frontiers | Frontiers in Energy Research

TYPE Original Research
PUBLISHED 30 October 2023
DOI 10.3389/fenrg.2023.1301266

Coordinating economic growth and carbon emission reduction in China: evidence from the optimal levels of energy price distortions

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RECEIVED 24 September 2023
ACCEPTED 11 October 2023
PUBLISHED 30 October 2023

CITATION
Sha R (2023), Coordinating economic growth and carbon emission reduction in China: evidence from the optimal levels of energy price distortions.
Front. Energy Res. 11:1301266.
doi: 10.3389/fenrg.2023.1301266

Distorted energy prices cause resource mismatch and hinder the coordinated development of economic growth and carbon emission reduction (CDEC) in China. Therefore, it is essential to determine the optimal levels of energy price distortions. This paper first measures the price distortions of fossil and renewable energy sources and applies a panel smooth transition regression model to assess the optimal threshold values for the degree of energy price distortions. The results show that 1) Fossil energy price distortions are negative, and the price distortion for renewable energy is positive. 2) Energy price distortions inhibit CDEC, and this effect is regionally heterogeneous. 3) The panel smooth transformation model results indicate that distorted energy prices have a nonlinear impact on CDEC. CDEC is significantly hampered in the low regime by distorted fossil energy prices and facilitated in the high regime. In contrast, the distorted renewable energy price shows positive in the low regime and negative in the high regime. We also obtain the optimal intervals for the degree of energy price distortions that promote CDEC. With the target of "growth" and "carbon reduction," this study provides a reference for improving the energy pricing mechanism and exploring the effective ways of CDEC.

KEYWORDS

energy price distortions, coordinated development, PSTR model, economic growth, carbon emission reduction

1 Introduction

China's economy has grown unprecedentedly due to reform and opening up. However, energy market reform has progressed relatively slowly and has "asymmetric" characteristics. As an essential input for national economic development (Cleveland et al., 1984; Stern, 1993), energy affects a country's core competitiveness. For the sake of economic stability as well as strategic needs, energy prices in China have long been government-dominated, resulting in deviations from their equilibrium levels and more severe distortions (Lin and Du, 2013). The distorted energy prices do not reflect the actual energy cost, resource scarcity, and environmental externalities. As a result, energy supply and demand imbalances are exacerbated, resulting in excessive fossil fuel consumption while weakening resource

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Abbreviations: CDEC, Coordinated development of economic growth and carbon emission reduction; MPC, Marginal Production Cost; MUC, Marginal User Cost; MEC, Marginal External Cost; PSTR, Panel smooth transformation model; E area, Eastern area; C-W areas, Central-Western areas.

allocation efficiency. Thus, it becomes a bottleneck restricting the coordinated development of economic growth and carbon emission reduction (CDEC) in China.

The emergence of distortions in energy prices in China has its unique historical background and realistic circumstances. Before the Reform and Opening-up, the "catching-up strategy" of prioritizing heavy industries and leveraging the country's resource agglomeration advantage and mobilization capacity to manage factor allocation resulted in several institutional arrangements that skewed energy pricing (Lin, 1994). After that, the government was exceedingly cautious in reforming energy pricing for economic stability and growth, as the low energy price policy adopted not only maintained Chinese enterprises' and products' international competitiveness but also prevented price hikes and inflation. Moreover, under the pressure of GDP growth as the assessment performance, local governments will tighten the control of energy prices to achieve rapid economic growth. As a result, under the government-led pricing mechanism, energy prices are not fully created by supply and demand, resulting in price distortions. Compared to the more comprehensive market-based energy pricing mechanisms in industrialized nations, China's market-based energy prices need further improvement.

China's economy increased at a 6.6% annual pace from 2013 to 2021, faster than the world's average annual growth rate of 2.6% during the same period, and its GDP contributed more than 30% to global economic growth, making it a significant powerhouse of global economic development. China's economy has long run at a breakneck pace, relying on massive amounts of energy, capital, and labor factors, particularly excessive use of low-cost energy, resulting in a host of problems such as energy scarcity, carbon emissions, and environmental damage (Ouyang et al., 2018; Wang et al., 2019). The previous crude development paradigm of high input, high pollution, and low yield has highlighted the conflict between economic development and environmental optimization (Ge et al., 2023). As a crucial link between economic growth and carbon emission reduction, optimizing resource allocation by enhancing the energy pricing mechanism has become an efficient means of exploring CDEC (Song and Cui, 2016; Zhang and Adom, 2018).

Considering that distorted energy prices affect economic growth and reduction of carbon emissions via resource allocation (Restuccia and Rogerson, 2008; Bartelsman et al., 2013), which in turn threatens CDEC. Therefore, this paper proposes the following questions: Will energy price distortions inhibit CDEC? Whether correcting energy price distortions would promote CDEC, and whether there is an optimal level of distortions to achieve CDEC is a valuable research topic. China aspires to realize CDEC. Accordingly, the feasibility of achieving CDEC through energy pricing marketization policies has become a hot topic. As the world's largest energy consumer and carbon emitter, China's contradiction between economic development and environmental protection is relatively prominent (Wang and Feng, 2021). Unfortunately, existing research has concentrated on a single dimension of the economy or environment affected by energy price distortions. Existing studies rarely discuss the relationship between distorted energy prices and CDEC and rarely explore the possibility of the optimal level of distortion. With China's energy price reform deepening, policymakers are exploring ways to keep energy price distortions at an optimal level to coordinate growth and emission reductions.

The contributions lie in the following aspects. First, this paper extends the measure of energy price distortions to the renewable energy sector, which systematically illustrates the evolutionary characteristics of distortions in energy prices and enriches the studies on the measurement of distortions. Second, this study estimates the effects of energy price distortions on CDEC and regional heterogeneity, which effectively expands the research on the relationship between energy price distortions and CDEC and provides a reference for exploring effective ways to achieve CDEC. Third, this paper extends the analysis of the nonlinear relationship between distorted energy prices and CDEC and estimates the optimal intervals in which energy price distortions promote CDEC, providing a basis for the degree of distortion correction and the selection of an appropriate correction strategy.

The rest of the paper is arranged as follows. Section 2 conducts a review of the relevant literature. Section 3 shows the research methodology and discusses the construction of the panel smooth transformation model. Section 4 provides the empirical results. The conclusions and policy implications are listed in Section 5.

2 Literature review

When actual energy prices deviate from their equilibrium level under distortions, energy cannot achieve Pareto optimal resource allocation (Lin and Wang, 2009; Wang et al., 2009; Li et al., 2020). Most studies often regard energy as a factor to examine the degree of price distortions (Atkinson and Cornwell, 1998; Tao et al., 2009). Lin and Du (2015) used a marketization index to measure the degree of factor price distortions, including energy. Skoorka (2000) employs a production frontier analysis that measures factor price distortions using the gap between actual and potentially optimal production points. Subsequently, several studies have used the shadow price approach to measure factor price distortions (Atkinson and Halvorsen, 1984; Ouyang and Sun, 2015). Based on a shadow price model, Tao et al. (2009) found that energy prices were severely distorted in China's industrial sector, second only to labor price distortion. The production function approach is the most commonly used method to calculate factor price distortions. Ouyang et al. (2018), Tan et al. (2019), and Guan and Xing (2022) measure energy price distortions using the Cobb-Douglas production function. Moreover, using other methods, some scholars measured the price distortions of different energy products such as coal, electricity, and natural gas (Chai et al., 2009; Brown et al., 2017; Cui and Wei, 2017; Shi and Sun, 2017).

Two opposing opinions exist on distorted energy prices affecting economic growth: the "inhibition view" and the "promotion view." The "inhibition view" argues that distorted energy prices hinder economic growth by impeding the efficient allocation of energy sources (Brandt et al., 2013; Shi and Sun, 2017). Lin and Wang (2009) pointed out that energy prices are mainly government-led and have been low for a long time in China. Regulations enacted in 2008 preventing refined oil and natural gas from adjusting prices have led to distorted energy prices that harm the economy. Ju et al. (2017) suggested that distorted energy prices significantly impeded China's economy. According to the "promotion view," energy price distortions promote economic growth. Distortions transmit the wrong price signals, leading to an underestimation of energy prices (Lin and Jiang, 2011; Ouyang and Sun, 2015) and thus a significant reduction in production costs. The high consumption of low-cost energy stimulates economic growth in the short term. Ouyang et al. (2018) found that firms obtained production factors at lower costs when energy prices are distorted, thereby promoting economic growth. Sun and Lin (2013) suggested that government regulations on energy prices have contributed to economic development by reducing excessive increases in energy prices.

Studies have concluded that price distortions promote carbon emissions. Distorted energy prices have reduced costs significantly, but they have also led to excessive consumption of high-emission, high-polluting sources, increasing carbon emissions. The IMF (2013) report suggested that price distortions undermined the allocation of resources by stimulating the overconsumption of energy, and therefore exacerbating carbon emissions. Wang et al. (2019) suggested that distorted oil prices promote CO_2 emissions in China's transportation sector. Li et al. (2019) analyzed the effects of energy prices and population on environmental pollution in China by constructing a time-varying coefficient panel data model, and concluded that energy price distortions exacerbated environmental pollution.

CDEC refers to reducing carbon emissions while ensuring economic development goals (Pata and Aydin, 2020). Previous studies rarely explored how distorted energy prices affect CDEC, and scholars mainly focused on the influence of price distortions on energy resource allocation efficiency. Distorted energy prices reduce the efficiency of energy resource allocation (Ouyang et al., 2018; Lin and Chen, 2019). As China's economy enters a new growth model emphasizing efficiency, accelerating market-oriented reforms in energy pricing becomes urgent (Dai and Cheng, 2016). Tan et al. (2019) found that relative price distortions between capital and energy, labor and energy, inhibit the improvement of total factor energy efficiency in China's secondary industry. Sha et al. (2021) showed the inhibiting effect of fossil energy price distortions on green economic efficiency in China. According to Gao and Yuan (2022), energy price distortions significantly hindered industrial green productivity in China. The optimal allocation of energy resources has become a significant determinant in the achievement of CDEC. Considering that price distortions lead to misallocating energy resources, which hinders CDEC. To achieve CDEC, exploring the characteristics of energy price distortions and their impact on CDEC is necessary.

By sorting out the above literature, this paper concludes: First, energy is typically considered a factor in previous studies to measure the distortion of prices, ignoring different energy products' price distortion characteristics. Some studies have measured and analyzed the distortions in fossil energy prices, but none have analyzed the renewable energy price distortion. Second, most studies generally concentrated on the effects of distorted energy prices on a single dimension of the economy or the environment without examining both aspects simultaneously. The achievement of CDEC is an essential prerequisite for China's high-quality economic development and an important manifestation of the country's independent emissions reduction. The theoretical basis of this paper is mainly based on the literature on energy price distortions and resource misallocation, which inspires this study to adopt a new perspective that energy price distortions affect CDEC by influencing energy resource allocation. As distortions negatively affect the economy and carbon reduction, it is necessary to explore further ways of encouraging CDEC under the constraints of distortions. Third, the existing literature seldom discusses the nonlinear effects of energy price distortions and the potential for correcting distortions. Owing to the historic reform of energy prices and the complex structure and size of the energy industry, the relationship between distorted energy prices and CDEC is more complex than linear. Therefore, exploring the nonlinear effects of energy price distortions and analyzing the optimal levels for moderate correction of energy price distortions is necessary.

3 Methodology

3.1 Panel smooth transformation model (PSTR)

This paper introduces a frontier method that deals with nonlinear relationships between variables, namely, the panel smooth transformation model (PSTR). It can handle nonlinear relationships with sharp or smooth switches between variables without existing information about structural changes in transition variables (Ulucak et al., 2020). Based on the panel threshold model proposed by Hansen (2000), the PSTR model not only inherits its advantages but also avoids the drawback that the indicator function of interval division can only take 0 or 1. The PSTR model has two advantages: First, it allows parameter variation across individuals and over time (Tiba, 2019; Pan et al., 2021). Second, the model has strong applicability in the case of endogeneity and nonlinear effects. The model is depicted below.

$$\begin{aligned} CDEC_{it} &= \alpha_i + \beta_0 D_{Type,it} + \sum_{j=1}^{n}\beta_j X_{j,it} \\ &\quad + \left(\beta_0' D_{Type,it} + \sum_{j=1}^{n}\beta_j' X_{j,it}\right) h_z\left(q_{it};\gamma,c\right) + \varepsilon_{it} \end{aligned} \tag{1}$$

$$h_z\left(q_{it};\gamma,c\right) = \left[1+\exp\left(-\gamma\prod_{z=1}^{m}q_{it}-c_z\right)\right]^{-1} \quad \gamma>0, c_1<c_2\ldots\le c_m \tag{2}$$

In Eq. 2, $D_{Type,it}$ represents energy price distortions, referring to D_{coal}, D_{oil}, D_{gas}, and D_{re}, respectively. β_0 is the coefficient of the linear part. $\beta' h_z(q_{it};\gamma,c)$ is the coefficient of the nonlinear part. $h_z(q_{it};\gamma,c)$ indicates the conversion function, which value is between 0 and 1. ε_{it} denotes the random disturbance term. In Eq. 3, $\boldsymbol{c}$ is the position parameter, that is, the threshold value. $\boldsymbol{\gamma}$ represents the smoothing parameter (i.e., slope coefficient), which measures the transformation's smoothness and the conversion speed between different systems. $\boldsymbol{m}$ is the number of position parameters of the transformation variables, generally taken as $\boldsymbol{m} = 1$ or $\boldsymbol{m} = 2$. $h_z(q_{it};\gamma,c) = 0$ indicates that the model is in the low regime; $h_z(q_{it};\gamma,c) = 1$ denotes the model is in the high regime. Equation 2 performs a continuous nonlinear smoothing transformation between the low and high regimes since $h_z(q_{it};\gamma,c)$ transforms continuously between 0 and 1.

TABLE 1 Evaluation indicator system for economic growth and carbon emission reduction.

System layers	Sub-system layers	Indicator layers	Attribute
Economic growth	The scale of economic growth	GDP *per capita*	+
		Disposable income *per capita*	+
		Total fixed asset investment	+
		GDP growth rate	+
	Innovation of economic growth	Resource allocation efficiency	+
	Structure of economic growth	Contribution of primary industry to GDP	−
		Contribution of secondary production to GDP	−
		Contribution of tertiary production to GDP	+
		Urbanization rate	+
	Social Development	Employment rate	+
Carbon emission reduction	Energy and Environment	Carbon emissions *per capita*	−
		Carbon intensity	−
		Carbon emissions efficiency	+
	Energy Scale	Coal consumption	−
		Clean Energy Consumption	+
	Energy mix	High-carbon energy consumption ratio	−
		Low-carbon energy consumption ratio	−
		Clean energy consumption ratio	+
	Resource Environment	Forest coverage	+
		Pollution control (industrial pollution treatment investment/GDP)	+

Note: +, indicates a positive indicator; −, indicates a negative indicator.

Before performing PSTR model estimation, testing whether the model has nonlinearity features is necessary. According to the study of Gonzlez et al. (2005), the following auxiliary regression function needs to be constructed at the first-order Taylor expansion of $h_z(.) = 0$.

$$\begin{gathered} CDEC_{it} = \mu_{it}\left(\beta_0 + \lambda_0 \beta_0{}'\right) D_{Type,it} + \sum_{j=1}^{n}\left(\beta_j + \lambda_0 \beta_j{}'\right) X_{j,it} + \\ q_{it}\left(\beta_0{}^{'*} D_{Type,it} + \sum_{j=1}^{n} \beta_j{}^{'*} X_{j,it}\right) + \varepsilon_{it} \end{gathered} \tag{3}$$

where $\beta^{'*}$ is the coefficient of $\boldsymbol{\gamma}$. $\lambda_0 = h_z(q_{it}; \gamma = 0, c) = 1/2$; $\mu_{it} = \varepsilon_{it} + R(y_{it}, \gamma, c)$. To test the parameters in the auxiliary regression equation, an asymptotically equivalent LM value (subject to the χ^2 distribution), LMF value (subject to the F statistic), and LRT statistic need to be constructed.

If the null hypothesis H0: $\boldsymbol{r} = 0$ is accepted, it means that there is no nonlinear effect in the model; if the null hypothesis H0 is rejected, it demonstrates the presence of a non-linear effect and the analysis should be continued using the PSTR model. Additionally, it is necessary to test whether the model has a unique transformation function or at least two. In other words, a test for residual nonlinearity. When H0: $\boldsymbol{r} = r^*$ is no longer rejected, r^* is the number of transition functions of the model.

3.2 Measurement of distortions in energy prices

This paper applies the marginal opportunity cost pricing approach to the measurement of the theoretical price of fossil energy.

$$\boldsymbol{P} = MPC + MUC + MEC \tag{4}$$

MPC (Marginal Production Cost) is associated with energy extraction; *MUC* (Marginal User Cost) corresponds to the expense spent for immediate use (Serafy, 1981). *MEC* (Marginal External Cost) indicates the degree of environmental damage caused by exploiting energy resources (Chen et al., 2005; Lei, 1996).

Based on the measures of Ju et al. (2019) and Sha et al. (2022), this paper calculates the degrees of price distortions for the four energy sources, and the data sources are similar to that literature. The degree of fossil energy price distortions is calculated using the deviation between the actual and theoretical energy prices, as follows.

$$D_{coal} = (P_c - P_{t1})/P_{t1} \tag{5}$$

$$D_{oil} = (P_o - P_{t2})/P_{t2} \tag{6}$$

$$D_{gas} = \left(P_g - P_{t3}\right)/P_{t3} \tag{7}$$

where D_{coal}, D_{oil}, and D_{gas} are coal, oil, and natural gas price distortions, respectively. P_c, P_o, and P_g implies the actual prices. P_{t1}, P_{t2}, and P_{t3} are theoretical prices.

The distortion in renewable energy price (D_{re}) is measured as follows.

$$D_{re} = (P_r - P_{t4})/P_{t4} \tag{8}$$

where P_r denotes the actual price and P_{t4} is its theoretical price.

3.3 Measurement of CDEC

Based on coupling theory and coordination theory, this paper builds a coupled coordination degree model for measuring the degree of CDEC, which is expressed in the following way.

$$\boldsymbol{C} = \left\{\frac{Y_a \times Y_b}{\left[(Y_a \times Y_b)/2\right]^2}\right\}^k \tag{9}$$

Where Y_a and Y_b represent the combined score of the economic growth system and carbon emission reduction system, respectively. C denotes the coupling degree of economic growth and carbon emission reduction. k is the adjustment factor, usually taken as 2.

$$\boldsymbol{T} = \lambda Y_a + \mu Y_b \tag{10}$$

$$\boldsymbol{D} = \sqrt{C^* T} \tag{11}$$

T indicates the comprehensive evaluation index of CDEC. λ and μ stand for the weights of economic growth and carbon emission reduction systems, respectively. This paper considers economic growth and carbon reduction systems equally important, so the weight is taken as $\lambda = \mu = 1/2$. D represents the coupled coordinated degree. Moreover, to reduce the bias caused by the subjective evaluation of indicators, this paper adopts the entropy weight method and TOPSIS method (Li et al., 2021) to assess the comprehensive evaluation index of the economic growth system and carbon emission reduction system.

3.4 Variables description

The degree of CDEC is used as the dependent variable. Based on the basic principles of science, feasibility, and hierarchy (Li and Yi, 2020; Wu, 2021), this paper constructs the evaluation indicator system for economic growth and carbon emission reduction as follows (Table 1):

The degree of openness (Open) and the total exports and imports to GDP, ratio is used to represent this variable. Industrial structure (Indus) is measured by the share of value added of secondary industry in the GDP, of each province. The provincial population at the end of the year serves as a proxy for population (Pop). Urbanization (Urban) is measured as the proportion of the population that lives in urban areas.

This paper adopts the panel data of 30 provinces in Mainland China (except Tibet) from 2006 to 2020. Data related to the calculation of energy price distortions and other data mentioned above are from the CEIC, database, Price Statistical Yearbook, Annual BP, statistical yearbook, Annual Reports of China Shenhua Energy Company Limited, National Bureau of Statistics, Annual Reports of China National Petroleum Corporation, Wind database, National Energy Administration, China Energy Statistical Yearbook, China Environmental Statistical Yearbook, China Statistical Yearbook, provincial statistical yearbooks, and Almanac of China Guodian Corporation.

4 Empirical results

4.1 Analysis of distortions in energy prices

Table 2 shows that the prices of all four energy products are distorted. Fossil energy prices are negatively distorted, with coal (−0.171) being the highest, with oil (−0.090) and natural gas (−0.058) following closely behind; renewable energy price distortion is positive, at 0.541. The negative distorted fossil energy prices indicate that the current energy pricing policy implemented by the government keeps fossil energy prices low for a long time to reduce production costs, stimulate rapid economic development, and maintain the international competitiveness of Chinese products.

Several reasons contribute to the highest degree of coal price distortion. First, coal still dominates the energy consumption mix in China, with coal consumption accounting for 56.9%[1] of total energy consumption in 2020. Although coal plays an imperative role in industrial development, its high environmental cost causes the price difference between its actual price and theoretical benchmark to grow. Second, the competitive function of the coal pricing mechanism has not been fully released. Coal trading market transactions are still far from getting to the requirements of a national unified market. Third, after nearly 5 years of downward price movement, the supply-side capacity clearing overlaid with the capacity removal policy, China's coal prices have been upward since 2016. To stabilize coal prices, the National Development and Reform Commission (NDRC) adopted a "benchmark price + floating price" pricing method for LCCs (Zuo, 2018). Therefore, the coal price is still under control, with a gap with the expected market-based price mechanism.

Negative distortions in oil and gas prices indicate that the prices are not fully marketized (Rioux et al., 2019; Lin and Kuang, 2020). As the Chinese government has been reforming oil prices since 1998, the pace of marketization was slow. However, the oil price distortion decreased by 46.8% in 2009, indicating that reforming refined oil prices in 2009 was crucial to alleviating distortions (Lin and Ouyang, 2014; Zhu and Chen, 2019). Natural gas has a lower MEC and is less distorted than other fossil fuels. Natural gas price distortion declined significantly in 2010, down 65.6% from the previous year, primarily owing to the 2010 natural gas resource tax reform. However, the reform of the market-based mechanism of natural gas pricing is still lagging, so its price distortion still exists.

The positive distorted renewable energy price implies that its actual price is larger than the theoretical benchmark, which the following reasons may cause. First, renewable energy is most commonly converted into electricity (Jiang et al., 2020; Lin and Xu, 2021). Electricity market price reform needs to be faster, which

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[1] Data source: National Bureau of Statistics. http://www.stats.gov.cn/tjsj/.

TABLE 2 Average price distortions of four energy products over the period 2006–2020.

	D_{coal}	D_{oil}	D_{gas}	D_{re}
2006	−0.064	−0.244	−0.171	1.012
2007	−0.217	−0.231	−0.211	1.001
2008	−0.253	−0.231	−0.266	0.489
2009	−0.186	−0.122	−0.186	0.519
2010	−0.237	−0.103	−0.064	0.630
2011	−0.248	−0.143	−0.107	0.476
2012	−0.227	−0.120	−0.093	0.517
2013	−0.190	−0.099	−0.067	0.486
2014	−0.171	−0.087	−0.075	0.551
2015	−0.129	−0.036	−0.019	0.575
2016	−0.080	0.026	0.039	0.601
2017	−0.146	0.018	0.056	0.428
2018	−0.157	0.008	0.079	0.312
2019	−0.126	0.006	0.106	0.277
2020	−0.134	0.005	0.114	0.244
E area (Eastern area)	−0.140	−0.077	0.054	0.642
C-W areas (Central-Western areas)	−0.189	−0.098	−0.122	0.483
Average	−0.171	−0.090	−0.058	0.541

restricts the formation of the market-oriented pricing mechanism of renewable energy, causing apparent distortions. Second, due to technology, scale, and market, the investment in R&D of renewable energy is high, leading to a high power generation cost (Ge et al., 2022). Compared with coal-fired power generation, renewable energy electricity prices lack a competitive advantage (Zhao et al., 2011; Trujillo-Baute et al., 2018). Third, renewable energy generation accounts for a small percentage of total energy production. Because renewable energy is intermittent and discontinuous, its quality is inferior to conventional energy. It is still necessary to subsidize renewable energy development. While subsidies can help cover high costs, the gap between the subsidized funds and the cost of renewable energy continues to widen (Zhang et al., 2020), further reducing the competitiveness of renewable energy.

The data used to calculate energy price distortions in this paper are from Sha et al. (2022), but unlike that, the time span is updated to 2020. There are several reasons for updating the time period: 1) To accurately measure the degrees of distortions and present more current information on energy price distortions in China. The results show that the degree of energy price distortions is coal (−0.171), oil (−0.090), natural gas (−0.058), and renewable energy (0.541), lower than coal (0.177), oil (−0.105), natural gas (0.084) and renewable energy (0.585) in the previous study. This result confirms that China's energy price distortions gradually improve as the market-based energy pricing reform deepens. 2) After updating the time period, it is shown that price distortions for coal, oil, and renewable energy, have continued to decrease. However, natural gas price distortion has been increasing. The result indicates that reforming the market-based mechanism of natural gas pricing among fossil energy sources is lagging. Compared to the previous article, the updated time period reveals the significance of this result. 3) Updating the time span not only enriches the information conveyed by the data but also shows the impact of the energy price reform policies implemented by the Chinese government on the degrees of energy price distortions, which helps this paper to analyze the current situation of energy price distortions in China.

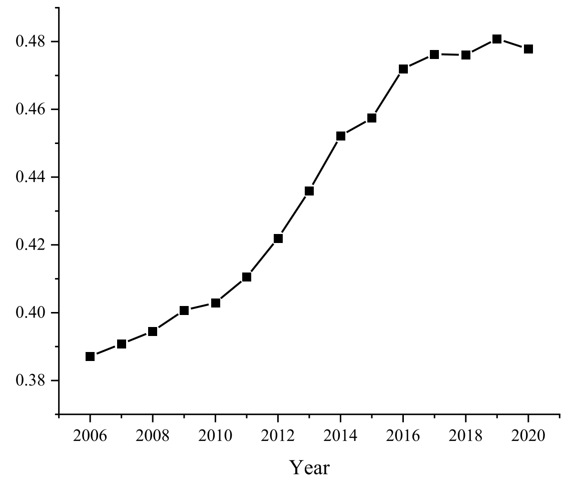

FIGURE 1
Trends in CDEC at the national level during 2006–2020.

The average values of distortions across regions show that fossil energy price distortions are higher in the C-W areas than in the E area. However, the opposite result is observed for renewable energy price distortion. The results prove that China's energy market is regional, coinciding with the study by Ma and Oxley (2011).

4.2 Description of CDEC

(1) National level

The national average value of CDEC is 0.436, which means China's CDEC belongs to the transitional phase of the grinding process. As shown in Figure 1, the mean value of the national CDEC is increasing, rising from 0.387 in 2006 to 0.478 in 2020, an increase of 23.42%. This result indicates that the interaction between our economic growth and carbon reduction system is strengthened. The government's awareness of the importance of coordinating economic growth with carbon emission reduction is a significant reason. With the introduction of the concept of green development in the 11th Five-Year Plan, the government has begun to formulate and implement measures to reduce carbon emissions and balance economic growth and reduction efforts.

(2) Regional level

Figure 2 presents apparent differences in CDEC degree among regions in China, showing high levels in the E area and low levels in the C-W areas, which aligns with the study of Weng et al. (2022).

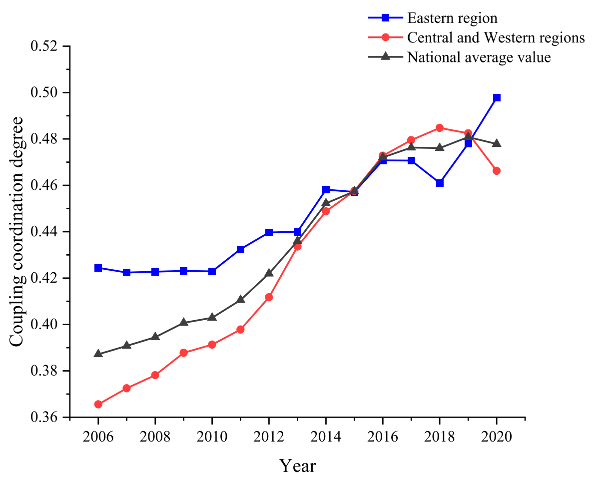

FIGURE 2
Trends in CDEC at the regional level during 2006–2020.

The mean value of CDEC in the E area is 0.448, which is higher than the national average and the C-W areas (0.429). The main reason for the difference is the higher economic agglomeration in the E area and the high investment in emissions reduction technology and environmental protection. High-energy-consuming enterprises are clustered in the C-W areas. Thus, the industrial structure of the C-W areas is unreasonable, economic development relies on resource development, and environmental protection needs to be more protected, resulting in low CDEC. A trend of increasing CDEC has been observed in the C-W areas between 2016 and 2019, probably attributed to the significant effect of removing production capacity in coal and steel industries during the 13th Five-Year Plan period. CDEC of the E area rose again after 2019, undoubtedly related to the region's good economic base, energy technology innovation, and other factors.

4.3 Basic regression results

Table 3 indicates that the coefficients of D_{coal}, D_{oil}, D_{gas} and D_{re} are all negative and are significant at 5%, suggesting that distorted energy prices inhibit CDEC. Similar findings were also found in the studies of Lin and Chen (2018); Du et al. (2021). When each percentage of price distortions increases, the degree of CDEC decreases by 6.8%, 3.4%, 3.0%, and 2.2%, respectively, suggesting differences in the influence of price distortions for various energy sources on CDEC.

Specifically, coal price distortion has the most significant inhibiting effect on CDEC. Distorted energy prices fail to reflect the scarcity of energy resources, the actual supply and demand, and environmental externalities, which weakens the resource allocation efficiency and results in a loss of economic output while exacerbating the high-carbon energy consumption, thereby inhibiting CDEC. Coal price distortion has the most significant negative impact on CDEC, which can be explained by the fact that coal remains China's dominant energy source. Due to the long-term reliance on coal resources, the industry forms a monopoly with a single economic structure. With an imperfect market trading mechanism, coal price distortion hinders CDEC. Furthermore, most control variable results align with this paper's expectations.

In Table 4, all distorted energy prices in the E and C-W areas significantly negatively impact CDEC, indicating that energy price distortions hinder regional CDEC. Distorted oil, gas, and renewable energy prices impede CDEC of the E area. Due to the "cumulative cycle effect," both the pace and scale of economic development in the

TABLE 3 The effects of energy price distortions on the national CDEC.

Variables	(1)	(2)	(3)	(4)
D_{coal}	−0.068** (0.031)			
D_{oil}		−0.034*** (0.006)		
D_{gas}			−0.030** (0.015)<	
D_{re}				−0.022*** (0.008)
lnOpen	0.016*** (0.006)	0.002** (0.001)	0.015*** (0.005)	−0.001 (0.005)
lnIndus	0.005 (0.024)	0.002 (0.002)	0.005 (0.019)	0.106*** (0.031)
lnPop	0.004 (0.005)	0.001* (0.001)	0.036*** (0.011)	0.026** (0.011)
lnUrban	0.020 (0.027)	−0.010*** (0.003)	0.113*** (0.026)	0.254*** (0.019)
Constant	0.402*** (0.059)	0.791*** (0.007)	0.203** (0.089)	0.579*** (0.104)
Wald test	878.69 [0.000]	878.62 [0.000]	891.70 [0.000]	409.94 [0.000]
Log likelihood	944.04	944.05	946.02	850.07
LR test	605.73 [0.000]	604.55 [0.000]	609.95 [0.000]	488.07 [0.000]
N	450	450	450	450

Note: ***$P < 0.01$.
**$P < 0.05$.
*$P < 0.1$, respectively. Robust standard errors are in parentheses and *p*-values are in brackets.

TABLE 4 The impact of energy price distortions on the regional CDEC.

Variables	E area				C-W areas			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
D_{coal}	−0.016* (0.009)				−0.037*** (0.011)			
D_{oil}		−0.264*** (0.099)				−0.021*** (0.007)		
D_{gas}			−0.013** (0.006)				−0.011* (0.006)	
D_{re}				−0.014* (0.008)				−0.006* (0.004)
lnOpen	0.115*** (0.013)	0.050*** (0.017)	0.003 (0.003)	0.004 (0.004)	0.009** (0.004)	0.004*** (0.001)	0.008*** (0.002)	0.004*** (0.001)
lnIndus	0.057*** (0.016)	0.030 (0.038)	−0.004 (0.009)	−0.004 (0.007)	−0.015 (0.019)	0.019*** (0.004)	−0.010 (0.019)	0.022*** (0.040)
lnPop	−0.036*** (0.008)	−0.031 (0.021)	0.002 (0.002)	0.009*** (0.003)	0.064*** (0.012)	−0.001 (0.001)	0.057*** (0.011)	−0.001 (0.001)
lnUrban	−0.246*** (0.049)	−0.036 (0.054)	−0.019 (0.012)	−0.068 (0.054)	0.144*** (0.032)	−0.011*** (0.004)	0.088*** (0.032)	−0.008** (0.004)
Constant	0.672*** (0.065)	0.638*** (0.174)	0.396 (0.370)	0.725*** (0.029)	−0.011 (0.089)	0.094 (0.066)	−0.012 (0.086)	0.873*** (0.009)
Wald test	158.24 [0.000]	158.37 [0.000]	144.08 [0.000]	152.30 [0.000]	764.17 [0.000]	837.87 [0.000]	740.99 [0.000]	740.81 [0.000]
Log likelihood	349.09	349.16	345.74	347.91	600.74	611.08	597.82	597.77
LR test	115.24 [0.000]	144.79 [0.000]	151.59 [0.000]	153.52 [0.000]	458.25 [0.000]	411.63 [0.000]	459.92 [0.000]	385.35 [0.000]
N	165	165	165	165	285	285	285	285

Note:***$P < 0.01$.

**$P < 0.05$.

*$P < 0.1$, respectively. Robust standard errors are in parentheses and *p*-values are in brackets.

TABLE 5 Results of linear and nonlinear tests of the PSTR model.

		D_{coal}	D_{oil}	D_{gas}	D_{re}
Linear test	LM	36.128 (0.000)	15.307 (0.002)	25.481 (0.005)	25.931 (0.001)
(H_0:$r = 0$;H_1:$r = 1$)	LM_F	6.023 (0.000)	4.895 (0.002)	2.461 (0.007)	3.149 (0.002)
	LRT	37.661 (0.000)	15.573 (0.001)	26.231 (0.003)	26.708 (0.001)
Nonlinear test	LM	3.603 (0.730)	2.719 (0.437)	4.725 (0.450)	5.784 (0.216)
(H_0:$r = 1$;H_1:$r = 2$)	LM_F	0.549 (0.771)	0.833 (0.476)	0.860 (0.508)	1.328 (0.259)
	LRT	3.618 (0.728)	2.728 (0.436)	4.750 (0.447)	5.821 (0.213)
$m = 1$	AIC	−5.921	−6.029	−6.019	−5.957
	BIC	−5.802	−5.956	−5.910	−5.866
$m = 2$	AIC	−5.940	−6.025	−6.001	−5.954
	BIC	−5.858	−5.943	−5.883	−5.853

Note: ***$P < 0.01$.
**$P < 0.05$.
*$P < 0.1$, respectively. Robust standard errors are in parentheses.

TABLE 6 Estimation results of the PSTR model.

Variables	D_{coal}	D_{oil}	D_{gas}	D_{re}
Low regime (β_0)	−0.170***	−0.514*** (0.075)	−0.143*** (0.055)	0.241**
	(0.024)			(0.113)
High regime (β_1)	0.192***	0.237*** (0.081)	0.169*** (0.044)	−0.198**
	(0.025)			(0.105)
Smoothing parameter (γ)	24.260	20.290	19.429	10.330
Location parameter (C)	−0.193	−0.061	−0.262	0.118

Note: ***$P < 0.01$.
**$P < 0.05$.
*$P < 0.1$, respectively. Robust standard errors are in parentheses.

E area have increased, boosting the demand for oil, gas, and renewable energy. Thus, the hindering effects of these three energy price distortions are more significant. There is a more significant inhibiting impact of coal price distortion on CDEC in the C-W areas, mainly because its industrial mix is dominated by coal, and the distorted coal price contributed significantly to its economic development, thereby increasing dependence on coal. The inertia of the crude development model has slowed the restructuring of the industrial structure in the C-W areas, and backward production cannot generate substantial economic benefits. Additionally, the C-W areas lack sufficient investments in the R&D of clean energy technologies, which hinders emissions reduction efforts.

4.4 Robustness test

The replacement of core variables, sub-sample regression, and the generalized method of moments for robustness tests are applied to test the robustness of the basic regressions. First, use green total factor productivity to replace the dependent variable (CDEC). Second, according to each province's marketization degree and market mechanism, the total sample is divided into the developed and post-developed provinces. Third, because of the possible bias in estimation due to endogeneity issues, this paper employs the differential GMM method (DIF-GMM) and system GMM method (SYS-GMM) for robustness tests. Overall, the three robustness estimations demonstrate that energy price distortions inhibit CDEC, indicating that the model estimates are robust.

4.5 Nonlinear effect analysis

Table 5 presents the results of linear and nonlinear residual tests. The results of linearity tests show that the LM, LMF, and LRT tests of the four energy price distortions reject the null hypothesis H_0: $r = 0$ at the 1% significance level, suggesting that distorted energy prices exert a nonlinear impact on CDEC. The nonlinear residual test shows that the p-values of the LM, LMF, and LRT for the four models of energy price distortions are greater than 0.05, which indicates that the null hypothesis H_0: $r = 1$ cannot be rejected. The result suggests that all four PSTR models of energy price distortions contain only one nonlinear transition function, that is, $r = 1$ is the optimal number of transformation variable functions. Moreover, the

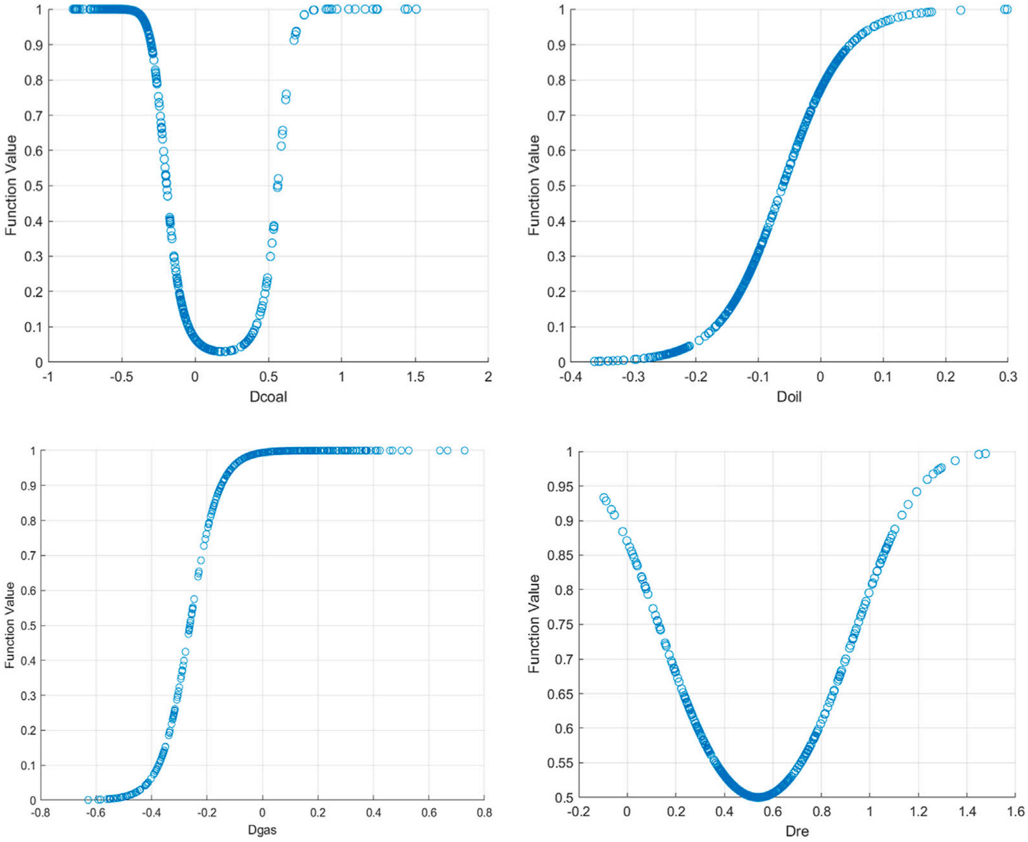

FIGURE 3
Transformation functions of energy price distortions.

number of location parameters is determined by the AIC and BIC criteria. $m = 2$ in which D_{coal} is located corresponds to AIC and BIC values less than $m = 1$ for the transition variable, and its optimal location parameter is $m = 2$. The AIC and BIC values corresponding to transition variables at $m = 1$ in the models of D_{oil}, D_{gas} , and D_{re} are less than $m = 2$, and the number of position parameters is determined as $m = 1$.

From the PSTR results in Table 6, the location parameters of the models in which D_{coal}, D_{oil}, D_{gas}, and D_{re} are located are −0.193, −0.061, −0.262, and 0.118, respectively. The effects of distortions on both sides of the location parameters are significantly different, indicating that the effects of distorted energy prices on CDEC are nonlinear and have prominent threshold characteristics. The coefficients of D_{coal}, D_{oil}, and D_{gas} are negative at the 1% level in the low regime and significantly positive at the 1% level in the high regime. The coefficient of D_{re} has a positive value in the low regime and a negative one in the high regime. They are significant at the 5% level.

Specifically, when D_{coal}, D_{oil}, and D_{gas} are below −0.193, −0.061, and −0.262, respectively, the distortions result in a low price of fossil energy, which increases fossil energy consumption, thereby hindering CDEC. However, when the degrees of fossil energy price distortions are greater than the respective location parameters, the distortions facilitate CDEC. In other words, as market-based energy pricing reforms continue to deepen, fossil energy prices have increased, and distortions have decreased, thus reducing the inhibiting effect of distortions on CDEC. If D_{re} is less than 0.118, the renewable energy price distortion is reduced and its price decreases, which promotes renewable energy consumption and contributes to CDEC. In contrast, when D_{re} exceeds 0.118, renewable energy becomes more expensive and has no price advantage compared with fossil energy, thus increasing the potential for fossil energy substitution. Therefore, it has an inhibiting effect on CDEC.

Based on different smoothing parameters and location parameters, the transformation functions of energy price distortions are shown in Figure 3. The transformation functions of distortions for all energy products' prices exhibit a gradual change, which indicates that the choice of the PSTR model is reasonable.

The PSTR results indicate that the impact of the four energy price distortions on CDEC is not monotonically facilitated or inhibited. The higher the fossil energy price distortions, the more pronounced the inhibiting effect on CDEC. The degree of CDEC is higher when the distorted renewable energy price is lower. This result is similar to the study of Du et al. (2021). According to Du et al. (2021), the nonlinear effect of energy price distortions on CDEC may be attributed to the reduced marginal contribution of energy price distortions to the constraint effect of CDEC. Furthermore, the effective intervals in which price distortions for different energy types contribute to CDEC are coal price distortion $[-0.193, +\infty)$, oil price distortion $[-0.061, +\infty)$; natural gas price distortion $[-0.262, +\infty)$, and renewable energy price distortion $(-\infty, 0.118]$, respectively.

5 Conclusion and policy implications

This paper estimates the impact of price distortions of four energy products on CDEC in China and further analyzes the nonlinear effects of distortions.

Following are the main conclusions. 1) The prices of all four types of energy are distorted. Fossil energy price distortions are negative, with coal (−0.171) being the highest, with oil (−0.090) and natural gas (−0.058) following closely behind. Renewable energy price distortion is positive at 0.541. 2) The national CDEC of economic growth and reduction of carbon emissions has an average value of 0.436 during the study period, which belongs to the teething process of the transition phase. CDEC is uneven across regions in China, showing high in the E area and low in the C-W areas. 3) Distorted energy prices inhibit CDEC in China, and there are differences in the effects of price distortions of different energy products. Distorted coal price has the most significant inhibitory impact on CDEC. Additionally, the impact of distortions on CDEC is regionally heterogeneous. Distorted oil, natural gas, and renewable energy prices impede eastern China's CDEC. In contrast, distorted coal price has a more substantial impeding effect on the C-W areas' CDEC. 4) Distorted energy prices exert a nonlinear impact on CDEC. The results of the PSTR model show that with the continuous correction of energy price distortions, the role of the promotional impact on CDEC gradually increases. Furthermore, the optimal intervals of distortions to promote CDEC are coal price distortion $[-0.193, +\infty)$, oil price distortion $[-0.061, +\infty)$; natural gas price distortion $[-0.262, +\infty)$, and renewable energy price distortion $(-\infty, 0.118]$, respectively.

Based on the empirical results, this paper proposes the following policy recommendations.

First, improving the market mechanism of energy prices and building a national unified price system. Coordinate the pace of pricing market reform of different energy products and rationalize the price ratios between various types of energy, such as fossil and renewable energy. According to the national unified large market construction guidance, accelerate the construction of a multi-energy systematized pricing mechanism and establish a unified system of energy prices to enhance the effective transmission of prices between the different types of energy. With the establishment of an energy pricing mechanism that reflects environmental externalities, resource scarcity, and supply and demand, energy price distortions can be corrected to obtain an optimal allocation of energy resources and ultimately achieve CDEC.

Second, formulating differentiated regional policies of energy prices. For eastern China, it should allow the market to play a fully effective role in energy pricing, reduce inefficient or even ineffective policy measures, guide enterprises to accelerate the renewal of energy-efficient capital and maximize the benefits of energy input. For the central-western areas, the dominance of energy pricing should gradually shift from the government to the market, making energy prices reflect the actual supply and demand and the scarcity of energy resources. Use of market-based instruments to regulate energy prices, unblock the impact of energy prices on demand, and provide more support for investment policies to increase access to financing and channels for energy companies to renew their capital. Moreover, it should break up the energy market's division, encourage the energy factor's free movement across regions, ensure that energy resources are allocated effectively, and promote CDEC.

Third, strategies to correct energy price distortions should be optimized. The estimation indicates that energy price distortions nonlinearly impact CDEC. Therefore, the government should clarify the policy measures and implementation efforts for adjusting energy prices in light of energy price distortions. With the changes in energy prices domestically and internationally, it is prudent to grasp the level of price deregulation and release of market-driven intensity. In this regard, the government should determine what level of price distortions to correct for different energy products and how to adjust them according to the economic development and emission reduction realities at the national, regional, and provincial levels. Taking the results of the optimal levels of energy price distortions in this paper as a reference, the government should actively promote the energy market-based pricing mechanism, adhere to the resource tax reform, and optimize energy price subsidies. In addition, efforts should be made to develop the digital economy, improve the construction of the carbon market, promote technological innovation, and alleviate distortions in energy prices so that the market-based mechanism can play a leading role in CDEC.

Although this study provides a valuable exploration of the relationship between energy price distortions and CDEC, due to the availability of data, the subject of this paper does not deeply explore the issue of relative energy price distortions. The relative distortions between energy product prices may affect the consumption proportionality of energy sources, thereby influencing CDEC. Therefore, it is necessary to analyze the relative energy price distortions further to understand the interactions between the prices of different energy products, which could provide a more detailed characterization of energy price distortions in China. Furthermore, it will be significant for policymakers if the study scope is expanded from China to emerging economies in future research.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

RS: Conceptualization, Data curation, Funding acquisition, Methodology, Project administration, Validation, Writing–original draft, Writing–review and editing.

Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. This work is supported by the National Social Science Foundation of China (Grant No. 20XJL012) and 2023 Intramural Cultivation Program of Philosophy and Social Sciences at Xinjiang University (Grant No. 23CPY017).

Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The handling editor JZ declared a shared affiliation with author RS at the time of the review.

Publisher's note

References

Atkinson, S. E., and Cornwell, C. (1998). Profit versus cost frontier estimation of price and technical inefficiency: a parametric approach with panel data. *South. Econ. J.* 64 (3), 753–764. doi:10.2307/1060791

Atkinson, S. E., and Halvorsen, R. (1984). Parametric efficiency tests, economies of scale, and input demand in US electric power generation. *Int. Econ. Rev.* 25, 647–662. doi:10.2307/2526224

Bartelsman, E., Haltiwanger, J., and Scarpetta, S. (2013). Cross-country differences in productivity: the role of allocation and selection. *Am. Econ. Rev.* 103 (1), 305–334. doi:10.1257/aer.103.1.305

Brandt, L., Tombe, T., and Zhu, X. (2013). Factor market distortions across time, space and sectors in China. *Rev. Econ. Dyn.* 16 (1), 39–58. doi:10.1016/j.red.2012.10.002

Brown, D. P., Eckert, A., and Eckert, H. (2017). Electricity markets in transition: market distortions associated with retail price controls. *Electr. J.* 30 (5), 32–37. doi:10.1016/j.tej.2017.04.010

Chai, J., Guo, J. E., Wang, S. Y., and Lai, K. K. (2009). Why does energy intensity fluctuate in China? *Energy Policy* 37 (12), 5717–5731. doi:10.1016/j.enpol.2009.08.037

Chen, L., Xing, Z., and Li, N. (2005). The environmental value of wind power. *Renew. energy* (05), 50–52. (in Chinese).

Cleveland, C. J., Costanza, R., Hall, C. A., and Kaufmann, R. (1984). Energy and the US economy: a biophysical perspective. *Science* 225 (4665), 890–897. doi:10.1126/science.225.4665.890

Cui, H., and Wei, P. (2017). Analysis of thermal coal pricing and the coal price distortion in China from the perspective of market forces. *Energy Policy* 106, 148–154. doi:10.1016/j.enpol.2017.03.049

Dai, X., and Cheng, L. (2016). Market distortions and aggregate productivity: evidence from Chinese energy enterprises. *Energy Policy* 95, 304–313. doi:10.1016/j.enpol.2016.05.009

Du, W., Li, M., Li, K., and Lin, J. (2021). Impact of energy market distortions on the productivity of energy enterprises in China. *Energy J.* 42 (4). doi:10.5547/01956574.42.4.wdu

Gao, K., and Yuan, Y. (2022). Does market-oriented reform make the industrial sector "Greener" in China? Fresh evidence from the perspective of capital-labor-energy market distortions. *Energy* 254, 124183. doi:10.1016/j.energy.2022.124183

Ge, T., Cai, X., and Song, X. (2022). How does renewable energy technology innovation affect the upgrading of industrial structure? The moderating effect of green finance. *Renew. Energy* 197, 1106–1114. doi:10.1016/j.renene.2022.08.046

Ge, T., Li, C., Li, J., and Hao, X. (2023). Does neighboring green development benefit or suffer from local economic growth targets? Evidence from China. *Econ. Model.* 120, 106149. doi:10.1016/j.econmod.2022.106149

Gonzlez, A., Tersvirta, T., and van Dijk, D. (2005). *Panel smooth transition regression models*. Research Paper 165. Quantitative Finance Research Centre. Sydney: University of technology.

Guan, H., and Xing, M. (2022). Impact of energy price distortion on green TFP based on spatial econometric model. *Math. Problems Eng.* 2022, 1–8. doi:10.1155/2022/1117675

Hansen, B. E. (2000). Sample splitting and threshold estimation. *Econometrica* 68 (3), 575–603. doi:10.1111/1468-0262.00124

International Monetary Fund (IMF), (2013). *Energy subsidy reform: lessons and implications*.

Jiang, Z., Lyu, P., Ye, L., and wenqian Zhou, Y. (2020). Green innovation transformation, economic sustainability and energy consumption during China's new normal stage. *J. Clean. Prod.* 273, 123044. doi:10.1016/j.jclepro.2020.123044

Ju, K., Su, B., Zhou, D., and Wu, J. (2017). Does energy-price regulation benefit China's economy and environment? Evidence from energy-price distortions. *Energy Policy* 105, 108–119. doi:10.1016/j.enpol.2017.02.031

Ju, K., Wang, Q., Liu, L., and Zhou, D. (2019). Measurement of the price distortion degree for exhaustible energy resources in China: a discount rate perspective. *Emerg. Mark. Finance Trade* 55 (12), 2718–2737. doi:10.1080/1540496x.2019.1587708

Lei, M. (1996). Study on integrated accounting between economy and natural resources (II)—— index Formation. *Syst. Engineering-Theory Pract.* (10), 91–98. (in Chinese).

Li, H., Huang, J., Hu, Y., Wang, S., Liu, J., and Yang, L. (2021). A new TMY generation method based on the entropy-based TOPSIS theory for different climatic zones in China. *Energy* 231, 120723. doi:10.1016/j.energy.2021.120723

Li, K., Fang, L., and He, L. (2019). How population and energy price affect China's environmental pollution? *Energy Policy* 129, 386–396. doi:10.1016/j.enpol.2019.02.020

Li, K., Fang, L., and He, L. (2020). The impact of energy price on CO2 emissions in China: a spatial econometric analysis. *Sci. Total Environ.* 706, 135942. doi:10.1016/j.scitotenv.2019.135942

Li, W., and Yi, P. (2020). Assessment of city sustainability—coupling coordinated development among economy, society and environment. *J. Clean. Prod.* 256, 120453. doi:10.1016/j.jclepro.2020.120453

Lin, B., and Chen, Y. (2019). Does electricity price matter for innovation in renewable energy technologies in China? *Energy Econ.* 78, 259–266. doi:10.1016/j.eneco.2018.11.014

Lin, B., and Chen, Z. (2018). Does factor market distortion inhibit the green total factor productivity in China? *J. Clean. Prod.* 197, 25–33. doi:10.1016/j.jclepro.2018.06.094

Lin, B., and Du, K. (2015). Energy and CO2 emissions performance in China's regional economies: do market-oriented reforms matter? *Energy Policy* 78, 113–124. doi:10.1016/j.enpol.2014.12.025

Lin, B., and Du, K. (2013). The energy effect of factor market distortion in China. *Econ. Res. J.* 48 (09), 125–136. (in Chinese).

Lin, B., and Jiang, Z. (2011). Estimates of energy subsidies in China and impact of energy subsidy reform. *Energy Econ.* 33 (2), 273–283. doi:10.1016/j.eneco.2010.07.005

Lin, B., and Ouyang, X. (2014). A revisit of fossil-fuel subsidies in China: challenges and opportunities for energy price reform. *Energy Convers. Manag.* 82, 124–134. doi:10.1016/j.enconman.2014.03.030

Lin, B. Q., and Kuang, Y. M. (2020). Natural gas subsidies in the industrial sector in China: national and regional perspectives. *Appl. Energy* 260, 114329. doi:10.1016/j.apenergy.2019.114329

Lin, B., and Wang, F. (2009). Impact of energy price increase on general price level in China: a study based on input-output model and recursive SVAR Model. *Econ. Res. J.* 44 (12), 66–79+150. (in Chinese).

Lin, B., and Xu, B. (2021). A non-parametric analysis of the driving factors of China's carbon prices. *Energy Econ.* 104, 105684. doi:10.1016/j.eneco.2021.105684

Lin, Y. (1994). The strategic decision is the key to the success of economic reform and development. *Econ. Sci.* (03), 3–7. (in Chinese).

Ma, H., and Oxley, L. (2011). Are China's energy markets cointegrated? *China Econ. Rev.* 22 (3), 398–407. doi:10.1016/j.chieco.2011.05.002

Ouyang, X., and Sun, C. (2015). Energy savings potential in China's industrial sector: from the perspectives of factor price distortion and allocative inefficiency. *Energy Econ.* 48, 117–126. doi:10.1016/j.eneco.2014.11.020

Ouyang, X., Wei, X., Sun, C., and Du, G. (2018). Impact of factor price distortions on energy efficiency: evidence from provincial-level panel data in China. *Energy Policy* 118, 573–583. doi:10.1016/j.enpol.2018.04.022

Pan, X., Wei, Z., Han, B., and Shahbaz, M. (2021). The heterogeneous impacts of interregional green technology spillover on energy intensity in China. *Energy Econ.* 96, 105133. doi:10.1016/j.eneco.2021.105133

Pata, U. K., and Aydin, M. (2020). Testing the EKC hypothesis for the top six hydropower energy-consuming countries: evidence from Fourier Bootstrap ARDL procedure. *J. Clean. Prod.* 264, 121699. doi:10.1016/j.jclepro.2020.121699

Restuccia, D., and Rogerson, R. (2008). Policy distortions and aggregate productivity with heterogeneous establishments. *Rev. Econ. Dyn.* 11 (4), 707–720. doi:10.1016/j.red.2008.05.002

Rioux, B., Galkin, P., Murphy, F., Feijoo, F., Pierru, A., Malov, A., et al. (2019). The economic impact of price controls on China's natural gas supply chain. *Energy Econ.* 80, 394–410. doi:10.1016/j.eneco.2018.12.026

Serafy, S. E. (1981). Absorptive capacity, the demand for revenue, and the supply of petroleum. *J. Energy Dev.*, 73–88.

Sha, R., Li, J., and Ge, T. (2021). How do price distortions of fossil energy sources affect China's green economic efficiency? *Energy* 232, 121017. doi:10.1016/j.energy.2021.121017

Sha, R., Ge, T., and Li, J. (2022). How Energy price distortions affect China's economic growth and carbon emissions. *Sustainability* 14 (12), 7312. doi:10.3390/su14127312

Shi, X., and Sun, S. (2017). Energy price, regulatory price distortion and economic growth: a case study of China. *Energy Econ.* 63, 261–271. doi:10.1016/j.eneco.2017.02.006

Skoorka, B. M. (2000). Measuring market distortion: international comparisons, policy and competitiveness. *Appl. Econ.* 32 (3), 253–264. doi:10.1080/000368400322688

Song, M., and Cui, L. B. (2016). Economic evaluation of Chinese electricity price marketization based on dynamic computational general equilibrium model. *Comput. Industrial Eng.* 101, 614–628. doi:10.1016/j.cie.2016.05.035

Stern, D. I. (1993). Energy and economic growth in the USA: a multivariate approach. *Energy Econ.* 15 (2), 137–150. doi:10.1016/0140-9883(93)90033-N

Sun, C., and Lin, B. (2013). Reforming residential electricity tariff in China: block tariffs pricing approach. *Energy Policy* 60, 741–752. doi:10.1016/j.enpol.2013.05.023

Tan, R., Lin, B., and Liu, X. (2019). Impacts of eliminating the factor distortions on energy efficiency—a focus on China's secondary industry. *Energy* 183, 693–701. doi:10.1016/j.energy.2019.06.155

Tao, X. M., Xing, J. W., Huang, X., and Zhou, W. (2009). The measurement of energy price distortions and factor substitution in Chinese industry. *J. Quantitative Technol. Econ.* 11, 3–16. (in Chinese).

Tiba, S. (2019). Modeling the nexus between resources abundance and economic growth: an overview from the PSTR model. *Resour. policy* 64, 101503. doi:10.1016/j.resourpol.2019.101503

Trujillo-Baute, E., del Río, P., and Mir-Artigues, P. (2018). Analysing the impact of renewable energy regulation on retail electricity prices. *Energy Policy* 114, 153–164. doi:10.1016/j.enpol.2017.11.042

Ulucak, R., Koçak, E., Erdoğan, S., and Kassouri, Y. (2020). Investigating the non-linear effects of globalization on material consumption in the EU countries: evidence from PSTR estimation. *Resour. policy* 67, 101667. doi:10.1016/j.resourpol.2020.101667

Wang, M., and Feng, C. (2021). The win-win ability of environmental protection and economic development during China's transition. *Technol. Forecast. Soc. Change* 166, 120617. doi:10.1016/j.techfore.2021.120617

Wang, Q., Qiu, H. N., and Kuang, Y. (2009). Market-driven energy pricing necessary to ensure China's power supply. *Energy Policy* 37 (7), 2498–2504. doi:10.1016/j.enpol.2009.03.008

Wang, X., Bai, M., and Xie, C. (2019). Investigating CO2 mitigation potentials and the impact of oil price distortion in China's transport sector. *Energy Policy* 130, 320–327. doi:10.1016/j.enpol.2019.04.003

Weng, Q., Lian, H., and Qin, Q. (2022). Spatial disparities of the coupling coordinated development among the economy, environment and society across China's regions. *Ecol. Indic.* 143, 109364. doi:10.1016/j.ecolind.2022.109364

Wu, C. (2021). Research on the synergistic effect of low-carbon economy in China. *J. Manag. World* 37 (08), 105–117. (in Chinese). doi:10.19744/j.cnki.11-1235/f.2021.0110

Zhang, L., and Adom, P. K. (2018). Energy Efficiency Transitions in China: how persistent are the movements to/from the frontier? *Energy J.* 39 (6). doi:10.5547/01956574.39.6.lzha

Zhang, R., Shimada, K., Ni, M., Shen, G. Q., and Wong, J. K. (2020). Low or No subsidy? Proposing a regional power grid based wind power feed-in tariff benchmark price mechanism in China. *Energy Policy* 146, 111758. doi:10.1016/j.enpol.2020.111758

Zhao, Z. Y., Zuo, J., Fan, L. L., and Zillante, G. (2011). Impacts of renewable energy regulations on the structure of power generation in China–a critical analysis. *Renew. Energy* 36 (1), 24–30. doi:10.1016/j.renene.2010.05.015

Zhu, H., and Chen, X. (2019). Asymmetric effects of oil prices and exchange rates on China's industrial prices. *Energy Econ.* 84, 104551. doi:10.1016/j.eneco.2019.104551

Zuo, Q. (2018). A look at the dual-track system of coal prices with a historical perspective. China Coal Network. Available at: http://www.ccoalnews.com/gcj/201807/27/c83055.html.