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Will High Carbon Prices Reduce Fossil Fuel Use in China? Evidence from Price Elasticity Estimates using Firm Data

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Abstract

China is transitioning from command-and-control energy-saving and carbon abatement policies to a carbon trading mechanism, aiming to reduce CO_2 emissions more cost-effectively, replacing implicit carbon pricing with explicit carbon pricing. This shift raises a critical question: will high carbon prices reduce fossil fuel consumption in China? If so, carbon trading could serve as a pivotal tool for limiting emissions while addressing policy conflicts with Europe under the Carbon Border Adjustment Mechanism (CBAM) to some extent.

Our study explores how Chinese manufacturing firms might respond to higher carbon prices by examining how they respond to energy prices. We do this by estimating long- and short-run energy price elasticities using firm-level data from 2007–2016. We leverage provincial energy price variations for long-run elasticity estimates through pooled cross-sectional analysis and examine short-run elasticity using an unbalanced panel model.

The results indicate that manufacturing firms are responsive to energy price changes in the long run but largely unresponsive in the short term, likely due to the short-term effects of technology lock-in. These findings suggest that transitioning to carbon trading is an effective strategy for reducing CO_2 emissions and mitigating China's CBAM liabilities on energy-intensive exports, though ensuring policy continuity remains a significant challenge.

Keywords Carbon price; Carbon trading; CBAM; Energy price elasticity

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Will High Carbon Prices Reduce Fossil Fuel Use in China?

Evidence from Price Elasticity Estimates using Firm Data

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1. Introduction

The escalating global concern regarding climate change has propelled carbon pricing to the forefront of low-carbon policy tools worldwide. As carbon pricing continues to expand globally, questions regarding its effectiveness have been a longstanding focus of inquiry. Early studies on carbon pricing policies suggest that carbon pricing serves as a catalyst for manufacturing firms to cut CO_2 emissions and enhance facility energy efficiency while maintaining production outputs (Kerr and Newell (2003); Del Río González (2008)). Real-world dynamics are shaped by profit-maximizing motives. As the price of emissions rises, firms are motivated to exert efforts in reducing CO_2 emissions. The imposition of costs on carbon emissions incentivizes firms to adopt energy-saving measures, thereby contributing to environmental sustainability.

Although carbon trading is theoretically recognized as an effective and cost-efficient instrument with the potential to achieve carbon abatement, increase productivity, and stimulate innovation, a key research challenge persists in understanding how firms might respond to rising carbon prices. Discerning individual firm responses to carbon pricing is necessary for policy formation (Adam, 2015), as micro-responses provide an important supplementary perspective for shaping macroeconomic policies related to carbon pricing. Several studies have investigated how firms react to carbon pricing. Jones and Levy (2007) contend that fungible carbon trading under loose regulatory caps would foster the development of trading systems infrastructure and capabilities, but would not incentivize significant investments in high-risk, low-emission technologies and actual CO_2 reduction. Nils Ohlendorf et al. (2022) find firms respond more to the higher carbon price floor of EU ETS using a survey of 113 German companies. Kim and Bae (2022) show firms in the manufacturing and power sectors respond differently to carbon prices in Korea, manufacturing firms reduce CO_2 emissions by improving energy efficiency while the power sector cuts CO_2 emissions by phasing out fossil fuels. However, evidence from a new panel of British firms shows that EU ETS has engendered heightened levels of low-carbon patent application and R&D expenditures among regulated firms without necessarily inducing immediate reductions in carbon intensity of output (Calel, 2020). Evidence from Lithuanian firm-level data suggests that EU ETS did not induce reduction in CO_2 emissions but cause a slight reduction in CO_2 intensity (Jaraitė, Maria, 2016).

Most of these studies focus on the qualitative analysis of firms' behavioral responses to carbon price or energy price variation, at low levels carbon price variation, and some of them investigate the effect of the implementation of carbon markets on regulated firms. Research on how firms respond precisely to price signals is scarce. More effort should aim shed light on overall energy price elasticity, which higher carbon prices will contribute to, as this gets the core issue of the extent to which price policy tools are useful to achieve net zero. For countries, like China, that have recently introduced carbon pricing it is useful to investigate how firms are likely to respond as carbon prices rise, driving up effective fossil fuel energy prices.

China is an interesting country to study the impact of energy pricing because of the presence of a large number of state-owned firms, where the profit motive might be weaker. Alternatively, state backed Chinese firms might face combined social and budget constraints which mean that higher energy prices are more likely to increase energy efficiency in an attempt to maintain both employment and budget balance at the same time, especially over the longer run.

Most of the existing research on price elasticity is based on aggregate data. However, findings derived from microdata may diverge from those obtained using aggregate data. Solow (1987) highlights the issue of aggregation bias when estimating inter-factor elasticities using aggregate data. Stern (2012) has also emphasized the need for additional long-run elasticity estimations based on microdata to obtain more precise and less biased results. Despite the significant calls for research based on microdata, there is still quite a paucity of literature using firm-level data. We try to fill the gap in this paper. While direct observation of carbon price signals is preferable, analyzing responses to energy price variations provides a valuable alternative, especially when related data is unavailable and when carbon prices remain at a low level. This underscores the need for a comprehensive exploration of the dynamics between energy price fluctuations and firm responses for a more nuanced understanding of the effectiveness of carbon trading.

In this study, we estimate the long-run and short-run price elasticities of coal, oil, and electricity demand, as well as for coal intensity, oil intensity, and electricity intensity in both own- and cross-price elasticity aspects. We use microdata from the Chinese National Tax Survey Database (CNTSD) during the period from 2007 to 2016; we estimate the annual provincial coal delivery price from 2007 to 2016 and calculate the average annual oil and electricity price in this period. We deploy pooled cross-section regressions to estimate the long-run price elasticities, this strategy allows us to treat provincial price variation as permanent price change and estimate the long-run elasticities taking advantage of a broad spectrum of provincial price variation. We estimate the short-run price elasticities taking advantage of the overlayed observations across years.

Our study contributes in several ways to the literature on firms' potential behavioral response to carbon pricing, price elasticity of energy demand, price elasticity of energy intensity, and energy substitution.

First, this work fills a gap in the research on the long-run and short-run price elasticity of energy demand (coal, oil, and electricity) and energy intensity (coal intensity, oil intensity, and electricity intensity) using microdata in China. There is a notable scarcity of research on inter-fuel substitution at the firm level. Most existing studies, including those cited earlier, have primarily focused on inter-fuel substitution using aggregate country or industry-level data. A limited number of studies have delved into this issue using firm-level data, prompting Stern (2009) to emphasize the need for additional research based on microdata encompassing a broader array of countries. Stern (2012) points out that many elasticities estimated in the literature likely pertain to short-run rather than the theoretically preferable long-run elasticities of substitution. Larger sample studies employing estimators conducive to long-run estimates, particularly for elasticities involving coal, are deemed essential. Stern (2012) underscores that the difficulty firms face in substituting between clean and dirty fuels directly influences the cost of climate-change mitigation, as emphasized by Acemoglu et al. (2012) from a macroeconomic perspective.

For China, the lack of provincial delivery coal price is another factor hindering the comprehensive investigation of the price elasticity of energy demand, as coal is the main energy type consumed by China, any analysis that ignores coal would not be useful for policy decisions. We make a deliberate effort to estimate the delivery coal price at the province level first, this allows the following price elasticity estimations. Cross-price elasticities also provide implications for energy substitution possibility. Especially in the long run, as *electrification* is an important part of the pathway toward net zero, price elasticity analysis enhances our understanding of the cost of electrification.

Second, our study provides new insights into the influence of ownership on firms' different responses to price signals. Most of the existing studies of price elasticity use aggregate data, so cannot provide an examination of the influence of the ownership structure. Public-owned firms still constitute a large fraction of industrial output in China. The interaction of public-owned firms and carbon pricing will play a big part in the roadmap of net zero, as carbon pricing assumes firms behave under the profit maximization principle, the non-profit-maximization feature of public-owned firms deserves extra attention.

The rest of the paper proceeds as follows. We describe the research background of China's marketization process and CBAM in section 2. In Section 3, we review the literature price elasticity estimations. The estimations methods and data are explained in sections 4 and 5. In section 6, we present the empirical results. In section 7, we present the robustness checks. In section 8, we discuss our conclusions and the policy implications of our results.

2. Background

The ongoing expansion of China's national carbon market aims to control CO_2 emissions cost-effectively. However, the low carbon price and the underperformance of the market raise concerns about the effectiveness of the carbon price signal in reducing fossil fuel consumption. This divergence brings into question whether the carbon market can serve as the primary tool for China to achieve its net-zero goal.

China's energy market has become increasingly market-oriented, beginning with the abolition of coal price regulation in 1993, followed by the deregulation of refined oil prices in 1998, leading to greater price variability. Although the reform of China's electricity market has lagged behind, changes in electricity prices have still occurred (Wang et al., 2021). This background provides a foundation for investigating price elasticity in China. In addition to concerns about the potential carbon reduction effects of China's carbon market, investigating carbon price responses can provide valuable insights into whether China can mitigate the impact of the CBAM by transitioning from traditional policies to a market-based approach.

As a crucial effort to meet the Paris Agreement targets, the EU aims to reduce net greenhouse gas emissions by at least 55% by 2030, with the EU Emissions Trading System (EU ETS) serving as the primary tool for achieving this objective. In December 2022, the European Council and the European Parliament reached a provisional agreement to increase emissions reductions in sectors covered by the EU ETS to 62% by 2030 (European Council, 2022). The emissions cap under the EU ETS decreases over time to meet this goal. However, concerns have arisen that tightening the ETS may render European energy-intensive industries uncompetitive (Joltreau and Sommerfeld, 2019; Kuik and Hofkes, 2010). In addition, the EU ETS has focused attention on the cost of the continuing free allocation of permits to EU industrial sectors.

To address these concerns and prevent carbon leakage, the EU decided to phase out free allocation of permits to energy intensive industry and implement the Carbon Border Adjustment Mechanism (CBAM). This decision comes despite ongoing debates about whether stricter regulations lead to carbon leakage (Franzen and Mader, 2018). CBAM aims to prevent carbon leakage and maintain a level playing field in high-emitting industries (Bellora and Fontagné, 2023). Numerous ex-ante simulation analyses suggest that a CBAM is necessary to reduce carbon leakage (Antimiani et al., 2013; Babiker and Rutherford, 2005; Elliott et al., 2010; Bellora and Fontagné, 2023). Carbon leakage occurs when domestic firms relocate production to regions with less stringent emissions policies or lose market share to unregulated foreign competitors. This is because domestic firms face higher production costs due to environmental policies, making unregulated foreign firms more competitive. However, Naegele and Zaklan (2019) argue that the costs of reallocating production and the relatively small differences in emission costs across countries, especially compared to labor costs, reduce the likelihood of leakage. They conducted an empirical analysis using embodied carbon in trade flows to evaluate whether EU ETS emission costs caused carbon leakage in European manufacturing from 2004 to 2011, finding no evidence that the EU ETS caused carbon leakage.

Despite potential resistance from other countries (Overland and Sabyrbekov, 2022; Tagliapietra and Wolff, 2021), a political agreement was reached in December 2022 at the EU level on introducing CBAM. It will gradually replace existing EU mechanisms addressing carbon leakage risk, particularly the free allocation of EU ETS allowances (European Council, 2022). CBAM is designed to function alongside the EU ETS, mirroring and complementing its impact on imported goods. After the transitional period ends in 2026, EU imports in certain energy intensive industrial sectors will be subject to a carbon tariff, requiring importers to purchase and surrender "CBAM Certificates," ensuring that the carbon tariff matches the carbon price paid by EU producers under the ETS rules.

Some studies argue that CBAM-like measures will be particularly challenging for developing countries (Zhang, 2011), especially China, due to the high share of energy-intensive industries in its exports (Li and Zhang, 2012). In the CBAM design, importers who can prove that exports have paid an explicit carbon price in their origin country will be credited accordingly to avoid double taxation. This mechanism is seen as a means to encourage other countries to implement carbon pricing tools. However, despite the launch of China's national carbon market in 2021, carbon prices remain relatively low. Traditional command-and-control policies still dominate China's emission reduction policy system (Lu et al., 2023). At the current stage, only explicit carbon prices will be considered in the calculation of compensation at the EU border, not including the implicit carbon price of command-and-control measures, which remains challenging to calculate (Black et al., 2022). This implies that even if non-EU countries implement stringent emissions measures, their exports to the EU will still be subject to CBAM unless they adopt carbon pricing mechanisms and keep the same level of carbon price. This could lead to opposition and possible retaliatory trade measures from other countries. Alternatively, non-EU countries might adjust their policy mix to adapt to CBAM, transitioning from command-and-control measures to carbon trading mechanisms.

CBAM will be phased in gradually and 100% liability applies in 2034. It is also the case that CBAM will also be accompanied by a gradual removal of free permits to EU industrial sectors which will mean that EU exports will no longer receive an exemption from paying for carbon emissions. This means CBAM have the effect of raising the costs of EU exports at the same time as it raises the costs of competing imports. With the continuing maturation of China's ETS, extending carbon pricing to cover the sectors covered by CBAM and to raise the price of carbon permits towards that of the EU ETS can mitigate the impact of CBAM on China. The extending has begun to happen with the recent announcement that the China's ETS will be extended to cover the steel, cement, and aluminum smelting industries (MEE, 2025). Thus, China is on a pathway towards higher carbon prices for more industrial sectors. It is against this background that our study examines the extent to which firms in China are sensitive to price fluctuations in carbon prices. It is not surprising that firms may not respond sensitively to low carbon prices, as there is little incentive for additional abatement when the carbon price falls below the existing marginal abatement cost. What is of greater interest, however, is whether firms would exhibit more pronounced responsiveness under relatively high carbon prices—a scenario anticipated in the future as China's ETS matures. Nevertheless, due to the current immaturity of the carbon market, its limited operational duration, and relatively low carbon prices, the existing conditions are insufficient to assess firms' responses to high carbon prices. As a result, this study shifts its focus to examining firms' energy price elasticities as a proxy for potential carbon price responsiveness. A finding that rising energy prices produce large negative effects on energy consumption will suggest that higher carbon prices will actually produce mitigating reductions in carbon emissions.

3. Literature review

The recent launch of China's national carbon market in 2021, coupled with the apparent underperformance of regional ETS pilots (Lu et al., 2023), creates a lack of sufficient data and conditions for directly examining responses to carbon pricing. As an alternative, this study explores energy price elasticity to assess how price signals influence energy consumption and emissions reductions, providing valuable insights for the development of long-term carbon pricing policies in China. To demonstrate the transferability of energy price elasticity to carbon price elasticity, we apply an assumed carbon price of 83 EUR/tonne (the average EU ETS carbon price in 2023) to China's manufacturing firms as an illustrative example. Using the CO_2 emission factors—1.9003 kg CO_2/kg for coal[1]—the equivalent carbon price increase is calculated to be 157.72 EUR/tonne for coal. Assume a currency exchange rate of 7.6 CNY /EUR, this equals to 1198.67 CNY/tonne for coal, this represents an increase of nearly 1.8 times the current coal price[2]. Using the CO_2 emission factors—3.0202kg CO_2/kg for oil, 0.5703tonne CO_2/MWh for electricity, equivalent carbon price increases are 1905 CNY /tonne for oil, and 0.36 CNY /kWh for electricity. The core of the transfer process from carbon price to energy price increases lies in the multiplication by a coefficient, where an increase in carbon price leads to a proportional rise in energy prices. This highlights the rationale for investigating energy price elasticities as a method to assess responses to carbon price signals.

We review research on energy price elasticities across various countries, listing the key studies in Table 1. A significant portion of recent energy price elasticity research has focused on developed countries, with many studies concentrating on electricity price elasticity, particularly in residential contexts, while research on coal and the manufacturing sectors remains relatively limited (Alberini and Filippini, 2011; Miller and Alberini, 2016; Dergiades and Tsoulfidis, 2008; Archibald & Gillingham, 1980; Ito, 2014). The insights gained from household responses to energy price fluctuations may not be directly transferable to firms. Discussions on the price elasticity of fossil fuels in industrial and manufacturing sectors primarily stem from earlier decades in developed countries, likely due to the historical dominance of fossil fuel consumption in these regions. Even within developed countries, the findings of these studies vary widely, reflecting the diverse contexts and methodologies employed (Bhattacharya, 1996).

China is the largest emitter of CO_2, with the majority of emissions stemming from the combustion of fossil fuels, particularly coal. China's unique energy endowment, economic structure, and energy price levels all influence its energy price elasticities.

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[1] Use information from "General Rules for the Calculation of Comprehensive Energy Consumption" (GB/T 2589-2008), "Guidelines for the Compilation of Provincial Greenhouse Gas Inventories" (NDRC Office Climate No. 1041), "Notice on the Management of Greenhouse Gas Emission Reporting for the Power Generation Industry Enterprises for 2023-2025" to calculate CO_2 emission factors.

[2] The average coal price in China is 675 CNY per ton (based on annual contracts for 5,500 kcal thermal coal, as reported by the NDRC)

Consequently, the price elasticities of fossil fuels estimated for developed countries in the past century seems cannot be directly applied to China. Therefore, obtaining precise and accurate estimates of energy elasticities for China is crucial for assessing the potential effectiveness of market-based policy tools, especially at this pivotal moment, when carbon markets are receiving unprecedented global attention. While some research has focused on China's energy price elasticities, most of it has concentrated on the aggregate national level. Coal, which constitutes a significant portion of China's energy resources, has led to a coal-dominated energy structure. The manufacturing sector, after electricity, is the largest energy consumer. However, only a few studies on elasticity have addressed coal and the manufacturing sector in China.

Table 1: Energy price elasticities in literature

Authors	**Energy**	**Data level**	**Short run**	**Long run**	**Sector**	**Country**
Burke and Abayasekara (2018)	Elec.	State-sector	-0.11	[-1.17, -1.71]	Indust.	US (2003-2015)
				[-0.95, -1.16]	Resid.	
				[-0.34, -0.60]	Comm.	
			-0.10	[-0.88, -1.02]	Total	
Hyland and Haller (2018)	Elec.	Firms	-0.309		Manuf.	Ireland (2004-2009)
	Oil		-0.675			
	Gas		-1.169			
Schulte and Heindl (2017)	Elec.	Household	-0.431		Resid.	Germany (1993-2008)
	Heat.		-0.5008			
Woodland (1993)	Coal	Establishments	[-0.407, -1.068]		Manuf.	Australian NSW (1977-1985)
	Oil		[-0.825, -2.302]			
	Gas		[-2.487, -3.87]			
	Elec.		[-0.97, -1.745]			
Fuss (1977)	Coal	Sector	-1.48		Manuf.	Canada (1961-1971)
	LPG		-2.39			
	Fuel oil		-1.3			
	Gas		-1.3			
	Elec.		-0.74			
	Gasoline		-1.59			
Goetzke and Vance (2021)	Gasoline	Micro	-0.05 and -0.29		Resid.	US (2009,2017)
Alberini and Filippini (2011)	Elec.	State	-0.15	-0.73	Resid.	US (1995-2007)
Miller and Alberini, (2016)	Elec.	Household	-0.387	-0.671	Resid.	US (1997-2009)
Jones (1995)	Oil	Sector	[-0.100, -0.115]	[-0.35, -0.48]	Indust.	US (1960-1992)
	Coal		[-0.108, -0.307]	[-0.39, -1.27]		
	Elec.		[-0.05, -0.08]	[-0.21, -0.29]		
	Gas		[-0.153, -0.17]	[-0.60, -0.63]		
Burke and Liao (2015)	Coal	Provincial	-0.2		Agg.	China (2008-2012)
Ma and Stern (2016)	Coal	Provincial	[-0.03, -0.199]		Agg.	China (2000-2010)
	Elec.		[-0.063, -0.369]			
	Gasoline		-1.704			
	Diesel		-0.888			

Ma and Oxley (2012)	Energy	Provincial	-0.4715		Agg.	China (1995-2004)
Masih and Masih (1996)	Coal	Country	-0.8296	-0.9914	Agg.	China (1953-1992)

Notes: Elec. denotes Electricity; Indust., Industry sector; Resid., Residential sector; Comm., Commercial sector; Manuf., Manufacturing sector; Agg., Aggregate economy.

Improving facility efficiency often incurs additional costs. Papageorgiou et al. (2013) emphasizes that the transition to clean technologies, essential for substantial CO_2 emissions reductions, requires appropriate incentives to encourage firms to shift from dirty to clean production. Firms' short-run and long-run behaviors may diverge significantly. Most price elasticity research on China relies on aggregate data and lacks a comparison between long-run and short-run elasticities, often concluding that demand is relatively inelastic. The unavailability of provincial coal prices and firm-level data may be key factors hindering more in-depth research.

Beyond own-price elasticity, comprehensive and precise estimates of cross-price elasticity are also limited. Certain studies, such as Ma et al. (2008), have expressed optimism about the feasibility of replacing dirty coal with cleaner energy sources. However, the notably low estimate of the elasticity of substitution between coal and electricity in final energy consumption by Ma and Stern (2016) suggests that the transition from coal to renewably generated electricity in end-use applications may involve substantial costs. Li and Lin (2016) estimated cross-price elasticities in China and found them to be inelastic, noting that fixed energy-using equipment and heterogeneous technologies limit the effectiveness of substitution strategies for energy conservation and environmental management. To some extent, the absence of both short-run and long-run estimates of cross-price elasticities, may have contributed to divergent conclusions and hindered a precise understanding of how price changes are responded to.

Energy intensity is a critical concern globally, particularly for China, where CO_2 emissions have not yet reached the peak. Higher energy prices may incentivize firms to reduce energy intensity (Cornillie and Fankhauser, 2004; Metcalf, 2008; Wing, 2008). Cornillie and Fankhauser (2004) identify energy prices as one of the two most significant drivers of more efficient energy use. These studies underscore the pivotal role that energy prices play in reducing energy intensity. As output expands, firms must decide which technologies to invest in to accommodate growth, thereby facilitating a departure from the lock-in effect that might otherwise arise from continued reliance on existing capital. Furthermore, research indicates that the price elasticity of coal intensity in China exhibits an increasing trend. For instance, Hang and Tu (2007) report a coal price elasticity of demand of -0.3 before 1995 and -1.6 after 1995. More precise estimates of both short-run and long-run own- and cross-price elasticities of energy intensity are crucial for informing more effective policymaking aimed at reducing energy intensity.

Elasticity estimation results show a pronounced sensitivity to the type of data (aggregate or disaggregate) and the estimation methodology (time series, panel, or cross-section regressions) used in primary studies. As highlighted by Lu and Stern (2016), estimation outcomes hinge critically on factors such as technological change, substitution dynamics among energy inputs, and fuel interactions.

Solow (1987) highlights the issue of aggregation bias when estimating inter-factor elasticities using aggregate data. Aggregate estimates, influenced by general equilibrium effects, may wrongly suggest factor substitution even when not technologically feasible, casting doubt on the reliability of substitution estimates derived from aggregate data. Solow argues that factor substitution, being a microeconomic phenomenon, is best scrutinized using microeconomic data. Contrasting macro studies, Bjørner and Jensen (2002) found low inter-fuel substitution within companies, attributing the lower elasticity to macro studies capturing derived demand effects in addition to technical substitution. Hyland and Haller (2018), in their estimation of partial and total fuel substitution elasticities based on panel data from manufacturing firms in Ireland, discovered that industry-level estimates indicated a higher degree of substitution between electricity and oil compared to the firm level. They observed a greater sensitivity of electricity demand to its own price but a weaker sensitivity to changes in the prices of other fuels, implying that incentivizing large-scale switching from fossil fuels to electricity usage may not be feasible through price instruments alone. To avoid biased estimations, we use microdata.

Labandeira et al. (2017) reveals that long-term energy price elasticities of demand consistently surpass short-term elasticities. Energy economists have identified two prominent characteristics in the analysis of energy use and prices: In time-series data, energy consumption exhibits minimal changes with changes in energy prices (Berndt and Wood, 1975). In cross-sectional data spanning countries, energy consumption is responsive to international variations in energy prices (see Griffin and Gregory, 1976; Pindyck, 1979). Apostolakis (1990) and Bacon (1992) observed that panel data studies tend to reveal greater substitutability, as measured by cross-price elasticities, compared to time-series studies. Bacon (1992) suggested that this discrepancy arises from the representation of long-run elasticities in the data, contrasting with the short-run elasticities generated by time-series data. Koetse et al. (2008) also found that cross-section estimates yield the highest elasticities of substitution, time series estimates yield the lowest, with fixed effects estimates falling in between. Cooper (2003) noted that short-run elasticities of demand for crude oil in 23 countries are minimally responsive to price changes, while long-run elasticities surpass their short-run counterparts. Lim et al. (2014) observed that electricity demand in the service sector in Korea is inelastic to short-run changes in both price and income; however, it becomes elastic in the long run. Atkeson and Kehoe (1999) proposed two models of energy use to replicate the observed low short-run and high long-run elasticities. They found that due to adjustment costs, the capital stock responds sluggishly to energy price fluctuations, given the high complementarity of energy and capital in production. In the long run, the capital stock and energy use adjust to permanent differences in energy prices. The models predict a low elasticity of energy use in the short run due to fixed proportions of energy use in existing capital. In the long run, agents invest in different capital goods with varied fixed energy intensities, resulting in responsive energy use to differences in energy prices. The lock-in mechanism accounts for the difficulty and cost associated with changing technology in the short run (Edelstein and Kilian, 2007).

Energy price shocks have played a minor role in driving fluctuations in most forms of investment in structures and equipment. One potential mechanism through which energy price shocks may influence non-residential fixed investment is the increase in the price of energy, raising the marginal cost of production. The extent of this effect depends on the cost share of energy. In reality, firms do not exhibit a sensitive response to energy price fluctuations in the short run. For instance, most U.S. firms perceive energy price shocks as shocks to the demand for their products rather than shocks to the cost of producing these products (see Lee and Ni 2002). Berndt and Wood (1975) demonstrated that the demand for energy as an input is derived from the demand for the firm's output. This may be because short-run price hedging means that 'price shocks' do not translate into changes in realized costs in the short-run. This highlights the crucial distinction between the short- and long-run responses.

Apart from the short- and long-run differences in energy price shocks, ownership is identified as another factor influencing firms' sensitivity to energy price variations.

The relationship between firm performance and ownership structure has been discussed widely. The prevailing assumption suggests that the private sector is inherently more efficient than the public sector. In public ownership, inefficiencies arise from deviations of enterprise objectives from profit maximization and inadequate monitoring mechanisms due to the lack of discipline from capital markets (Lindsay, 1980). State-owned enterprises, while benefiting from better access to capital, technology, inputs, and human resources, often operate with noneconomic objectives and under softer budget constraints (Brandt et al., 2022). Chen, et al. (2020) find that the decline of energy intensity is driven mainly by privately owned firms and energy-intensive firms. Consequently, one possible outcome is that, in comparison to private firms, state-owned or public firms may exhibit a less sensitive response to fluctuations in energy prices. However, there are also contrary viewpoints that hold alterations in firm ownership does not significantly impact firm performance (Himmelberg, Hubbard, Palia, 1999). Estrin and Pérotin (1991) contend that public ownership complicates the owner-manager relationship by expanding the chain of principals and agents, as objectives are politically determined and conveyed through a policy-making administrative structure to management; However, the comparative efficiency between public and private ownership hinges on the effectiveness of monitoring by capital markets or market structure of monopoly and the reluctance of public firms to optimize the use of labour, especially via capital-labour trade-offs. However, in response to an energy price increase, a publicly owned firm may have stronger incentives than a privately owned firm to adjust its energy consumption, due to its limited ability to optimize labor costs. However, empirical research on the heterogeneity of ownership in relation to energy price elasticity remains limited.

Our study aims to fill this energy price elasticity research gap by investigating the firm-level responses toward energy prices variation. Through an examination of microdata, we seek to enhance the understanding of how firms navigate the challenges posed by changing energy prices in the context of evolving carbon pricing policies.

4.Methods

Aligned with prior literature (Bjørner and Jensen, 2002), this study adopts the assumption of weak separability in energy inputs within the production function. Under this framework, the optimal combination of energy inputs remains independent of the mix and prices of other factors. Notably, the power sector emerges as a focal point due to its significant coal consumption, accounting for approximately 60% of the total coal consumption in China (IEA, 2024). However, it warrants attention that the power market is heavily regulated in China, with government-determined electricity feed-in tariffs. Given the power sector's pivotal role in ensuring electricity supply, coal consumption for electricity generation transcends simple cost-dependent considerations.

As a result, we exclude the energy-producing sector from our analysis, focusing solely on final energy consumers. This deliberate focus enables us to delve into the dynamics of energy consumption and responses to price signals among end-users, thereby providing valuable insights into energy market behavior and policy implications.

4.1 Long-run estimation method

Utilizing cross-sectional data offers a valuable approach to capturing long-run price elasticities, particularly when significant price variations exist among regions (Espey and Espey, 2004). Due to characteristics of its survey sampling methodology, in different years, the micro firm dataset comprises randomly sampled observations from all firms, representing independent cross-sections over time. The pooling of random samples offers distinct advantages over utilizing cross-sectional data alone, as it facilitates more precise estimators and test statistics with enhanced statistical power (Wooldridge, 2009). Long-run energy price elasticity refers to the responsiveness of the demand for the energy to changes in price over an extended period, we assume it remains stable in our research period. We incorporate year dummy variables into our pooling estimations, allowing intercepts to vary across different periods. This accommodates the possibility that firms may exhibit diverse distributions across different years while ensuring that price elasticity remains stable. Leveraging the pooled cross-section dataset, we conduct estimations to derive the long-term price elasticity.

The estimations focus on cross and own-price demand elasticities concerning coal, oil, and electricity, which represent the predominant fuel types in China, as well as coal intensity, oil intensity, and electricity intensity. Given the marginal role of gas consumption in China's energy landscape, compounded by limited expansion primarily constrained by gas pipeline infrastructure, gas is not included as a primary fuel type in our analysis. The transition to gas consumption is predominantly influenced by access considerations rather than price dynamics. Therefore, we do not include it in our analysis.

Utilizing a comprehensive ten-year dataset comprising firm-level observations, our study benefits from a substantial sample size conducive to robust analyses. The regression model for the long run is as follows in Equation 1.

$$\ln\, y_{jkt} = \sum_{j=1}^{n} \ln EP_{jpt} + \ln PP_{it} + \sum X_{pt} + \delta_i + \theta_t + \varepsilon,$$

where *j* = coal, oil and electricity

(Equation 1)

The variable y_{jkt} denotes the physical consumption or intensity of energy *j* in firm k in year t, *j* represents different energy types including coal, oil, and electricity. EP_{jpt} signifies the price of energy *j* in province *p* during year *t*, while PP_{it} represents the product price level within the industry of the firm. Additionally, X_{pt} encompasses a series of control variables specific to province p in year t, such as $\ln GDPPC_{pt}$ ($GDPPC_{pt}$ is GDP Per Capita), Growth_{pt} (GDP growth rate), $\ln K/L_{pt}$ (K/L is capital per labor). In the regressions concerning physical energy consumption, we include the actual output of the firm as a control variable. Conversely, in regressions focusing on energy intensities, wherein energy intensity is computed as energy consumption divided by real output, we refrain from including real output in the control variables to mitigate collinearity issues. δ_i represents industry level fixed effect, θ_t donates year fixed effect, and ε signifies the error term.

Given the time constraints of the micro-level data in our study, the duration of the data period does not facilitate the direct estimation of long-run price elasticities using time series analysis. In our research, we employ cross-sectional-time series analysis to leverage multi-year information and effectively capture long-run effects, taking advantage of the distinct energy price variations across regions. Notably, we opt not to control for province fixed effects in our regression models when aiming to capture the long-run effect. Instead, we include year- and industry-fixed effects to account for time and sector-specific trends. And we control for other key provincial factors to account for additional regional characteristics that may influence energy elasticity. By adopting this approach, we enable meaningful energy demand comparisons across different provinces while treating energy price variations among provinces as permanent differences. This methodology enhances our ability to discern the long-term impact of energy prices on firm behavior and energy consumption patterns.

Sectors characterized by varying energy intensities may exhibit divergent sensitivities to changes in energy prices, attributed to differences in firms' energy cost shares across industries. By incorporating industry-fixed effects into our regressions, we effectively control for this industry-specific feature and other factors at the industry level that may influence energy consumption and energy intensities. Furthermore, we introduce the interaction between the logarithmic forms of energy prices and firms' ownership in our regression analyses to examine the influence of ownership category on energy price elasticity. We designate public-owned firms as the benchmark group.

4.2 Short-run estimation method

For short-run elasticity estimations, we take advantage of the energy price variations over time during the research period. Due to the large sample size in each year of our dataset, there is significant overlap of firms across years, particularly evident in consecutive years, providing an opportunity to explore short-term price elasticity by examining firms' responses to energy prices over time in the short run. To ensure estimation reliability in our analysis, we exclude firms that appear in only one year (Determined by the times their unique firm ID appears across different years) and construct an unbalanced panel dataset with the remaining firms. When focusing on short-run elasticities, we include province fixed effects in our estimations to mitigate the confounding effects from other provincial factors and the long-run energy price variation. The regression model for the short run is as follows in Equation 2:

$$\ln\ y_{jkt} = \sum_{j=1}^{n} \ln EP_{jpt} + \ln PP_{it} + \sum X_{pt} + \delta_i + \theta_t + \gamma_p\ + \varepsilon,$$

j = coal, oil and electricity

(Equation 2)

In our estimations for short-term price elasticities, γ_p represents the province fixed effect, capturing the regional-specific factors influencing energy consumption or energy intensity dynamics. All other variables remain consistent with those utilized in the long-run estimations, ensuring comparability and continuity in our analysis. The variable y_{jkt} denotes the physical consumption or intensity of energy *j* in firm *k* in year *t*, *j* represents different energy types including coal, oil, and electricity. EP_{jpt} signifies the price of energy j in province p during year t, while PP_{it} represents the product price level within the industry of the firm. Additionally, X_{pt} encompasses a series of control variables specific to province p in year t, such as $\ln GDPPC_{pt}$ ($GDPPC_{pt}$ is GDP Per Capita), Growth_{pt} (GDP growth rate), $\ln K/L_{pt}$ (K/L is capital per labor). In the regressions concerning physical energy consumption, we include the actual output of the firm as a control variable. Conversely, in regressions focusing on energy intensities, wherein energy intensity is computed as energy consumption divided by real output, we refrain from including real output in the control variables to mitigate collinearity issues. δ_i represents industry level fixed effect, θ_t donates year fixed effect, and ε signifies the error term.

The inclusion of province fixed effects allows us to effectively control for energy price variations across different regions, thereby isolating the short-term impact of energy price changes from the long-run. Additionally, we maintain control over key covariates, such as GDP per capita, GDP growth rate, and capital per labor, to account for their potential influence on energy demand and energy intensity. These measures ensure the reliability of our findings, contributing to a comprehensive understanding of the short-term dynamics in energy consumption behavior.

5.Data

5.1 Micro firm data

The main data utilized in this study are sourced from the Chinese National Tax Survey Database (CNTSD), an extensive annual survey administered by China's Ministry of Finance and State Administration of Tax. This database provides comprehensive details on energy consumption and economic metrics at the firm level, encompassing coal, oil, natural gas, and electricity. Its expansive coverage of diverse firms addresses the scarcity of large-sample micro-firm perspectives in understanding energy price elasticity.

The large number of observations annually bolster the robustness and reliability of this research, offering an unbiased and comprehensive examination of the own- and cross-price elasticities. The expansive nature of this massive sample size also enables an in-depth exploration of the impact of ownership on the firms' sensitivity to energy price change. Manufacturing is a relatively energy-intensive part of the economy and is potentially very exposed to higher energy prices resulting from higher carbon prices. The sensitivity of manufacturing firms to price signals is crucial for determining the effectiveness of the carbon market. Therefore, we focus only on the analysis of manufacturing firms in our paper. Statistical summary is shown in table 2.

5.2 Energy prices

The energy price data utilized in this study were sourced from the National Development and Reform Commission, which reports data every 10 days. For oil and electricity prices, the annual average was computed directly. Notably, the energy price in the capital of each province was adopted as the representative energy price at the provincial level.

In the case of coal prices, due to the unavailability of delivered coal price data, we had to calculate these. To derive the delivery coal price for each province, we factored in railway and shipping costs alongside trading hub prices. It is imperative to mention that we do not include road transportation in our calculation methodology. What matters for our analysis is that provincial changes in relative prices from year to year are unbiased estimates.

A meticulous compilation of data encompassing main coal production spots, coal flow routes, coal railway freight rates, railway distances from production areas to provincial capitals, as well as coal shipping rates and distances, was conducted to calculate coal transportation costs to every province. The detailed calculation of coal's provincial delivery price is presented in Appendix A.

Table 2: Summary Statistics, 2007–2016

Variables	Observations	Unit	Mean	Standard deviation	Minimum	Maximum
Coal	57515	Tonne	99973.543	453582.548	0	16260152.000
Oil	55884	Tonne	13262.520	143259.573	0	17985016.000
Electricity	64707	KWh	231343406.730	3438749229.451	0	755423182848.000
Coal intensity	57515	Tonne/1000 RMB	0.262	0.717	0	43.605
Oil intensity	55884	Tonne/1000 RMB	0.109	0.617	0	30.654
Electricity intensity	64707	KWh/1000RMB	2845.120	17289.038	0	523398.813
Coal price	60828	RMB/tonne	449.120	105.250	153.750	718.677
Oil price	64709	RMB/tonne	7316.860	1131.400	249.387	10591.896
Electricity price	64709	RMB/KWh	0.684	0.107	0.335	1.030
Output	64709	1,000 RMB	1511031.810	9050161.836	343.510	700771072.000
GDP growth rate	64709	%	11.035	2.535	-2.500	19.100
GDP per capita	64709	RMB	35134.454	16898.175	6545.097	110426.063
capital per labor	64709	10000RMB	14.851	7.376	3.428	57.514
Lag profit	38702	1000RMB	52872.544	656221.990	-13597748.000	41628088.000
Public firms	3,747					
Private firms	12,608					
Foreign firms	15,902					

Notes: The table provides summary statistics for the main variables of firms consuming more than 10,000 tonnes of standard coal, after excluding outliers. The notably high value of electricity intensity can be attributed to the presence of electricity-intensive firms situated in regions that benefit from inexpensive hydroelectric power. These firms elevate the overall average electricity intensity. Nonetheless, this does not affect the robustness of our estimations.

5.3 Product prices, GDP and capital-to-labour ratio

In response to fluctuations in product prices, firms often tend to overlook concurrent increases in energy prices, thereby displaying reduced sensitivity to energy price signals. To mitigate the impact of variations in product prices, we employ the Producer Price Index (PPI) disaggregated by two-digit sectors within each province to standardize the price level of products. This province-industry level PPI data is sourced from China's Price Statistical Yearbooks, with the price level established in 2006 serving as the reference constant. We utilize the logarithmic transformation of PPI to ensure analytical robustness.

Provincial GDP growth rate data are sourced from the Chinese Statistical Yearbooks, providing a comprehensive overview of economic performance at the regional level. Real provincial GDP per capita is derived by multiplying the GDP per capita in the base year (2006) by the Per Capita Regional GDP Index for each respective year.

The capital-to-labor ratio, a crucial metric in assessing production efficiency, is computed as the ratio of capital to labor. Capital is quantified by the stock of fixed assets, a fundamental component in the productive capacity of an economy. In alignment with Zhang (2004), our methodology involves estimating the fixed assets in 1952 and subsequently calculating the capital stock for each province in subsequent years. This is achieved through the perpetual inventory method, which facilitates the tracking of capital stock evolution over time at constant prices. Subsequently, we adjust the capital figures to 2006 constant prices. Meanwhile, labor input is quantified by the number of employed persons. By integrating these key variables, our analysis offers a nuanced understanding of regional economic dynamics and productivity trends.

5.4 Ownership

We categorize firms based on three fundamental ownership structures: public-owned, private, and foreign ownership. The determination of firms' ownership characteristic is based on their taxpayer category code. Public ownership encompasses firms identified by taxpayer category codes denoting state-owned, collective, state-owned sole proprietorship, state-owned joint venture enterprise, collective joint venture enterprise, and state-owned and collectively owned joint venture enterprise. Private firms are comprised of those designated by taxpayer category codes indicating private, privately owned sole proprietorship, private partnership enterprise, private limited liability company, and private limited company with shares. Foreign firms encompass entities categorized as Hong Kong, Macao, and Taiwan Investment Enterprises (including joint venture enterprise, cooperative enterprise, solely funded enterprises by investors from Hong Kong, Macao, and Taiwan, Limited Liability Company with Investment from Hong Kong, Macao, and Taiwan, and Other Enterprises with Investment from Hong Kong, Macao, and Taiwan), as well as foreign-invested enterprises (such as Sino-foreign joint venture enterprise, Sino-foreign cooperative enterprise, foreign-owned enterprise, and Foreign-Invested Joint Stock Limited Company). Firms for which we cannot ascertain the ownership structure are excluded from the analysis.

5.5 Data cleaning

The Ten Thousand Enterprises program, a cornerstone of China's energy-saving and low-carbon initiatives, was implemented in 2011 to address the nation's burgeoning energy consumption. This program targets enterprises characterized by annual comprehensive energy consumption exceeding 10,000 tonnes of standard coal, alongside select energy-intensive units consuming more than 5,000 tonnes of standard coal annually within specific sectors. Notably, by 2010, these enterprises accounted for over 60% of the nation's total energy consumption, rendering them focal points of China's energy-saving endeavors (NDRC, 2011). To minimize the influence of firms with low energy consumption — where energy costs account for only a small proportion of total costs, and to address potential confounding effects from the Ten Thousand Enterprises program, our analysis exclusively focuses on firms with annual energy consumption exceeding 10,000 tonnes of standard coal. We also drop the outliers Table 3 illustrates the percentage of energy consumption and CO_2 emissions from manufacturing firms with energy consumption exceeding 10,000 tonnes of standard coal, relative to the total firms in the manufacturing sector in the dataset. The high proportion indicates that focusing on firms with energy consumption above this threshold is appropriate and representative.

We further exclude upper-bound outliers with extremely high energy intensity. In the first step, we apply the interquartile range (IQR) method within each two-digit industry-year cell to identify and remove outliers. This level of aggregation ensures sufficient sample size for the IQR method while allowing for meaningful identification of atypical observations. Outliers are defined as those with energy intensity values exceeding the 75th percentile plus 1.5 times the IQR. Due to limited observations in some four-digit industries, the IQR method is not applied at the more disaggregated level. However, upon inspecting the distribution of electricity intensity in the remaining sample, we find that extreme values persist. To address this, we further exclude the top 2% of firms with the highest electricity intensity within each four-digit industry-year cell.

Table 3: Share of Energy Consumption and CO_2 Emissions from Large Energy-Consuming Manufacturing Firms (＞10,000 Tonnes of Standard Coal) Within the Manufacturing Sector in the Dataset.

Year	Energy proportion (%)	CO_2 proportion (%)
2007	94.65	95.04
2008	93.91	92.73
2009	90.30	90.40
2010	87.11	85.31
2011	87.12	85.20

2012	86.42	84.20
2013	87.01	84.98
2014	88.78	87.00
2015	87.74	85.60
2016	86.72	84.73

Data source: calculated by authors. The proportions are computed after excluding upper-bound outliers from the dataset.

By focusing on these key energy consumers, our study aims to discern their responsiveness to price signals, a critical determinant of the efficacy of carbon market mechanisms. To elaborate, we aggregate the standard coal equivalent of coal, oil, and electricity consumption for each firm, retaining those with total energy consumption exceeding 10,000 tonnes of standard coal. Given the prevalence of missing data across the three energy types, where the absence of any one type leads to missing total energy data, we adopt a pragmatic approach to address this challenge.

In instances where data for oil or electricity consumption is missing, we impute these values as zero when calculating total energy use for regression analyses on coal and coal intensity. Similarly, when data for coal or electricity consumption is absent, we impute these values as zero for regression analyses on oil and oil intensity. Likewise, missing values for coal or oil consumption are treated as zero when analyzing electricity and electricity intensity.

Importantly, the total energy consumption, even with missing data of any specific energy type, consistently exceeds 10,000 tonnes of standard coal, ensuring the inclusion of only relevant observations. Additionally, to facilitate meaningful comparisons and analyses, provincial GDP per capita, provincial capital per labor, firms' output and profit, and product prices are standardized to 2006 constant prices.

6.Results

6.1 Long-run price elasticity of energy demand

Table 4 presents the long-term own- and cross-price elasticities of energy demand (coal, oil, and electricity) for manufacturing firms in China, whose total annual energy consumption exceeds 10,000 tonnes of standard coal. Columns 1 through 4 depict the estimations of price elasticities for coal, oil, and electricity demand in the manufacturing sector. Meanwhile, columns 4 through 6 present the estimations of the ownership effect. We include year dummy, industry dummy variables and other provincial factors in our long-run estimations.

Table 4: Long-run price elasticities of energy demand

	(1)	(2)	(3)	(4)	(5)	(6)
	Ln coal	Ln oil	Ln elec	Ln coal	Ln oil	Ln elec

Ln coal price	-1.239***	-0.303	0.163	-1.431***	-0.207	0.256
	(0.263)	(0.445)	(0.195)	(0.199)	(0.473)	(0.210)
Ln oil price	-0.675	0.304	-0.287	-1.500	0.0733	-0.174
	(1.271)	(0.677)	(0.537)	(1.611)	(0.848)	(0.661)
Ln elec price	-1.208**	0.727	-0.978***	-0.461	1.422*	-1.011**
	(0.513)	(0.771)	(0.315)	(0.620)	(0.772)	(0.396)
Ln product price	0.391*	0.113	0.473***	0.254	0.136	0.478***
	(0.195)	(0.237)	(0.101)	(0.187)	(0.178)	(0.0734)
GDP growth rate	0.0422	-0.0200	0.0141	0.0513	-0.00473	0.0114
	(0.0422)	(0.0464)	(0.0255)	(0.0505)	(0.0468)	(0.0279)
Ln GDP per capita	-0.631**	0.470	-0.0335	-0.696**	0.411	-0.0395
	(0.264)	(0.330)	(0.128)	(0.276)	(0.350)	(0.154)
Ln capital per labor	-0.111	0.0208	-0.0852	-0.142	0.0617	-0.0609
	(0.155)	(0.190)	(0.0801)	(0.150)	(0.214)	(0.0891)
Ln real output	0.527***	0.0868	0.519***	0.536***	0.00919	0.479***
	(0.0529)	(0.0725)	(0.0262)	(0.0709)	(0.0814)	(0.0320)
Private x ln coal price				0.00414		
				(0.0146)		
Foreign x ln coal price				-0.119***		
				(0.0205)		
Private x ln oil price					-0.0388***	
					(0.0121)	
Foreign x ln oil price					0.0118	
					(0.0145)	
Private x ln elec price						-0.0188***
						(0.00652)
Foreign x ln elec price						0.00281
						(0.00638)
Observations	53,881	52,409	60,826	26,702	26,767	30,916
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes	Yes	Yes

Notes: Standard errors in parentheses *p < 0.10, **p < 0.05, ***p < 0.01. The standard errors are clustered at the province level.

The long-run price elasticity of coal demand to coal price changes is estimated to be -1.239, demonstrating a statistically significant association at the 1% confidence level. Moreover, in addition to coal, electricity demand exhibits sensitivity to its own price changes over the long term. As indicated in column 3, the price elasticity of electricity demand to electricity price changes is estimated to be -0.978, with a statistically significant coefficient at the 1% level. Conversely, oil demand appears to be relatively insensitive to oil price changes for manufacturing firms in the long run.

Interestingly, when electricity prices increase by 1%, coal demand is projected to decrease by 1.208% in the long run, with the coefficient being statistically significant at the 10% level. This observation suggests that coal serves as a complementary good for electricity. However, the other cross-price elasticities between coal, oil, and electricity are found to be insignificant, indicating weak substitution tendencies among energy factors in the long run in China. The relative price factor significantly contributes to this lack of substitution. Coal is much cheaper than oil and electricity, and the large price gap between these energy sources makes substitution economically unfeasible even with price variations of a specific energy. China has abundant coal reserves but limited oil and gas resources, with a significant reliance on oil imports. This easy and secure access to coal locks in coal as the primary energy type in China to some extent.

The question of the feasibility of electrification has garnered significant attention, and our findings may imply that achieving electrification goals cannot be solely reliant on price-based policies. Instead, additional policy instruments are deemed necessary to complement price-based measures and facilitate the transition towards electrification. These results underscore the complexities involved in energy market dynamics and highlight the importance of comprehensive policy frameworks in driving sustainable energy transitions.

The coefficient associated with the regional development level, measured by regional GDP per capita, is statistically significant. A 1% increase in GDP per capita corresponds to a decrease in coal demand in the province by 0.631%. This finding suggests that as economic development progresses, manufacturing firms tend to utilize less coal. This observation aligns with the insights provided by the Environmental Kuznets Curve, indicating that China, particularly within the manufacturing sector, has transitioned to the later stages of the curve. Further advancements in development are likely to lead to reductions in coal usage, thereby contributing to improved environmental quality.

Columns 4 through 6 examine the influence of ownership on the price elasticity of energy demand over the long run. By incorporating interactions between ownership type and the logarithmic forms of energy prices, with public-owned firms serving as the benchmark group, our results reveal that private and foreign firms exhibit greater sensitivity to energy price changes overall. Specifically, in response to a 1% increase in coal price, foreign firms reduce coal demand by 0.119 percentage points more than public-owned firms. Similarly, with a 1% increase in oil price, private firms reduce oil demand by 0.0388 percentage points more than public-owned firms, and with a 1% increase in electricity price, private firms decrease electricity demand by 0.0188 percentage points more than public-owned firms.

6.2 Short-run price elasticity of energy demand

In the long run, firms have sufficient time to adjust their production processes, input structures, and technologies in response to changes in energy prices. To capture firms' long-term responsiveness, we exploit persistent regional differences in energy prices across provinces. These enduring disparities have led to observable divergences in energy consumption patterns shaped over many years, reflecting cumulative adjustments in production scale, energy mix, and technological adoption. Our estimation of long-run elasticity thus reflects the equilibrium outcome of these gradual and comprehensive adaptations to price signals. Nevertheless, understanding firms' short-run responses remains crucial. In the short term, firms face greater constraints and fewer adjustment margins, which may result in behavior that diverges significantly from their long-run responses. Measuring these immediate reactions to energy price fluctuations is essential for assessing the near-term impact of carbon pricing.

Table 5 presents our short-run own- and cross-price elasticities for coal, oil, and electricity. In our estimations, we rigorously control for province, industry, and year-fixed effects to account for regional, sectoral, and time variations. Leveraging the overlapped observations across years and incorporating a full set of fixed effects enables us to discern the immediate responses of firms to energy price changes. Notably, the inclusion of province-level fixed effects largely absorbs energy price variations across provinces, thereby focusing our analysis on firms' short-term reactions to transient price differences rather than long-term responses.

Our results reveal a noteworthy finding: in the short run, oil is the only fuel with a significant own-price elasticity, while both coal and electricity do not respond sensitively to their own price variations. A 1% increase in oil prices induces a 0.961% decrease in oil demand, with a 5% confidence level. Additionally, a 1% increase in oil prices causes a 1.517% decrease in coal demand, suggesting that coal and oil are complementary goods in the short run.

Another significant finding is that an increase in electricity prices leads to a corresponding increase in oil demand. Specifically, a 1% increase in electricity prices induces a 3.553% increase in oil demand, with the coefficient being statistically significant at the 5% confidence level. This significant short-term substitution between oil and electricity contrasts with the lack of significant substitution observed in the long run. Conversely, we did not observe a significant increase in coal demand in response to electricity price hikes, indicating a lack of substitution between electricity and coal in the short run. This disparity suggests that, compared to coal, oil offers greater ease of transportation and storage, thereby facilitating short-term substitution dynamics between these two energy sources.

Apart from the specific electricity-oil and oil-coal cross-price elasticities and oil own-price elasticity mentioned above, none of the other own- and cross-price elasticities were found to be significant in the short run. Specifically, coal and electricity demand were not sensitive to their own price changes, and most observed fuel substitutions were insignificant.

Moreover, we utilized the lagged profit of the firm to measure the firm's income level. Our results indicate that higher profits correspond to increased oil and electricity consumption in the short run, suggesting a positive relationship between firm income levels and energy usage during this timeframe. Additionally, significant differences in coal price elasticity were observed among foreign firms compared to public firms, both in the short run and in the long run. This may be attributed to the fact that foreign firms, through their connections with parent companies, have access to more diverse strategies for reducing coal consumption—drawing on experiences from their home countries, where coal use has been declining for decades.

Table 5: Short-run price elasticity of energy demand

	(1)	(2)	(3)	(4)	(5)	(6)
	Ln coal	Ln oil	Ln elec	Ln coal	Ln oil	Ln elec

Ln coal price	-0.665	-0.614	0.368	-0.630	-0.389	0.290
	(0.583)	(0.924)	(0.233)	(0.682)	(1.077)	(0.236)
Ln oil price	-1.517***	-0.961**	-0.238	-0.965**	-0.468	-0.106
	(0.299)	(0.406)	(0.161)	(0.444)	(0.653)	(0.225)
Ln elec price	0.836	3.553**	-0.0305	0.579	4.125**	-0.509
	(1.239)	(1.614)	(0.736)	(2.059)	(1.814)	(1.145)
Ln product price	0.156	-0.0137	0.465***	0.187	0.229	0.481***
	(0.248)	(0.342)	(0.0867)	(0.205)	(0.171)	(0.0622)
GDP growth rate	-0.0385	-0.0966	-0.0446	0.0653	-0.0947	-0.0129
	(0.0534)	(0.123)	(0.0298)	(0.0728)	(0.137)	(0.0324)
Ln GDP per capita	-0.564	-0.681	1.995	-1.636	0.0849	2.319*
	(2.024)	(3.531)	(1.185)	(2.571)	(3.484)	(1.343)
Ln capital per labor	0.604	4.298***	-0.480	1.614	3.154**	-0.513
	(1.349)	(1.228)	(0.709)	(1.921)	(1.521)	(0.800)
Ln lag profit	-0.0319	0.0638***	0.0689***	-0.00843	0.0467**	0.0778***
	(0.0342)	(0.0229)	(0.0154)	(0.0526)	(0.0224)	(0.0202)
Ln real output	0.386***	0.212***	0.557***	0.302**	0.150	0.506***
	(0.0797)	(0.0667)	(0.0220)	(0.125)	(0.109)	(0.0234)
Private x ln coal price				-0.0108		
				(0.0354)		
Foreign x ln coal price				-0.117***		
				(0.0373)		
Private x ln oil price					-0.0259	
					(0.0231)	
Foreign x ln oil price					-0.0170	
					(0.0237)	
Private x ln elec price						-0.0179
						(0.0132)
Foreign x ln elec price						0.00184
						(0.0106)
Observations	11,191	10,503	12,301	5,252	5,070	5,955
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes	Yes	Yes
Province FE	Yes	Yes	Yes	Yes	Yes	Yes

Notes: Standard errors in parentheses *p < 0.10, **p < 0.05, ***p < 0.01. The standard errors are clustered at the province level.

6.3 Long-run price elasticity of energy intensity

Table 6 presents the results of long-run price elasticities for energy intensity among manufacturing firms. A 1% increase in coal prices corresponds to a decrease in coal intensity by 1.546%, a statistically significant finding at the 1% level. Conversely, the own-price elasticity of oil intensity was found to be not significant. However, with a 1% increase in electricity prices, electricity intensity decreases by 1.287%, a statistically significant result at the 1% level. These findings suggest that higher fuel prices incentivize firms to enhance energy efficiency through technology upgrades. Another result is that a 1% increase in electricity prices would cause a 1.517% decrease in coal intensity.

Regarding the ownership structure, the results on energy intensity differ from those observed for energy demand. In the long run, private firms do not exhibit greater sensitivity in reducing energy intensities in response to energy price increases.

Instead, foreign firms demonstrate a higher propensity to decrease energy intensity in response to energy price hikes. Specifically, with a 1% increase in coal prices, foreign firms reduce coal intensity by an average of 0.130 percentage points more than public-owned firms, a statistically significant result at the 1% level. Similarly, with a 1% increase in electricity prices, foreign firms decrease electricity intensity by 0.0126 percentage points more than public-owned firms.

This discrepancy can be attributed to the technology catch-up process within the manufacturing sectors of China. Foreign firms often have greater access to advanced energy-saving technologies abroad and may incur lower costs when upgrading technologies. Consequently, foreign firms are better positioned to improve their energy efficiency and achieve their profit maximization targets in response to energy price increases. Our results reveal that private firms are no more or less responsive than public firms to energy price changes in terms of energy intensity in the long run, especially for electricity. Although private firms are more exposed to market prices in general, which also include other factor markets such as labor and capital, they may find it more economical to adjust these factors rather than upgrade equipment to reduce energy intensity. Additionally, their shorter development history and worse financial constraints compared to public firms may hinder their ability to invest in new technologies. These findings underscore the nuanced effects of ownership structure on energy intensity adjustments in the context of evolving technological landscapes and market dynamics.

Table 6: Long-run price elasticities of energy intensity

	(1)	(2)	(3)	(4)	(5)	(6)
	Ln coal intensity	Ln oil intensity	Ln elec intensity	Ln coal intensity	Ln oil intensity	Ln elec intensity
Ln coal price	-1.546***	-0.531	0.0787	-1.771***	-0.373	0.237
	(0.310)	(0.522)	(0.209)	(0.243)	(0.525)	(0.253)
Ln oil price	-0.732	0.574	-0.156	-1.757	0.460	0.115
	(1.492)	(0.873)	(0.534)	(1.939)	(1.049)	(0.706)
Ln elec price	-1.517**	0.0943	-1.287***	-0.665	0.772	-1.372***
	(0.591)	(0.855)	(0.352)	(0.702)	(0.801)	(0.473)
Ln product price	0.319	0.625**	0.916***	0.122	0.670***	0.954***
	(0.217)	(0.283)	(0.0967)	(0.196)	(0.211)	(0.0572)
GDP growth rate	0.0417	-0.00948	0.0234	0.0444	0.0130	0.0217
	(0.0458)	(0.0496)	(0.0285)	(0.0550)	(0.0485)	(0.0312)
Ln GDP per capita	-0.702**	0.350	-0.232	-0.699**	0.337	-0.217
	(0.300)	(0.397)	(0.151)	(0.313)	(0.428)	(0.188)
Ln capital per labor	-0.160	0.0190	-0.0854	-0.213	0.0684	-0.0656
	(0.180)	(0.235)	(0.0889)	(0.165)	(0.253)	(0.112)
Private x ln coal price				0.0232		
				(0.0142)		
Foreign x ln coal price				-0.130***		
				(0.0205)		
Private x ln oil price					0.00923	
					(0.0154)	
Foreign x ln oil price					-0.00973	
					(0.0155)	

Private x ln elec price						0.0189**
						(0.00888)
Foreign x ln elec price						-0.0126*
						(0.00697)
Observations	53,881	52,409	60,826	26,702	26,767	30,916
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes	Yes	Yes

Notes: Standard errors in parentheses *p < 0.10, **p < 0.05, ***p < 0.01. The standard errors are clustered at the province level.

6.4 Short-run price elasticity of energy intensity

For the short-run price elasticities of energy intensity, as shown in Table 7, we find that the own- and cross-price elasticities of coal are not significant. A 1% increase in oil prices can cause a 1.574% decrease in coal intensity, a 1.100% decrease in oil intensity, and a 0.320% decrease in electricity intensity. Consistent with the results of price elasticity in demand, this suggests that oil serves as a complementary input with other fuels in the short run, and production using oil is significantly influenced by price fluctuations. Additionally, the results show a notable positive correlation between electricity prices and oil intensity. Specifically, a 1% increase in electricity prices is associated with a significant 3.633% increase in oil intensity, observed at the 5% level. This substitution effect aligns consistently with the findings from short-run estimations for absolute consumption.

Examining the influence of ownership structure, we observe that foreign firms exhibit greater sensitivity to coal price changes in the short run. However, for oil and electricity, we do not discern any significant differences attributable to ownership structure. These results underscore the nuanced dynamics at play in short-run energy intensity adjustments, with foreign firms demonstrating heightened responsiveness to coal price fluctuations. Conversely, the absence of significant ownership-related effects for oil and electricity suggests a more uniform response across different ownership structures in these energy domains. Such insights offer valuable implications for understanding the short-term dynamics of energy intensity adjustments within the manufacturing sector.

In contrast to the estimation results for energy absolute consumption, the income effect exhibits an opposite influence on energy intensity. Specifically, an increase in the lagged profit of the firm is associated with a decrease in energy intensity. With a 1% increase in lagged profit, firms, on average, decrease coal intensity by 0.207%, oil intensity by 0.153%, and electricity intensity by 0.109%, with all these effects being statistically significant. These findings suggest that in instances of relaxed financial constraints, firms can allocate more resources toward equipment upgrades, thereby enhancing energy efficiency. While relaxed financial constraints may lead to increased production decisions and consequently higher energy consumption, as observed in the estimations of absolute energy consumption, improved financial conditions also enable firms to undertake measures aimed at enhancing energy efficiency.

This nuanced relationship underscores the multifaceted interplay between financial conditions and energy intensity adjustments within the manufacturing sector.

The ability of firms to invest in energy-efficient technologies and processes is contingent upon their financial health, highlighting the importance of financial factors in shaping firms' energy management strategies. These insights offer valuable implications for policymakers and industry stakeholders seeking to promote energy efficiency improvements in manufacturing operations.

Table 7: short-run price elasticities of energy intensity

	(1)	(2)	(3)	(4)	(5)	(6)
	Ln coal intensity	Ln oil intensity	Ln elec intensity	Ln coal intensity	Ln oil intensity	Ln elec intensity
Ln coal price	-0.776	-0.605	0.296	-0.635	-0.161	0.339
	(0.613)	(0.996)	(0.229)	(0.689)	(1.188)	(0.265)
Ln oil price	-1.574***	-1.100**	-0.320*	-1.085**	-0.547	-0.184
	(0.304)	(0.448)	(0.161)	(0.505)	(0.698)	(0.256)
Ln elec price	0.750	3.633**	-0.161	0.203	4.207**	-0.923
	(1.298)	(1.712)	(0.760)	(2.028)	(1.933)	(1.269)
Ln product price	0.320	0.385	0.864***	0.281	0.622**	0.905***
	(0.270)	(0.363)	(0.0839)	(0.208)	(0.227)	(0.0628)
GDP growth rate	-0.0464	-0.123	-0.0444	0.0442	-0.120	-0.00765
	(0.0548)	(0.130)	(0.0305)	(0.0726)	(0.145)	(0.0363)
Ln GDP per capita	-1.452	-1.880	1.523	-1.839	-0.314	2.245
	(2.005)	(3.754)	(1.265)	(2.593)	(3.683)	(1.476)
Ln capital per labor	0.430	4.680***	-0.371	1.313	3.283*	-0.380
	(1.274)	(1.377)	(0.749)	(1.782)	(1.604)	(0.831)
Ln lag profit	-0.207***	-0.153***	-0.109***	-0.191***	-0.206***	-0.124***
	(0.0377)	(0.0368)	(0.0186)	(0.0562)	(0.0510)	(0.0228)
Private x ln coal price				0.0101		
				(0.0343)		
Foreign x ln coal price				-0.121***		
				(0.0357)		
Private x ln oil price					-0.0163	
					(0.0256)	
Foreign x ln oil price					-0.0115	
					(0.0250)	
Private x ln elect price						-0.00193
						(0.0122)
Foreign x ln elec price						0.00634
						(0.0107)
Observations	11,191	10,503	12,301	5,252	5,070	5,955
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes	Yes	Yes
Province FE	Yes	Yes	Yes	Yes	Yes	Yes

Notes: Standard errors in parentheses *p < 0.10, **p < 0.05, ***p < 0.01. The standard errors are clustered at the province level.

7. Robustness checks

7.1 Change the threshold to 5000 tonnes of standard coal

To ensure the robustness of our findings, we conducted an additional analysis using a different threshold for firm selection. While firms consuming over 10,000 tonnes of standard coal account for a significant portion of China’s total energy consumption and carbon emissions—and thus are a major focus of policy attention—this section explores the effects of using a lower threshold.

By lowering the threshold to 5,000 tonnes of standard coal, we increase the number of observations in our analysis, thereby including more energy-intensive manufacturing firms that might be covered by the national carbon market in the future. This approach allows us to capture a broader spectrum of firms while still focusing on those with significant energy consumption.

The results, presented in Appendix B, are largely consistent with the main findings in Section 6, except for the significance of oil's own price elasticity of demand in the short run. When we include relatively less energy-intensive observations in our analysis, the sensitivity of oil demand to oil price fluctuations diminishes. This suggests that immediate responses to oil price changes tend to occur among firms with larger energy consumption. Overall, in the long run, firms exhibit sensitivity to variations in energy prices. However, in the short run, the price elasticities are not responsive. This indicates that while energy pricing can drive long-term adjustments in firm behavior, immediate responses to price changes are more muted.

7.2 Change the Research Period

The impacts of positive and negative energy price shocks can exhibit asymmetry, with price increases showing greater predictive power compared to decreases (Mork, 1989, 1994; Mork et al., 1994; Bernanke, et al.,1997, p.103). This interest in asymmetries dates back to the late 1980s, particularly after it was observed that the significant decline in crude oil prices in 1986 did not lead to a substantial economic expansion.

In our analysis, coal is the most critical fuel due to China's reliance on coal for its energy needs. From 2007 to 2013 of the entire research periods, coal prices were increasing. After 2013, coal prices began to decline. To address the potential impact of asymmetries on price elasticity, we conducted regressions focusing on the period when coal prices were rising. The results presented in the Appendix C confirm the robustness of our findings: even during the period of increasing coal prices, short-run price elasticity remains inelastic overall. This analysis reinforces our main conclusions.

The robustness check using data from 2007 to 2013 is consistent with the results in Section 6, and even confirms the notable exception of oil. Contrary to coal and electricity, firms are responsive to oil prices in the short run but unresponsive to oil prices in the long run.

The possible reason for this is that China relies heavily on imported oil from international markets. The price differences among different regions within China are not significant, making it unsurprising that long-run estimations, which utilize regional price variations, show no significant impact. However, international oil prices fluctuate significantly in the short run, and firms in China respond sensitively to these fluctuations. This sensitivity is because oil accounts for only a small fraction of the overall energy structure. It is easier for firms to reduce or halt production processes that use oil when oil prices are high, leading to a more immediate and flexible response in the short term.

8. Conclusions and discussion

In this study, we conduct estimations of long- and short-run own- and cross-price elasticities pertaining to physical coal, oil, and electricity demand, as well as long- and short-run own- and cross-price elasticities of coal intensity, oil intensity, and electricity intensity in China. Leveraging firm-level data fills the gap in micro-level price elasticity estimations, providing enhanced accuracy and mitigating biases associated with aggregate data. Moreover, the lack of provincial coal price data poses challenges for disaggregated price elasticity estimations in China using past data. To address this, we construct provincial level coal price data enabling precise estimations using micro-firm data.

In the long run, coal and electricity demand exhibit price responsiveness, with own price elasticity of coal demand estimated at -1.24 and own price elasticity of electricity demand at -0.98. Similarly, long-run own price elasticity of coal intensity is -1.55, and that of electricity intensity is -1.29. It is worth noting that elasticities which are lower than -1 mean energy costs fall as energy prices rise. These findings suggest that both coal and electricity are sensitive to price changes in the long run, with energy intensity exhibiting even greater responsiveness compared to physical energy consumption. The magnitude of the long-run price elasticity in our study is approximately in the same range as findings from other countries such as the United States, Australia, and Canada.

Conversely, in the short run, own price elasticities of coal and electricity, as well as coal intensity and electricity intensity, are found to be insignificant. Short-term adjustments in equipment and technology in response to energy price changes are deemed difficult and costly. Moreover, the technology lock-in effect limits firms' ability to alter specific energy use in response to price variations when output levels remain constant. Carbon pricing, acting as an implicit energy price, may encounter challenges in inducing immediate CO_2 emissions reduction due to these constraints. However, in the long run, carbon pricing is expected to effectively reduce CO_2 emissions by stimulating energy efficiency improvements.

The price elasticity of oil demand and oil intensity presents an exception, displaying opposite results compared to coal and electricity. In the long run, oil demand and intensity are not sensitive to price changes, but they are sensitive in the short run. Small variations in oil prices among regions do not induce significant differences in oil usage. Thus, it is unsurprising that long-run estimations based on regional differences are insignificant. In the short run, production processes that use oil may be directly curtailed in response to rising oil prices. This conclusion is supported by the observation that coal and electricity use did not increase when oil prices rose; instead, they decreased. This suggests that production did not continue with alternative energy sources but was largely shut down.

Cross-price elasticity estimations reveal a significant substitution effect of oil for electricity, particularly in the short run. A 1% increase in electricity prices leads to a 3.55% increase in oil demand and a 3.63% increase in oil intensity in the short run. Conversely, the evidence does not support electricity substituting for coal or oil, highlighting the limitations of relying solely on price signals for electrification efforts. In the long run, an increase in electricity prices results in decreased coal demand and coal intensity, implying that electricity and coal are complementary goods. Additionally, in the short run, an increase in oil prices leads to a decrease in both coal demand and coal intensity, indicating a complementary relationship between oil and coal in the short run. Relaxed financial constraints, measured by lagged profit, lead to increased energy use but decreased energy intensity in the short term, likely due to technological upgrades facilitated by improved financial conditions.

Private and foreign-owned firms exhibit a slightly higher sensitivity to energy price fluctuations compared to state-owned firms. This is likely due to the fact that state-owned firms, which bear greater social responsibilities and have more soft budgets, are less responsive to changes in energy prices. However, the gap in sensitivity is small, suggesting that even state-owned firms are sufficiently responsive to carbon price signals. The underlying mechanism may lie in the effectiveness of incentive structures within state-owned firms, which drive them to pursue profit maximization once their social responsibilities are fulfilled. Therefore, concerns about the lack of responsiveness to carbon price variations among state-owned firms should not pose a significant issue in the broader framework of utilizing market-based tools to achieve net-zero emissions. Meanwhile, only foreign firms show a heightened responsiveness in energy intensity. This may be attributed to their advantages in accessing advanced technologies and international resources, which have been particularly significant during China's technology catch-up process. However, as technological gaps between countries narrow, the greater sensitivity of foreign firms to energy intensity may gradually diminish.

Overall, these findings provide valuable insights into the dynamics of energy demand and intensity adjustments, highlighting the complexities and nuances involved in responding to energy price changes. They underscore the importance of considering both short-term and long-term implications in energy policy formulation and implementation. Importantly, our analysis reveals that, in the long run, energy-intensive manufacturing firms are responsive to price signals. This is encouraging news for the expansion and tightening of China's national carbon market and using it to reduce China’s CBAM liability in energy intensive manufacturing exports.

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Appendix A: Calculation of Coal's Provincial Delivery Price

For coal flow routes, the coal flow routes information outlined in the 12th Five-Year Plan for the Development of the Coal Industry (NDRC, 2012) served as a cornerstone. When determining the starting point of the coal transportation route in the coal production province, careful consideration was given to selecting the closest producing site relative to the destination capital city, aligning with the distribution of primary coal production sites as delineated in the Construction Plan for Coal Mining Base (NDRC, 2007). It is worth noting that for those coal production areas wherein the coal utilized is self-produced, transportation costs were presumed to be negligible, and thus, were omitted from our analysis.

Additionally, it is pertinent to acknowledge that Gansu, Qinghai, Ningxia, and Xinjiang, while recognized as coal production areas, were not included in our analysis due to the absence of coal price data in our dataset. Moreover, given the relatively lower presence of manufacturing firms in these provinces compared to others, a decision was made to exclude them from our analytical framework. Coal transportation routes for provinces are shown in table A1.

Table A1: Coal transportation routes for provinces with starting hub price

Province	Destination	Departure	Route
Beijing	Beijing	Datong (Shanxi)	Datong (Shanxi)-railway-Beijing
Tianjin	Tianjin	Datong (Shanxi)	Datong (Shanxi)-railway-Tianjin
Hebei	Shijiazhuang	Datong (Shanxi)	Datong (Shanxi)-railway-Shijiazhuang
Shanxi			self-production for self-use
Inner Mongolia			self-production for self-use
Liaoning	Shenyang	Tongliao (Inner Mongolia)	Tongliao (Inner Mongolia)-railway-Shenyang
Jilin	Changchun	Tongliao (Inner Mongolia)	Tongliao (Inner Mongolia)-railway- Changchun
Heilongjiang			self-production for self-use
Shanghai	Shanghai	Datong (Shanxi)	Datong (Shanxi)-railway-Qinhuangdao (Hebei)-shipping-Shanghai
Jiangsu	Zhangjiagang	Datong (Shanxi)	Datong (Shanxi) -railway-Qinhuangdao (Hebei)-shipping-Zhangjiagang
Zhejiang	Ningbo	Datong (Shanxi)	Datong (Shanxi) -railway-Qinhuangdao (Hebei)- shipping-Ningbo
Anhui			self-production for self-use
Fujian	Fuzhou	Datong (Shanxi)	Datong (Shanxi) - railway - Qinhuangdao (Hebei)- shipping-Fuzhou

Jiangxi	Nanchang	Jincheng (Shanxi)	Jincheng (Shanxi) - railway-Nanchang
Shandong			self-production for self-use
Henan	Zhengzhou	Jincheng (Shanxi)	Jincheng (Shanxi) - railway-Zhengzhou
Hubei	Wuhan	Jincheng (Shanxi)	Jincheng (Shanxi) - railway-Wuhan
Hunan	Changsha	Liupanshui (Guizhou)	Liupanshui (Guizhou) - railway-Changsha
Guangdong	Guangzhou	Datong (Shanxi)	Datong (Shanxi) - railway-Qinhuangdao (Hebei) - shipping-Guangzhou
Guangxi	Nanning	Liupanshui (Guizhou)	Liupanshui (Guizhou) -railway-Nanning
Hainan	Haikou	Datong (Shanxi)	Datong (Shanxi) -railway-Qinhuangdao (Hebei) - shipping-Haikou
Chongqing	Chongqing	Xianyang (Shaanxi)	Xianyang (Shaanxi) - railway-Chongqing
Sichuan	Chengdu	Liupanshui (Guizhou)	Liupanshui (Guizhou) - railway-Chengdu
Guizhou			self-production for self-use
Yunan	Kunming	Liupanshui (Guizhou)	Liupanshui (Guizhou) - railway-Kunming
Shaanxi			self-production for self-use

The Daqin Railway, renowned as a pivotal coal transportation artery, links Datong and Qinhuangdao, serving as a critical conduit for coal shipment. In our analysis, we employed the fixed length of the Daqin Railway to represent the mileage between Datong and Qinhuangdao. Furthermore, to ascertain the railway transportation distances between other cities, we diligently acquired data by consulting authoritative railway websites[3]. Rail transport costs are comprised of four primary components: the base rate for loading, distance charge, construction fund charge, and electrification surcharge. Specifically, the distance charge is computed by multiplying the distance by the prevailing freight rate, with additional summation of the other three components. It is pertinent to highlight that the freight rate and the base rate for loading are subject to variation over time. To capture this temporal variability, we meticulously collected price data on railway coal transportation for each year from the Railway Freight Tariff Schedule (NDRC, 2004; 2008; 2011; 2012; 2013; 2014; 2015; 2016).

A notable consideration pertains to the distinct freight charge methodology observed for the Daqin Railway compared to other railway routes. Notably, coal freight on this particular line, wherein both the origin and destination stations

[3] The querying website is https://kelibiao.com/

reside, is subject to unique tariffs. Herein, the base rate for loading is rendered inapplicable, denoted as 0, and a special distance charge rate is deployed. The specifics of these price adjustments are elucidated in Table A2.

Table A2: Railway rates

year	Construction fund charge	Base rate for loading	Electrification surcharge	Distance Charge Rate	Distance Charge Rate for Daqin
unit	Yuan/tonne	Yuan/tonne	Yuan/tonne	Yuan/tonne-km	Yuan/tonne-km
2007	0.033	9.3	0.012	0.0434	0.0751
2008	0.033	9.6	0.012	0.0484	0.0751
2009	0.033	9.6	0.012	0.0484	0.0751
2010	0.033	9.6	0.012	0.0484	0.0751
2011	0.033	10.8	0.012	0.0553	0.0751
2012	0.033	12.2	0.012	0.0629	0.0751
2013	0.033	13.8	0.012	0.0753	0.0751
2014	0.033	15.5	0.012	0.089	0.0901
2015	0.033	16.3	0.012	0.098	0.1001
2016	0.033	16.3	0.012	0.092	0.1001

The annual average Ocean Coal Freight Index (OCFI), denoted in Yuan per tonne, serves as a pivotal metric for assessing shipping costs between harbours[4]. Given its intrinsic nature as the specific shipping cost per tonne of cargo between two designated ports, the necessity for shipping distance data is obviated. Consequently, the transportation cost is computed as the combination of the railway transportation cost and the shipping cost, the latter being applicable solely if water shipping is encompassed within the designated route.

[4] Data source is iFinD database.

Appendix B: Change the threshold to 5000 tonnes of standard coal

Table B1: Long-run price elasticities of energy demand

	(1)	(2)	(3)	(4)	(5)	(6)
	Ln coal	Ln oil	Ln elec	Ln coal	Ln oil	Ln elec
Ln coal price	-1.097***	-0.403	0.128	-1.172***	-0.303	0.146
	(0.322)	(0.427)	(0.165)	(0.250)	(0.462)	(0.165)
Ln oil price	-0.574	0.0794	-0.306	-1.616	-0.103	-0.233
	(1.186)	(0.563)	(0.474)	(1.353)	(0.763)	(0.582)
Ln elec price	-1.679**	0.692	-0.769**	-0.999	1.341*	-0.843***
	(0.612)	(0.736)	(0.277)	(0.619)	(0.784)	(0.298)
Ln product price	0.202	0.323**	0.493***	0.0425	0.321***	0.475***
	(0.188)	(0.144)	(0.0745)	(0.173)	(0.103)	(0.0687)
GDP growth rate	0.0412	-0.0706	0.0195	0.0560	-0.0664	0.0150
	(0.0428)	(0.0435)	(0.0209)	(0.0485)	(0.0438)	(0.0203)
Ln GDP per capita	-0.646*	0.529*	-0.0847	-0.661**	0.502	-0.0983
	(0.320)	(0.307)	(0.107)	(0.304)	(0.324)	(0.125)
Ln capital per labor	-0.0764	-0.0121	-0.0495	-0.0903	0.0141	-0.0195
	(0.185)	(0.180)	(0.0638)	(0.173)	(0.192)	(0.0647)
Ln real output	0.355***	0.145**	0.547***	0.343***	0.0708	0.507***
	(0.0505)	(0.0548)	(0.0188)	(0.0685)	(0.0654)	(0.0209)
Private x ln coal price				0.00412		
				(0.0144)		
Foreign x ln coal price				-0.118***		
				(0.0200)		
Private x ln oil price					-0.0401***	
					(0.00966)	
Foreign x ln oil price					-0.00170	
					(0.0116)	
Private x ln elec price						-0.00839
						(0.00527)
Foreign x ln elec price						0.0117**
						(0.00540)
Observations	85,859	83,981	98,383	44,363	44,495	52,055
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes	Yes	Yes

Notes: Standard errors in parentheses *p < 0.10, **p < 0.05, ***p < 0.01. The standard errors are clustered at the province level.

Table B2: Short-run price elasticities of energy demand

	(1)	(2)	(3)	(4)	(5)	(6)
	Ln coal	Ln oil	Ln ele	Ln coal	Ln oil	Ln elec
Ln coal price	-0.434	-0.693	0.311	-0.554	-0.763	0.229
	(0.677)	(0.946)	(0.194)	(0.700)	(1.028)	(0.153)
Ln oil price	-0.923***	-0.699	-0.406**	-0.946***	-0.944	-0.210
	(0.249)	(0.472)	(0.154)	(0.318)	(0.780)	(0.257)
Ln elec price	1.078	3.347*	-0.166	1.396	4.308**	-0.570
	(1.368)	(1.633)	(0.627)	(1.864)	(1.838)	(0.832)
Ln product price	-0.0872	0.229	0.534***	-0.403*	0.233***	0.554***
	(0.223)	(0.157)	(0.0679)	(0.208)	(0.0758)	(0.0436)
GDP growth rate	-0.0241	-0.129	-0.0174	0.0717	-0.148	0.00344
	(0.0614)	(0.111)	(0.0284)	(0.0683)	(0.119)	(0.0296)
Ln GDP per capita	-0.885	0.520	1.734	-3.401	-0.188	2.668**
	(2.440)	(3.348)	(1.054)	(2.366)	(3.021)	(1.095)
Ln capital per labor	1.750	4.101***	-0.601	2.609*	3.167**	-0.656
	(1.200)	(1.130)	(0.563)	(1.303)	(1.172)	(0.638)
Ln lag profit	-0.0651*	0.0629***	0.0702***	-0.0571	0.0562**	0.0707***
	(0.0333)	(0.0176)	(0.0104)	(0.0445)	(0.0218)	(0.0122)
Ln real output	0.255***	0.247***	0.541***	0.158	0.165**	0.499***
	(0.0611)	(0.0462)	(0.0198)	(0.0950)	(0.0751)	(0.0224)
Private x ln coal price				0.0153		
				(0.0314)		
Foreign x ln coal price				-0.0994**		
				(0.0390)		
Private x ln oil price					-0.0204	
					(0.0180)	
Foreign x ln oil price					-0.0227	
					(0.0175)	
Private x ln elec price						-0.0117
						(0.00922)
Foreign x ln elec price						0.00819
						(0.00596)
Observations	18,973	18,113	21,401	9,615	9,408	11,137
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes	Yes	Yes
Province FE	Yes	Yes	Yes	Yes	Yes	Yes

Notes: Standard errors in parentheses *p < 0.10, **p < 0.05, ***p < 0.01. The standard errors are clustered at the province level.

Table B3: Long-run price elasticities of energy intensity

	(1)	(2)	(3)	(4)	(5)	(6)
	Ln coal intensity	Ln oil intensity	Ln elec intensity	Ln coal intensity	Ln oil intensity	Ln elec intensity
Ln coal price	-1.429***	-0.668	0.0561	-1.519***	-0.552	0.104
	(0.394)	(0.518)	(0.166)	(0.329)	(0.528)	(0.191)
Ln oil price	-0.613	0.156	-0.276	-1.897	-0.127	-0.125
	(1.385)	(0.716)	(0.470)	(1.588)	(0.976)	(0.582)
Ln elec price	-2.169***	0.136	-1.036***	-1.325*	0.904	-1.121***
	(0.712)	(0.847)	(0.292)	(0.698)	(0.846)	(0.343)
Ln product price	0.213	0.798***	0.926***	0.0181	0.791***	0.922***
	(0.187)	(0.168)	(0.0643)	(0.156)	(0.110)	(0.0557)
GDP growth rate	0.0478	-0.0714	0.0266	0.0617	-0.0609	0.0216
	(0.0476)	(0.0469)	(0.0228)	(0.0539)	(0.0475)	(0.0218)
Ln GDP per capita	-0.846**	0.431	-0.277**	-0.806**	0.451	-0.269*
	(0.384)	(0.386)	(0.119)	(0.369)	(0.418)	(0.139)
Ln capital per labor	-0.112	-0.0316	-0.0552	-0.141	-0.000366	-0.0290
	(0.223)	(0.228)	(0.0690)	(0.199)	(0.238)	(0.0749)
Private x ln coal price				0.0369**		
				(0.0153)		
Foreign x ln coal price				-0.143***		
				(0.0216)		
Private x ln oil price					0.00174	
					(0.00990)	
Foreign x ln oil price					-0.0257**	
					(0.0125)	
Private x ln elec price						0.0261***
						(0.00662)
Foreign x ln elec price						-0.00544
						(0.00635)
Observations	85,859	83,981	98,383	44,363	44,495	52,055
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes	Yes	Yes

Notes: Standard errors in parentheses *p < 0.10, **p < 0.05, ***p < 0.01. The standard errors are clustered at the province level.

Table B4: Short-run price elasticities of energy intensity

	(1)	(2)	(3)	(4)	(5)	(6)
	Ln coal intensity	Ln oil intensity	Ln elec intensity	Ln coal intensity	Ln oil intensity	Ln elec intensity
Ln coal price	-0.525	-0.732	0.255	-0.606	-0.704	0.219
	(0.725)	(1.069)	(0.196)	(0.746)	(1.215)	(0.169)
Ln oil price	-0.890***	-0.912*	-0.440***	-1.122***	-1.205	-0.317
	(0.270)	(0.527)	(0.150)	(0.351)	(0.864)	(0.266)
Ln elec price	1.083	3.846**	-0.237	1.643	5.096**	-0.623
	(1.426)	(1.830)	(0.654)	(1.856)	(2.040)	(0.934)
Ln product price	0.194	0.608***	1.004***	-0.0823	0.611***	1.038***
	(0.282)	(0.154)	(0.0584)	(0.223)	(0.100)	(0.0395)
GDP growth rate	-0.0336	-0.161	-0.0188	0.0477	-0.190	0.00220
	(0.0647)	(0.124)	(0.0291)	(0.0729)	(0.135)	(0.0319)
Ln GDP per capita	-1.942	0.122	1.081	-4.109	-0.237	2.147*
	(2.423)	(3.656)	(1.144)	(2.522)	(3.302)	(1.219)
Ln capital per labor	1.695	4.483***	-0.468	2.401*	3.387**	-0.512
	(1.163)	(1.235)	(0.606)	(1.269)	(1.295)	(0.661)
Ln lag profit	-0.295***	-0.128***	-0.117***	-0.295***	-0.162***	-0.133***
	(0.0342)	(0.0301)	(0.0160)	(0.0368)	(0.0469)	(0.0190)
Private x ln coal price				0.0443		
				(0.0327)		
Foreign x ln coal price				-0.106**		
				(0.0390)		
Private x ln oil price					-0.00275	
					(0.0191)	
Foreign x ln oil price					-0.0180	
					(0.0183)	
Private x ln elect price						0.00442
						(0.00766)
Foreign x ln elec price						0.0109*
						(0.00612)
Observations	18,973	18,113	21,401	9,615	9,408	11,137
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes	Yes	Yes
Province FE	Yes	Yes	Yes	Yes	Yes	Yes

Notes: Standard errors in parentheses *p < 0.10, **p < 0.05, ***p < 0.01. The standard errors are clustered at the province level.

Appendix C: Change the Research Period

Table C1: Long-run price elasticities of energy demand (2007-2013)

	(1)	(2)	(3)	(4)	(5)	(6)
	Ln coal	Ln oil	Ln elec	Ln coal	Ln oil	Ln elec
Ln coal price	-1.439***	-0.595	0.209	-1.633***	-0.474	0.314
	(0.329)	(0.451)	(0.186)	(0.276)	(0.441)	(0.194)
Ln oil price	-0.732	0.708	-0.473	-1.479	0.545	-0.399
	(1.436)	(0.709)	(0.540)	(1.806)	(0.761)	(0.656)
Ln elec price	-1.126*	0.538	-0.920***	-0.340	1.086	-0.976**
	(0.549)	(0.728)	(0.326)	(0.676)	(0.687)	(0.433)
Ln product price	0.250	-0.0569	0.631***	0.325	0.00423	0.593***
	(0.331)	(0.387)	(0.106)	(0.330)	(0.314)	(0.0723)
GDP growth rate	0.0540	-0.0229	0.0259	0.0514	-0.00228	0.0206
	(0.0468)	(0.0501)	(0.0300)	(0.0550)	(0.0512)	(0.0332)
Ln GDP per capita	-0.474*	0.649**	0.0160	-0.527*	0.614*	0.0460
	(0.265)	(0.298)	(0.116)	(0.287)	(0.322)	(0.141)
Ln capital per labor	-0.179	-0.0197	-0.0897	-0.200	0.00975	-0.0932
	(0.145)	(0.172)	(0.0773)	(0.153)	(0.205)	(0.0893)
Ln real output	0.538***	0.0930	0.516***	0.537***	0.0154	0.479***
	(0.0560)	(0.0770)	(0.0283)	(0.0728)	(0.0838)	(0.0343)
Private x ln coal price				0.00648		
				(0.0170)		
Foreign x ln coal price				-0.115***		
				(0.0216)		
Private x ln oil price					-0.0318*	
					(0.0158)	
Foreign x ln oil price					0.0219	
					(0.0140)	
Private x ln elec price						-0.0202**
						(0.00776)
Foreign x ln elec price						-0.00145
						(0.00701)
Observations	44,181	43,065	49,524	22,513	22,597	25,863
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes	Yes	Yes

Notes: Standard errors in parentheses *p < 0.10, **p < 0.05, ***p < 0.01. The standard errors are clustered at the province level.

Table C2: Short-run price elasticities of energy demand (2007-2013)

	(1)	(2)	(3)	(4)	(5)	(6)
	Ln coal	Ln oil	Ln ele	Ln coal	Ln oil	Ln elec
Ln coal price	-0.509	0.131	0.259	-1.064	0.215	0.193
	(0.682)	(1.262)	(0.408)	(0.866)	(1.434)	(0.382)
Ln oil price	-1.514***	-0.610*	-0.282*	-0.687**	-0.0609	-0.201
	(0.253)	(0.353)	(0.137)	(0.313)	(0.379)	(0.194)
Ln elec price	1.433	5.763**	-1.061	1.738	7.178**	-2.098*
	(1.296)	(2.500)	(0.700)	(1.921)	(2.746)	(1.056)
Ln product price	0.103	0.0785	0.642***	0.270	0.273	0.588***
	(0.336)	(0.418)	(0.0940)	(0.320)	(0.280)	(0.0776)
GDP growth rate	-0.0609	-0.167	0.0242	0.0221	-0.200	0.0621
	(0.0610)	(0.186)	(0.0443)	(0.0761)	(0.199)	(0.0515)
Ln GDP per capita	-1.584	2.580	0.860	-5.233*	5.345	1.762
	(2.391)	(3.626)	(1.581)	(2.770)	(3.313)	(1.689)
Ln capital per labor	1.174	2.523	-0.286	2.904	-0.0806	-0.747
	(1.502)	(1.598)	(0.851)	(1.927)	(1.758)	(1.013)
Ln lag profit	-0.0193	0.0707***	0.0675***	0.00483	0.0357	0.0809***
	(0.0365)	(0.0224)	(0.0187)	(0.0680)	(0.0320)	(0.0254)
Ln real output	0.392***	0.193**	0.579***	0.269**	0.146	0.537***
	(0.0814)	(0.0715)	(0.0236)	(0.125)	(0.118)	(0.0258)
Private x ln coal price				-0.0318		
				(0.0355)		
Foreign x ln coal price				-0.131***		
				(0.0403)		
Private x ln oil price					-0.0242	
					(0.0257)	
Foreign x ln oil price					-0.0102	
					(0.0263)	
Private x ln elec price						-0.0237
						(0.0149)
Foreign x ln elec price						-0.0119
						(0.0126)
Observations	8,679	8,164	9,415	4,161	4,010	4,640
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes	Yes	Yes
Province FE	Yes	Yes	Yes	Yes	Yes	Yes

Notes: Standard errors in parentheses *p < 0.10, **p < 0.05, ***p < 0.01. The standard errors are clustered at the province level.

Table C3: Long-run price elasticities of energy intensity (2007-2013)

	(1)	(2)	(3)	(4)	(5)	(6)
	Ln coal intensity	Ln oil intensity	Ln elec intensity	Ln coal intensity	Ln oil intensity	Ln elec intensity
Ln coal price	-1.795***	-0.895*	0.115	-2.017***	-0.684	0.310
	(0.391)	(0.518)	(0.197)	(0.343)	(0.477)	(0.231)
Ln oil price	-0.789	1.006	-0.319	-1.725	0.998	-0.0597
	(1.677)	(0.922)	(0.514)	(2.174)	(1.003)	(0.693)
Ln elec price	-1.406**	-0.143	-1.261***	-0.534	0.350	-1.392**
	(0.634)	(0.847)	(0.368)	(0.767)	(0.742)	(0.513)
Ln product price	0.221	0.547	1.121***	0.214	0.615*	1.106***
	(0.315)	(0.407)	(0.113)	(0.293)	(0.315)	(0.0720)
GDP growth rate	0.0549	-0.00592	0.0403	0.0443	0.0204	0.0343
	(0.0507)	(0.0568)	(0.0336)	(0.0599)	(0.0556)	(0.0376)
Ln GDP per capita	-0.521	0.571	-0.192	-0.496	0.598	-0.135
	(0.308)	(0.350)	(0.140)	(0.337)	(0.384)	(0.181)
Ln capital per labor	-0.238	-0.0214	-0.0814	-0.286	0.00608	-0.0939
	(0.169)	(0.214)	(0.0833)	(0.174)	(0.239)	(0.111)
Private x ln coal price				0.0258		
				(0.0174)		
Foreign x ln coal price				-0.127***		
				(0.0215)		
Private x ln oil price					0.0126	
					(0.0185)	
Foreign x ln oil price					-0.00278	
					(0.0160)	
Private x ln elec price						0.0152
						(0.0102)
Foreign x ln elec price						-0.0187**
						(0.00743)
Observations	44,181	43,065	49,524	22,513	22,597	25,863
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes	Yes	Yes

Notes: Standard errors in parentheses *p < 0.10, **p < 0.05, ***p < 0.01. The standard errors are clustered at the province level.

Table C4: Short-run price elasticities of energy intensity (2007-2013)

	(1)	(2)	(3)	(4)	(5)	(6)
	Ln coal intensity	Ln oil intensity	Ln elec intensity	Ln coal intensity	Ln oil intensity	Ln elec intensity
Ln coal price	-0.571	0.297	0.223	-0.943	0.689	0.258
	(0.751)	(1.368)	(0.402)	(0.962)	(1.619)	(0.362)
Ln oil price	-1.569***	-0.740**	-0.395**	-0.757**	-0.169	-0.332
	(0.243)	(0.350)	(0.159)	(0.320)	(0.401)	(0.200)
Ln elec price	1.521	6.062**	-1.173	1.683	7.198**	-2.432**
	(1.408)	(2.649)	(0.733)	(2.038)	(3.013)	(1.146)
Ln product price	0.318	0.536	1.035***	0.306	0.669**	0.985***
	(0.373)	(0.431)	(0.0930)	(0.332)	(0.319)	(0.0750)
GDP growth rate	-0.0729	-0.194	0.0261	-0.00615	-0.219	0.0699
	(0.0655)	(0.198)	(0.0427)	(0.0796)	(0.216)	(0.0526)
Ln GDP per capita	-2.986	1.461	0.342	-6.263**	5.166	1.698
	(2.505)	(3.710)	(1.691)	(2.846)	(3.498)	(1.728)
Ln capital per labor	1.044	2.593	-0.231	2.679	-0.334	-0.705
	(1.577)	(1.633)	(0.857)	(1.981)	(1.640)	(0.932)
Ln lag profit	-0.194***	-0.153***	-0.104***	-0.197***	-0.224***	-0.113***
	(0.0399)	(0.0412)	(0.0190)	(0.0687)	(0.0516)	(0.0230)
Private x ln coal price				-0.00488		
				(0.0358)		
Foreign x ln coal price				-0.130***		
				(0.0399)		
Private x ln oil price					-0.0155	
					(0.0302)	
Foreign x ln oil price					-0.00378	
					(0.0276)	
Private x ln elect price						-0.00611
						(0.0147)
Foreign x ln elec price						-0.00466
						(0.0138)
Observations	8,679	8,164	9,415	4,161	4,010	4,640
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes	Yes	Yes
Province FE	Yes	Yes	Yes	Yes	Yes	Yes

Notes: Standard errors in parentheses *p < 0.10, **p < 0.05, ***p < 0.01. The standard errors are clustered at the province level.