in 2004 to 0.867 in 2019). The results showed that the energy conservation and emission reduction policies in China have achieved certain positive results in recent years. The average efficiency value was only 0.546, indicating that the CEE of China's EIIs still had great room for improvement. For the sake of meeting carbon neutrality by 2060, China must make greater efforts to promote improvements in CEE.

Table 2. Results of the SFA model.

Parameters	Coef.	Std. Err.	Parameters	Coef.	Std. Err.
$LnY + LnC$	−2.449 *** (−7.30)	0.335	$(LnY + LnC) \times (LnY + LnC)$	0.161 *** (6.50)	0.025
LnK	−1.662 * (−2.75)	0.604	$T \times LnK$	−0.008 (−0.74)	0.010
LnL	0.281 (0.56)	0.504	$T \times LnL$	−0.007 (−0.77)	0.009
LnE	4.735 *** (9.33)	0.507	$T \times LnE$	0.029 *** (3.24)	0.009
$LnK \times LnL$	0.298 *** (3.65)	0.082	$T \times (LnY + LnC)$	−0.009 (−1.30)	0.007
$LnK \times LnE$	−0.163 ** (−2.38)	0.068	T	0.240 *** (3.64)	0.066
$LnK \times (LnY + LnC)$	−0.115 ** (−2.43)	0.047	$T \times T$	−0.002 ** (−2.41)	0.001
$LnL \times LnE$	−0.191 *** (−2.88)	0.066	ED	0.166 *** (2.68)	0.062
$LnL \times (LnY + LnC)$	0.072 (1.49)	0.048	$\mathrm{Ln}ER$	0.165 *** (8.35)	0.020
$LnE \times (LnY + LnC)$	−0.248 *** (−5.61)	0.044	$\mathrm{Ln}TP$	−0.111 *** (−10.75)	0.010
$LnK \times LnK$	0.052 (0.48)	0.106	$\mathrm{Ln}FDI$	−0.022 ** (−2.09)	0.010
$LnL \times LnL$	−0.202 *** (−2.64)	0.076	CON	10.679 (0.41)	26.324
$LnE \times LnE$	0.744 *** (8.86)	0.084	-	-	

Note: *** means $p < 0.01$, ** means $p < 0.05$.

As reported in Table 2, it should be noted that the negative coefficient of non-efficiency term (LnER, LnTP and LnFDI) means an improvement in CEE, while the non-efficiency variable of ED showed a positive effect and so hindered improvements in CEE, which mean that the price distortion was not conducive to carbon neutrality. As concluded by Tan and Lin [10], ED can affect CEE through energy input and improve CEE by increasing the energy price. The distorted energy prices will reduce the production cost and increase enthusiasm for the energy input, which reduces the motivation of enterprises to technology innovation and hinders improvements in production efficiency. Secondly, ED can also affect CEE indirectly through resource allocation. The price of production factors cannot reflect the demand and supply of the market, which will lead to the allocation distortion of production factors [27]. The distortion of energy allocation indicates that energy is not utilized by the sectors that really need it, which leads to more severe energy waste, pollutant emissions, and resource shortages [20]. The affecting channels are further verified in the following.

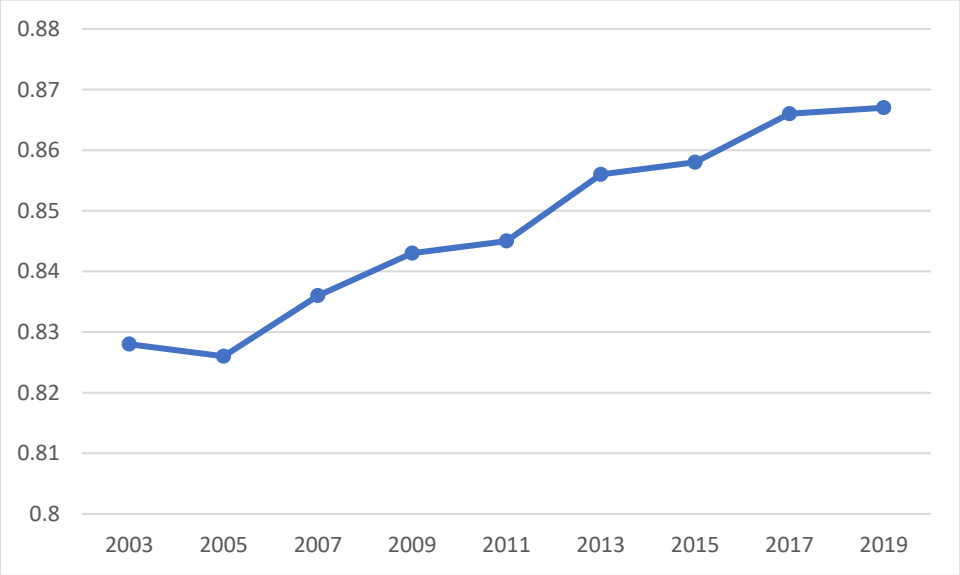


Figure 4. The changing trend of CEE in major cities in China's EIIs.

4.3. Further Discussion of Affecting Channels

As distorted energy prices affect the technical progress, energy structure, and carbon emissions in EIIs, we further analyzed how energy price distortions affect CEE. Firstly, panel unit root tests were conducted to verify the relationships among price distortion, carbon emission efficiency, and other controlled variables. The results in Table 3 show that all variables rejected the null hypothesis with unit roots at the 10% significance level; therefore, all variables were stable.

Table 3. Panel unit root test.

Test	lnCE	ED	lnRGDP	lnURB	lnFDI
LLC	−8.377 ***	−11.204 ***	−1.324 *	−45.695 ***	−5.743 ***
AD-Fisher	8.464 ***	6.934 ***	5.206 ***	4.690 ***	7.030 ***

Note: *** means $p < 0.01$, * means $p < 0.1$.

In analyzing the impact of energy price distortions on carbon emission efficiency, in order to address possible endogeneity issues, we used the system GMM approach and the IV-2SLS approach. The system GMM approach has the advantage of dealing with dynamic panel data and effectively utilizing instrumental variables. It is able to overcome the endogeneity problem in dynamic panel data by considering both the level and difference information of the variables, and it can automatically select appropriate lagged terms as instrumental variables for better identification of causality. The IV-2SLS method, on the other hand, has the advantage of being able to effectively address the endogenous explanatory variable problem by visualizing how the instrumental variables affect the endogenous variables as well as their impact on the explanatory variables through a two-stage estimation process. Compared to some other traditional methods, these methods are able to deal with the endogeneity problem more accurately and provide more reliable estimation results for study. The results are shown in Table 4.

Table 4. The evaluating results of energy price distortion on CEE in China's EIIs.

Variables	Fixed Effect	System-GMM	IV-2SLS	
	lnCE	lnCE	ED	lnCE
L.lnCE	-	−0.023	-	-
	-	(−0.04)	-	-
L.ED	-	-	0.684 ***	-
	-	-	(11.86)	-
L2.ED	-	-	0.258 ***	-
	-	-	(4.22)	-
ED	−0.039 ***	−0.108 *	-	−0.041 ***
	(−4.49)	(−1.84)	-	(−4.32)
lnRGDP	0.027 ***	0.214 *	0.021	0.037 ***
	(2.86)	(1.76)	(0.92)	(3.97)
lnURB	0.022	−0.128	0.015	0.018
	(1.41)	(−1.33)	(0.45)	(1.15)
lnFDI	0.002	−0.002	−0.010 ***	0.003 *
	(1.25)	(−0.15)	(−3.03)	(1.90)
Constant	−0.561 ***	−2.081 *	−0.288	−0.658 ***
	(−5.84)	(−1.65)	(−1.25)	(−6.60)
R-squared	0.755	/	/	0.799
Observations	578	510	510	510
Region FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES

Note: *** means $p < 0.01$, * means $p < 0.1$.

As shown in column 1, energy price distortion (ED) was negatively correlated with carbon emission efficiency (lnCE) at the 1% significance level, meaning that when the energy price distortion increased by 1%, the CEE decreased by 0.039%. Therefore, distorted fossil fuel prices reduced CEE in China's EIIs. Further considering the impact of the first-order lag term of CEE, the evaluated coefficients of system GMM showed that there was negative correlation between energy price distortion and CEE, and the evaluated coefficient ($\beta = -0.108$) was larger than that in the double fixed effect model. Adopting the first-order lag term and second-order lag term of energy price distortion as instrumental variables, the first-stage regression results showed a significant positive correlation between the instrumental variable and energy price distortion ($\beta = 0.684$ and 0.258), while the second-stage regression results showed a negative correlation between energy price distortion and CEE. Meanwhile, the chosen instrumental variables were tested using the F-statistic. The F-statistic of the first-stage regression was much greater than 10, indicating that there was no problem of weak instrumental variables. The instrumental variables selected were appropriate, and the results indicated that the relationship between energy price distortion and CEE still holds after considering endogeneity issues. In summary, the negative correlation between energy price distortion and CEE in China's EIIs was robust.

In order to assess the channels of impacts of technological progress and energy structure, the mediated effects model above is further adopted, and the results of the estimated coefficients are shown in Tables 4 and 5. As shown in Table 4, the combined effect of energy price distortion on carbon emission efficiency is −0.039, and the energy price distortion coefficient in column 3 of Table 5 is 0.355, which implies that for every 1% increase in energy price distortion, the share of fossil energy consumption will increase by 0.355%, which is not beneficial to the clean transformation of the energy structure. Meanwhile, Table 5 further shows that after controlling for the impact of technological innovation, the mediating effect of technological innovation on CEE is −0.009, accounting for 23.5% of the total effect; after controlling for the impact of the energy consumption structure, the mediating effect of the energy consumption structure on CEE is −0.012, accounting for 30.77% of the total effect.

Table 5. The evaluating results of mediating effect.

Variables	lnTE	lnCE	lnES	lnCE
ED	−0.187 **	−0.029 ***	0.355 ***	−0.027 ***
	(−2.56)	(−3.72)	(3.71)	(−3.19)
lnTE	-	0.049 ***	-	-
	-	(8.09)	-	-
lnES	-	-	-	−0.033 ***
	-	-	-	(−5.05)
lnRGDP	−0.162 **	0.035 ***	−0.575 ***	0.008
	(−2.26)	(4.11)	(−4.69)	(0.93)
lnURB	−0.091	0.026 *	0.533 ***	0.039 ***
	(−0.89)	(1.88)	(2.78)	(3.03)
lnFDI	0.036 ***	0.000	−0.033 **	0.001
	(3.43)	(0.21)	(−2.28)	(0.64)
Constant	1.894 **	−0.654 ***	3.136 ***	−0.457 ***
	(2.54)	(−7.88)	(2.91)	(−5.12)
Observations	578	578	578	578
R-squared	0.906	0.787	0.635	0.793
Region FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES

Note: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

This study adopted the bootstrap method with a 95% confidence interval to retest the mediating effect of technical innovation and energy consumption structure, and the sample size was set to 1000. When the 95% confidence interval did not include 0, the mediating effects were significant.

From Table 6, it can be seen that the 95% percentile confidence intervals for indirect and direct effects were [−0.018, −0.001] and [−0.044, −0.015], and the 95% bias-corrected deviation correction confidence intervals were [−0.018, −0.001] and [−0.046, −0.015]. The above intervals did not include 0, so the indirect effects of technical innovation and the direct effect of energy price distortion on CEE were significantly established. The results fully proved that technical innovation played a partial mediating role between energy price distortion and CEE in China's EIIs. Similarly, based on the results in Table 7, it can be concluded that the energy consumption structure also played a partial mediating role between energy price distortions and CEE. Therefore, the mediating effects were robust.

Table 6. The mediating test of technical innovation by bootstrapping.

	Observed Coef.	Bootstrap Std. Err.	Z	P [95% Conf. Interval]		BC [95% Conf. Interval]	
Indirect effect	−0.009	0.004	−2.22 **	−0.018	−0.001	−0.018	−0.001
Direct effect	−0.029	0.008	−3.76 ***	−0.044	−0.015	−0.046	−0.015

Note: P was percentile confidence interval; BC was bias-corrected confidence interval; *** $p < 0.01$, ** $p < 0.05$.

Table 7. The mediating test of energy structure by bootstrapping.

	Observed Coef.	Bootstrap Std. Err.	Z	P [95% Conf. Interval]		BC [95% Conf. Interval]	
Indirect effect	−0.012	0.004	−2.90 ***	−0.021	−0.006	−0.020	−0.005
Direct effect	−0.027	0.008	−3.29 ***	−0.042	−0.010	−0.044	−0.012

Note: P was percentile confidence interval; BC was bias-corrected confidence interval; *** means $p < 0.01$.

In summary, the empirical results indicate a significant negative correlation between energy price distortions and technological innovation indicators. As energy prices become

more distorted, research-and-development investment and the adoption of new technologies decrease. In addition, the analysis of the energy consumption structure shows that with the distortion of energy prices, the proportion of fossil energy consumption, indeed, increased. The results of the mediation effect test further support the view that energy price distortions have a negative impact on CEE through these two mechanisms. Therefore, the alternative hypothesis of Hypothesis 1 has been confirmed

As distorted fossil fuel prices affect CEE through two mediating channels of preventing technical innovation and the energy consumption structure, then how does government environment regulation policy affect the two channels? We evaluated the possible moderated mediating effect through Equations (13)–(16).

As shown in column 1 in Table 8, the coefficient of the interaction term between energy price distortion and environmental regulation was −0.125 and was significant at the 10% level, while the coefficient of technical innovation in CEE was 0.047, which proved that there was a moderating mediating effect on environmental regulation. Government environmental regulation mitigated the crowding-out effect of energy price distortion on technical innovation; the reasons could be that environmental regulation increased incentives in technical innovation investment. At the same time, in column 3 in Table 8, the coefficient of the interaction term between energy price distortion and environmental regulation was −0.169, while the coefficient of the energy consumption structure was −0.034, which proved that there was a moderating mediating effect in environmental regulation, and the moderating path in the energy consumption structure was the first half path. Environmental regulations can mitigate the negative impact of energy price distortions on the energy consumption structure; the reasons could be that the measures of environmental regulations increase the proportion of clean energy consumption and so mitigate the negative effect of price distortions.

Table 8. The moderating effect of environment regulation.

Variables	lnTE	lnCE	lnES	lnCE
ED	−0.162 **	−0.025 ***	0.383 ***	−0.019 **
	(−2.42)	(−3.11)	(3.82)	(−2.40)
lnTE		0.047 ***		
		(7.65)		
lnES				−0.034 ***
				(−5.87)
lnER	−0.035	−0.010 ***	−0.029	−0.013 ***
	(−1.40)	(−3.29)	(−0.46)	(−3.78)
$ED \times nER$	−0.125 *	−0.017 **	−0.169 *	−0.028 ***
	(−1.81)	(−2.21)	(−1.73)	(−4.25)
lnRGDP	−0.134 *	0.042 ***	−0.550 ***	0.017 *
	(−1.83)	(4.89)	(−4.21)	(1.85)
lnURB	−0.076	0.027 *	0.558 ***	0.043 ***
	(−0.74)	(1.94)	(2.90)	(3.34)
lnFDI	0.034 ***	0.000	−0.035 **	0.001
	(3.25)	(0.25)	(−2.45)	(0.50)
Constant	1.421 *	−0.768 ***	2.691 **	−0.609 ***
	(1.82)	(−8.88)	(2.06)	(−6.22)
Observations	578	578	578	578
R-squared	0.907	0.793	0.638	0.805
Province FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES

Note: *** means $p < 0.01$, ** means $p < 0.05$, * means $p < 0.1$.

Therefore, when examining data with varying degrees of environmental regulation, it is observed that as environmental regulation strengthens, the negative impact of energy price distortions on technological progress decreases. Similarly, the negative impact on the energy consumption structure has also reduced. This indicates that environmental

regulations play a regulatory role, as assumed. The alternative hypothesis of Hypothesis 2 is also supported.

5. Conclusions and Policy Proposals

To achieve the target of carbon neutrality, evaluating CEE and the possible affecting channels of fossil energy price distortion on CEE is of great importance for mitigating carbon emissions in China's EIIs. Based on theoretic analysis and panel data in 2003–2019, this study estimates the changing urban CEE using the SFA model. The results showed that although the CEE showed an increasing trend during the inspection period, the overall level was only 0.546, which reflected great room for cutting carbon emissions. The impact of fossil energy price distortion on CEE was further evaluated by the mediating effect and moderated mediating effect model. The results indicated that distorted energy prices have a negative impact on CEE. This negative impact is exerted by hindering technological innovation and increasing the proportion of distorted fossil fuels in the energy consumption structure. But government environment regulations can moderate the negative effect of fossil energy price distortion on CEE by moderating the suppressing effect on technical innovation and improving the energy consumption structure.

Based on the findings above, several policy suggestions were further proposed to improve CEE in China's EIIs.

Firstly, as distorted energy prices affect CEE negatively, conducting energy price reform should be the primary way to improve CEE. Energy price reform includes three options: (1) Strengthening supervision of coal prices. Although coal prices fluctuate with market demand, further improving the mechanism of the coal price market, fully leveraging the main role of market mechanisms in coal allocation, and making coal prices reflect production costs and downstream demand of the market were important means to reduce price distortion. The issue of environmental costs should be particularly considered in the coal price. The realization of China's carbon goals required the reflection of environmental costs in energy prices. Therefore, the development of the carbon market helped to greatly rationalize coal prices. (2) Improving the mechanism for adjusting oil and gas prices. Although the refined oil price mechanism was already in line with international standards, there was still a time lag in adjusting the refined oil prices, which cannot really reflect the supply-and-demand relationship between international and domestic markets. Natural gas prices are mainly based on direct pricing and guided pricing, and the market-oriented mechanism is still not completed. We need to further promote natural gas price reform, streamline the transmission mechanism of terminal gas prices, and make the price reflect the differential characteristics of market demand. (3) Deepening the pricing reform of power products. The price of power products should reflect the cost of energy conservation and emission reduction. The policies should focus on reforming the terminal electricity price to reflect the clean development cost and compensation mechanism of the power structure, so that the costs and benefits of power generation, transmission and distribution, and electricity consumption in the power system can be freely transmitted.

Of course, energy price reform may face political and economic challenges. Politically, for example, resistance from relevant interest groups and difficulties in policy coordination may affect the reform process. In this regard, an interest-balancing mechanism should be established, and policy synergies should be strengthened. Economically, short-term economic fluctuations and regional disparities need attention. A gradual reform strategy could be adopted, with regionally differentiated policies.

Secondly, improving technical innovation and the implementation of low-carbon techniques, technical innovation has been the fundamental way to improve CEE. In China's EIIs, low-carbon technical innovation made enterprises input energy products and reduce carbon emissions. Government needs to support technical innovation by directly increasing research-and-development funding, supporting enterprise innovation, providing education and training, and providing tax exemptions and financial subsidies. Particularly, for the promotion and utilization of low-carbon techniques and equipment, government must increase

policy support and enhance the enthusiasm of enterprises to adopt low-carbon technologies. Meanwhile, cultivating technical talent and improving the market environment, encouraging leading enterprises to integrate upstream and downstream enterprises, and implementing collaborative innovation in industrial sectors must be carried out.

Thirdly, as the energy consumption structure is an important preventing channel of improving CEE, changing the energy consumption structure and promoting favorable energy substitution should be effective ways to mitigate the negative effect of energy price distortion. In terms of primary energy consumption, enterprises should show higher market demand for natural gas than coal and oil. From a market perspective, effective guiding policies should lie in providing effective subsidies for low-carbon energy and enhancing the industry's demand orientation for low-carbon energy. On the other hand, they should reduce the proportion of thermal power and enhance the competitive advantage of clean electricity. In terms of policy orientation, it is necessary to specify and implement carbon emission standards and increase the production costs of enterprises through the internalization of externalities.

Fourthly, environmental regulations must be strengthened to moderate the adverse effect and improve carbon emission efficiency. Environmental regulation policies include command policies and market-based policies. Command-based policy is reflected in policy documents issued by the government regarding carbon emissions, which stipulate carbon emission standards and regulate carbon emission behavior through government command. It is necessary to further encourage the participation of the public and environmental organizations, implement the supervision of regulatory policies, and improve the effectiveness of policy implementation. Market-based regulation is reflected in adopting market theory to guide enterprises' carbon emission reduction behavior. Such energy rights trading and carbon emissions trading can transmit energy conservation and emission reduction costs to downstream enterprises. In the implementation process, it is necessary to further strengthen top-level design, build a diversified market trading entity, enhance the coordinated development of market-oriented regulation, and jointly promote emission reduction practices in China's EIIs.

Last, but not least, globally, many countries face energy price distortions in the process of economic development. Some governments have intervened in energy prices to varying degrees for the purposes of ensuring the stability of energy supply and social equity. For example, some developing countries, in order to promote the process of industrialization, subsidize energy prices in order to reduce the production costs of enterprises and attract investment. While such subsidy policies may have promoted economic growth in the short term, they have often led to distorted energy prices in the long term, which is not conducive to the healthy development of the energy market and improvements in carbon emission efficiency. Similarly, energy price distortions may also exist in some developed countries in the process of energy transition. For example, government policies may lead to irrational price relationships between renewable energy and traditional energy sources, which affects the efficiency of resource allocation in the energy market and, thus, has an impact on carbon emission efficiency.

Although this study focused on China's energy-intensive industries, it has implications for other countries or regions facing similar energy price distortions and carbon emission problems. Future research can be conducted in the following directions: First, the dynamic evolution and long-term impact of energy price distortions can be examined through the dynamic evolution of energy price distortions in different stages of economic development and policy environments. With the adjustment of the economic structure and changes in energy policies, energy price distortions may change. Examining this dynamic evolution process can help predict future trends in energy price distortions and provide a forward-looking basis for policy formulation. Second, renewable energy technology must be developed for energy price distortion and carbon emission efficiency on the impact of the discussion. With the progress of renewable energy technologies, their position in the energy market has become increasingly important. Studying how renewable

energy technologies change the energy price formation mechanism and how to improve carbon emission efficiency by promoting technological innovation and adjusting the energy consumption structure will help to further improve energy policies and carbon emission management strategies.

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