Welfare Effects of Reducing Coal Production in China*

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Abstract

We study the short-run welfare effects of reducing coal production in China. We leverage a 2016 policy that temporarily reduced coal supply to estimate an equilibrium model of the coal market. In the counterfactual simulation, we find that the policy decreases the equilibrium quantity by 20.1% and consumer surplus by 170.7 billion RMB, resulting in a deadweight loss of 97.1 billion RMB. The loss is an order of magnitude greater than the health cost savings attributed to reduced air pollutants. A Pigouvian tax internalizing the health costs of air pollution would reduce the quantity by 5.8% during the policy period.

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1 Introduction

China accounts for over half of global coal production and consumption in 2023. There are widespread concerns that the continued reliance on coal not only worsens China's air pollution (Almond et al., 2009; Chen et al., 2013; Ebenstein et al., 2017) but also undermines China's energy transition and global efforts to mitigate climate change (McGrath, 2019; WSJ, 2022; Bloomberg, 2022). Policy interventions that reduce this reliance can create significant tradeoffs between the loss of economic surplus and the gains from environmental improvements. In this paper, we quantify both the aggregate and distributional welfare effects of reducing coal production in China.

Our empirical analysis uses variations induced by a reform targeting coal producers. As part of a broader initiative to reduce coal consumption and air pollution while preserving employment and profitability of the coal mining industry, the Chinese government in April 2016 called for small coal mines to be closed and large mines to reduce output. As provinces started to comply with the supply reduction policy, coal prices surged, and the government phased out the policy at the end of 2016. Our data show that the average coal price in the second half of 2016 increased by 34.6% to 503 RMB/ton, up from 373 RMB/ton in the same period of 2015.

We combine the temporary policy intervention with a comprehensive dataset on coal shipment between provinces to analyze the demand and supply of coal. Our data cover the period from 2014 to 2016 and include monthly prices at the province level and shipment quantities from producers to end users both within a province and across provinces. We validate the shipment data with the production and consumption data reported by other sources. We then document two stylized facts about the coal market. First, the share of coal shipped from one province to another is highly stable over time, despite varying price dispersions across provinces. Second, policy compliance varies across firm types and provinces. In particular, large state-owned coal mines and major coal producing provinces drive the decrease in supply.

We then formulate a model that incorporates key institutional features of China's massive and partially regulated coal market. First, coal procurement in the electricity and other sectors have undergone significant market reforms since 2013, essentially allowing the market to set prices that equilibrate demand with supply. Second, large coal producers and buyers often operate under long-term quantity contracts, which partly explains the observed stability of shipment shares between provinces. In our model, the market is competitive. We specify a demand function and a supply function for each province. A province's supply can be shipped both within the province and to other provinces, and depends on the average price at its destination provinces. The price in each province is determined by local demand and the supply shipped into the province.

We next estimate the demand and supply of coal across provinces. To identify the demand function, we construct price instruments using variations in the policy start dates and policy compliance levels across provinces. The key identifying assumption is that the policy exclusively affects supply and is therefore not correlated with the demand unobservables. We then identify pre-policy supply using the estimated demand residuals based on a covariance restriction (MacKay and Miller, 2024; Döpper et al., 2024).

Using the estimated model, we quantify the changes in economic surplus and environmental benefits of the policy. Specifically, we simulate a "no-policy" equilibrium for June and December 2016 based on the estimated demand and pre-policy supply functions. At the aggregate level, we find that the policy decreases equilibrium coal quantity by 20.1% and increases equilibrium prices by 15.0%. The resulting loss in consumer surplus is 170.7 billion RMB, and the overall deadweight loss is 97.1 billion RMB. To quantify the benefits of saved emissions, we estimate a mapping from province-level coal demand (shipment) to consumption and a mapping from consumption to aerial pollutant concentration. We find that the policy reduces coal consumption by 4.6% in the second half of 2016, translating to a reduction in health costs from aerial pollutants of 17.9 billion RMB.

For the distributional impact of the policy, we find substantial heterogeneity in welfare effects across provinces. In particular, Shaanxi, the third largest coal producer and 16th most populous province with 37 million people, benefits the most from the policy, which increases its total surplus by over 7 billion RMB. In contrast, coastal provinces, which are the largest coal consumers, see the largest decreases in surplus despite improved air quality. The province with the largest loss in surplus of 24 billion RMB is Hebei, the 6th most populous province with 75 million people.

We also quantify the distortion due to differential enforcement of the policy across provinces. We find that the policy disproportionately reduces supply in provinces with lower marginal costs. Although this policy may be efficient if higher-cost regions also supply to regions with higher marginal benefits from reduced aerial pollution, we find that the environmental benefits do not offset the effects of inefficient production reductions. A uniform national production tax that reduces the national aggregate quantity by the same amount as the observed policy reduces the spatial distortion, leading to only 36.3% of the policy's economic surplus loss.

These results also suggest that the policy may have reduced coal production too much relative to the social objective function of the total economic surplus and health benefits from reduced aerial pollution. A national tax maximizing this objective function would be set at 42 RMB/ton, which would raise the prices by 4.1% and reduce the quantity by 5.8% relative to the no-policy baseline. We also note that the optimal production and consumption of coal would likely be far lower than the observed levels if we further take into account the social cost of carbon.

Contribution and Related Literature

In this paper, we present new empirical evidence on how industrial policy affects economic surplus and environmental outcomes by studying China's temporary reduction of its coal production. In particular, we quantify the welfare implication from the uneven implementation of the policy across provinces. Our paper thus joins the growing literature that empirically analyzes the effects of industrial policy (Kline and Moretti, 2014; Aghion et al., 2015; Alder et al., 2016; Juhász, 2018; Kalouptsidi, 2018; Lane, 2018; Miravete et al., 2018; Lashkaripour and Lugovskyy, 2018; Criscuolo et al., 2019; Rotemberg, 2019; Barwick et al., 2019; Giorcelli, 2019; Yi et al., 2019; Hanlon, 2020;

Bai et al., 2020; Fan and Zou, 2021; Giorcelli and Li, 2021; Guo and Xiao, 2022; Aldy et al., 2022).[1] Our finding on the uneven implementation of the policy also quantifies the economic impact of fragmented local governance in response to a top-down directive (Huang, 1999; Mertha, 2009).

Our paper is also related to the empirical literature on measuring the economic costs of environmental regulations. A number of papers focus on productivity impacts (for example, Jaffe et al. (1995); Berman and Bui (2001); Greenstone (2002); Greenstone et al. (2012); He et al. (2020)). Ryan (2012) and Fowlie et al. (2016) emphasize the roles of market power and measure welfare effects. Chen et al. (2025) study how conglomerates reallocate production in response to policies that aim to lower energy consumption. In this paper, we analyze a competitive equilibrium market.

We also note that there have been few equilibrium analyses of China's coal industry in economics despite its enormous importance to China's economy and the global environment. One reason might be the lack of granular and recent data.[2] For example, Zhou et al. (2019) study the evolution of coal mining firms' productivity, and Zheng (2024) studies the effects of buyer market power on productivity and safety, both using a production function approach based on manufacturing census data from before 2007. In our paper, we are able to use the price and shipment data of coal within and across provinces from a more recent period and estimate the demand and supply of coal at the province-month level.

In the rest of the paper, we first describe the main institutional features of China's coal market in Section 2. Section 3 describes the various datasets used in the analysis. We document stylized facts about China's coal market in Section 4. Sections 5 and 6 present the demand and supply models and their estimation. Counterfactual simulations are in Section 8, and we conclude in Section 9.

2 Background

2.1 Coal Industry in China

2.1.1 Coal Types, Quality and Mining Technology[3]

Over 70% of China's coal production are bituminous coal, and 23% are anthracite.[4] High-purity bituminous coal and about half of anthracite are used for coking, which in turn produces coke for steel making. The rest of these two types of coal are mainly used by power plants for electricity production. The main uses of lower-purity coal are for construction (cement making) and heating.

[1] See, e.g., Rodrik (2008), Harrison and Rodríguez-Clare (2010), and Neumark and Simpson (2015) for a review of the broad industrial policy literature.

[2] Existing studies that estimate or calibrate the coal demand or supply typically use aggregate annual data (see, for example, (Burke and Liao, 2015; Shi et al., 2018; Teng et al., 2019)). A number of papers have studied the coal-mining industry in other countries, with a focus on safety and productivity (Sider, 1983; Gowrisankaran et al., 2015), technology adoption (Rubens, 2022), labor market competition (Delabastita and Rubens, 2022; Demirer and Rubens, 2025), and the decline of the US coal industry (Watson et al., 2023).

[3] This section is based on Aden, Fridley and Zheng (2009) and National Energy Report (2020).

[4] Coals are usually classified by the carbon content (by weight). The carbon content is over 86% for anthracite and between 45% to 86% for bituminous coal. The remaining coal falls into the categories with lower carbon content, such as subbituminous, lignite and brown coal (American Geosciences Institute, n.d.).

Coal purity and extraction methods vary significantly across regions. Shanxi and Inner Mongolia have the largest reserves and are the largest coal-producing provinces, accounting for over half of national output.[5] Shanxi also produces the highest-quality coal, with an average heat content (defined as the total energy produced per kilogram after complete combustion) of about 6,242 kcal/kg, compared to the national average of 5,350 kcal/kg and the US average of 5,600 kcal/kg. Over 90% of mines in China are pithead mines, where coal is extracted from deep underground. The average mine depth is 456 meters. This extraction method is more costly than open-pit mining more commonly found in other major coal-producing countries, such as Australia, India, and US.

2.1.2 The Formation of the Coal Market

Historically, the Chinese government exercised tight control over both the supply and demand of coal through planned prices and quantities. The government partially liberalized the market in 1993 by allowing coal to be traded while maintaining special contracts that gave the large state-owned power plants the option to buy coal from mines at planned quantities and prices (Yang et al., 2018). The special contract prices were typically lower than the prevailing market prices. When contracted coal was insufficient to meet electricity demand, power plants turned to the spot market to purchase additional coal. The government further liberalized the market in a series of reforms, and fully abolished the special contracts in 2013 (State Council of the People's Republic of China, 2013). These reforms also changed the procurement, operation, and investment decisions of power plants, which then started to respond to fluctuating coal prices in a manner more consistent with profit-maximizing firms (Xu and Chen, 2006; Ma, 2011; Liu et al., 2013; Zhao and Ma, 2013; Gao and Van Biesebroeck, 2014; Eisenberg, 2019, 2024).

2.1.3 Method of Sales

Long-Term Contracts During our sample period, coal buyers and producers trade via both long-term (annual or multi-year) contracts and the spot market. Major buyers include coal power plants, municipal central heating systems,[6] construction firms, steel makers, and fertilizer manufacturers. A long-term contract is signed directly between a coal producer and an end user (not a trading intermediary). Provincial governments are often involved to help firms find their matches, especially in large coal producing provinces, which bear political responsibility to ensure coal supply to other provinces' power plants and heating systems (NDRC, 2021). These contracts would nominally promise an annual delivery quantity but allow prices to adjust at a quarterly or even monthly basis, based on the spot market prices (Shanghai Securities News, 2014, 2015; ICBC, 2016). As a result, actual delivered quantities may deviate from the contractual terms (International Energy Network, 2016a).

[5] Appendix Figure G.1 shows the distribution of coal reserves.

[6] Across northern China, most residential apartments, government facilities, and schools receive heating through municipal centralized systems that primarily burn coal to generate heat. This infrastructure consists of large coal-fired boilers that heat water, which is then distributed through an extensive network of insulated pipes to various buildings (Chen et al., 2013).

Price Discovery A standard practice is for buyers and sellers to use public monthly price indices to formulate a price. The most commonly used indices during and after our study periods are average transaction prices (net of transportation costs) of coal sold to power plants in different regions (NDRC, 2016b, 2017). Specifically, buyers and sellers update their contract prices based on the signing prices (which may depend on coal quality in addition to projected supply and demand) and the average delivery prices in the past month published by coal trade associations and port authorities, which may include trades based on the contracts and in the spot market.[7]

Contract Compliance While we do not have data on contract compliance, the government has long-standing policies that penalize under-fulfillment of the long-term contracts (NDRC, 2016a). For example, in 2017, power plants that failed to buy at least 75% of their committed volume (by weight) in the signed contracts faced restrictions on their electricity sales (Gao, 2017). In more recent years, long-term contracts have been the main component of coal trades, consistently accounting for more than 75% coal for electricity (Zhou et al., 2024). The government also prioritizes allocating rail transportation for coal sold via long-term contracts.[8] Finally, we note that power plants are usually optimized to burn coal of a specific grade and thus have incentives to procure from consistent sources. Plants that source from multiple mines may need to use a coal blending technique to maintain efficiency, which can increase operational costs (Sloss, 2014; Zhao, 2021).

2.2 Economic Policies

2.2.1 Coal Supply Reform

In the five-year plan published by National Development and Reform Commission (NDRC, China's macroeconomy management agency) in 2016, the Chinese government outlined a plethora of goals and plans to restructure the coal-mining industry. Specifically, the government explicitly called for improving the industry's profitability, limiting coal production, and reducing the industry's environmental impact.[9] Based on this plan, the State Council, China's chief administrative body, issued orders in February 2016 to limit the number of working days for coal mines from 330 to 276 days. The order also called for the closure of small coal mines. We refer to these orders as the **supply reduction policy** in the paper.[10]

[7] International Energy Network (2016b) provides an example on how to reset the monthly price using the average coal prices sold to power plants (BSPI) and the average price of coal for other uses (OPI) around the gulf of Bo Hai, both published by Qinhuangdao Ocean Shipping Coal Trading Market Co. Given the contract price p, the indices p_t^{BSPI} and p_t^{OPI} in month t, and the heat content of coal h measured in kcal/kg, the new price in month $t+1$ is adjusted to $0.5p + \left(0.25p_t^{\text{BSPI}} + 0.25p_t^{\text{OPI}}\right)\frac{h}{5,500\text{kcal/kg}}$. The government advises buyers and sellers to explicitly specify this particular form of the formula (dynamic price updates linear in average coal prices) in their long-term contracts. Contract prices, the price indices and the assigned weights could differ across firms and across years.

[8] Around 60% of coal is transported via rail (Sun, 2025).

[9] In Appendix A, we provide snapshots of the original document and its translation.

[10] Literally translated, NDRC planned to reduce coal mining capacity, and the Chinese press often referred to this policy as "capacity reduction policy", reflecting the closure of small mines. Given that the implementation of the policy reduced the output of operating mines but did not require them to, for example, divest and reduce the capability of production, we use the term "supply reduction" as a compromise.

The actual dates of implementation and compliance with the policy varied across provinces and coal mine ownership types. Shanxi, historically China's largest coal-producing province, was the first to implement the policy in April 2016. Other leading coal producing provinces such as Shaanxi and Inner Mongolia began their implementation in May and June 2016, respectively. Large state-owned coal mines were also subject to more stringent monitoring.

Coal prices surged in the second half of 2016 relative to the prior months in 2016 and to the same period in 2015. NDRC officially suspended the policy in October and increased import from Australia amid concerns over meeting the (highly inelastic) winter heating and power demand (Lai, 2016; Shi et al., 2018), but the reversal was not immediate and did not apply to all producers until at least January 2017 (Zhong, 2016).

2.2.2 Other Economic Policies

We also note two other sets of significant economic policies during our sample period. First, the government expanded credit and increased infrastructure spending to counter the decline in housing and stock market prices in 2015 and 2016 (Brandt et al., 2020). Many infrastructure projects, such as the national high-speed rail system, experienced rapid expansion in subsequent years (Reuters, 2016). Second, the government started to close small or unproductive plants in other industries.[11] These closures reduced 10% of the state-owned steel capacity in 2016 (Lu, 2016). However, we expect the plant closures to have a small effect on coal demand given that the output share of closed plants is likely low. In fact, China's steel output slightly increased in 2016 relative to 2015 (Xinhua, 2017).[12]

3 Data

3.1 Data Sources

We assemble our data from a number of sources. Our primary data come from the China Coal Transportation and Distribution Association, a major trade group in the coal industry. The data include monthly shipment quantities of coal between provinces from 2012 to 2016. The tonnage data combine raw coal, washed coal and other derivative products with high coal content (such as coke and briquette).[13] The shipment data include shipment to the own province and other

[11] It is of separate interest that the government, as opposed to the market, needs to order the shutdown of the plants. A plausible explanation is that many plants are supported by the local governments to provide employment despite being unprofitable. To facilitate the shutdown of coal and steel plants, China's Ministry of Finance created a fund of $15.3 billion to provide relief to the laid-off employees (Lu, 2016).

[12] China also paused the constructions of new power plants in 2016 (Ren et al., 2021), but given the long approval and construction time, these plants likely would not be operational in 2016 even without the pause, and the additional delays would not affect coal demand.

[13] Consistent with the standard NBS practice, the data account for transportation of the tonnage of final end products from the raw coal producers to the end users. More specifically, if 1 ton of raw coal was extracted in province A, transported to province B for washing (removing impurities) with quantity reduced to $x < 1$, and burned at power plants in province C, the data would only include x in transportation from A to C and not count the $A - B$ transportation. We also note that not all raw coal needs washing, and many coal mines are integrated with washing

provinces.

From the same provider, we also obtain monthly production data for key state-owned (SOE) coal mines, which are the largest coal mines in each province.[14] The production data reflect the total tonnage of excavated raw coal.

We collect additional data on coal imports, mine capacity, consumption, and prices. We obtain monthly coal imports in total tonnage from outside China to each province between 2014 and 2016 from the firm International Coal.[15] The mine-level, semi-annual capacity data from 2014 to 2016 is from the survey of National Energy Administration (NEA). The capacity reflects the government-approved maximum production levels.[16]

We collect monthly national coal consumption by sectors (including various grades of coal and high-coal-content products) from China Coal Resource, a leading consulting firm in China's coal industry. The data cover all major coal-consuming sectors such as electricity production, heating and cement production. Although we do not have data on monthly coal consumption at the province level, we collect the monthly output of main products in coal-consuming sectors (such as total electricity production from coal power plants) by province from China's National Bureau of Statistics (NBS).

The publicly available coal price data are based on coal used for electricity generation and heating. This type of coal, which includes a variety of coals with different heat contents and purity, is collectively referred to as "steam coal" or "thermal coal." We collect monthly province-specific prices of steam coal using the China Steam Coal Price Index from the Price Monitoring Center of NDRC. The index is based on data from 1,600 firms that rely on coal as the main fuel source, including major coal-fired power plants and heating facilities. Prices of coal used for coking are based on prices in Ganqimaodu in Inner Mongolia, a major hub of coking coal distribution.

Finally, to study the impact of coal consumption on air pollution, we collect air quality data at the monitoring station level from the Ministry of Environmental Protection. We focus on hourly concentrations of PM2.5 and PM10, because the concentrations of common air pollutants are highly correlated.

3.2 Using Shipment as Coal Supply and Demand

In the rest of the paper, we treat coal shipment from a province as that province's supplied quantity, and total shipment into a province as its demanded quantity. Our objective is to use these data to estimate demand and supply functions of coal and to assess the first-order policy effects on economic surplus and environmental outcomes. We do not further differentiate among coal types

facilities and need not transport coal to a third province for processing.

[14] NDRC designates an SOE coal mining firm as a "key SOE" based on a number of criteria, which include capacity, reserves, mining technology and coal quality (whether the coal is mainly for electricity production).

[15] The firm provides the data through the website https://mcoal.in-en.com/. We do not consider China's export, which accounts for less than 0.2% of coal production during our sample period.

[16] In principle, the annual production should not exceed the approved level, and monthly production should not exceed more than 10% of the 1/12 of the annual level.

within the quantity data. Given our research questions, several potential concerns about the data may warrant discussion.

First, to what extent can a single demand function capture the composite demand for a variety of coal and coal products combined in our quantity data? What is the appropriate price for this composite demand? We note that in China, the demand for different coal products is likely highly correlated. Importantly, the widespread use of coal blending techniques enables power plants to substitute across different coal types in the event of shortages. Other end users such as heating facilities are likely even less sensitive to coal quality. We also observe a high correlation between thermal and coking coal prices (Figure 1). Therefore, we construct a composite price for each province and month that weights the steam and coking price by the respective annual consumed quantities in that province. This price should account for the vast majority of coal uses.

Second, how do our shipment quantity data compare to the tonnage of raw coal extracted and consumed? We compare the annual provincial shipment data with the official data of annual raw coal production and consumption from the NBS in Appendix B. Our shipment data are slightly lower (by about 4% to 8%) than the NBS statistics, which shows that our data capture the bulk of coal supply and consumption by weight. We also find that data from both sources exhibit similar declines in 2016, consistent with the production restrictions. Finally, we show that the data from both sources are comparable at the province-year level.

Third, provincial level consumption may differ significantly from shipment during the policy. We highlight this distinction because coal users can smooth consumption through inventory when prices abruptly increase and shipment (purchased quantity) drops, and aerial pollution depends on the consumption (burned quantity) of coal. The annual consumption data from NBS in 2016 do not capture this monthly variation from April to December. We thus impute monthly provincial coal consumption based on the output of main products in sectors relying on coal (Appendix C).

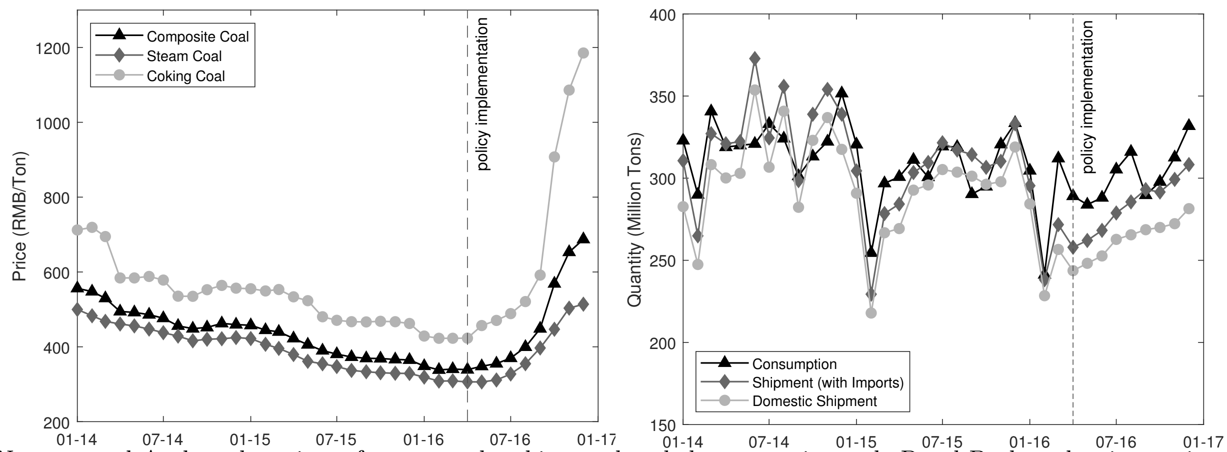
Table 1: Summary Statistics

	Mean	SD	p25	Median	p75
(A) Coal-Consuming Provinces					
Quantity (Million Tons/Month/Province)					
Demand	10.09	8.69	4.07	6.79	12.61
Consumption	10.27	7.44	4.97	7.53	13.42
Price (RMB/ton)	463.37	121.84	389.91	455.04	529.52
N=1080; based on 30 coal-consuming provinces in 2014-2016					
(B) Coal-Producing Provinces					
Quantity (Million Tons/Month/Province)					
Supply	11.44	20.10	1.34	3.65	10.16
Capacity	11.32	17.55	1.86	5.55	12.89
N=900; based on 25 coal-producing provinces in 2014-2016					
(C) Foreign Import					
Quantity (Million Tons/Month)	16.62	4.68	13.55	15.72	19.19
N=36; 2014-2016					

Notes: panel A shows summary statistics for 30 coal-consuming provinces. The demand consists of shipment from Chinese provinces and foreign imports. Coal consumption is aggregated from consumption in all sectors using coal for each province (Appendix C). The price is the weighted average of thermal and coking coal prices by the destination province's consumption shares of the two coals, plus a calibrated transportation cost (Appendix D) based on coal origins and destinations. Panel B reports summary statistics for 25 coal-producing provinces. Supply is the sum of all shipments from that province each month. Capacity is aggregated from the mine-level data from NEA. Panel C reports total imports.

Figure 1: Prices and Quantity of Coal

A: Price (RMB/Ton) B: Quantity (Million Tons)



Notes: panel A plots the prices of steam coal, coking coal and the composite coal. Panel B plots the time series of shipment between provinces, import, and consumption aggregated across provinces. The vertical broken line refers to the start of the supply reduction policy (April 2016).

3.3 Summary Statistics

Table 1 summarizes our main data set. There are 30 coal-consuming provinces and 25 coal-producing provinces. All coal-producing provinces also consume coal. Figure 1 plots the time series of the quantity-weighted average coal price and total quantity. The reported prices in the table and figure include transportation costs based on coal origins, which account for approximately 17.5% of the composite price.[17] All prices are based on 2016 RMB.

We note several features of the data. First, the average shipment per province and month falls below consumption after the policy, which reflects the effects of the policy that reduced coal supply. We interpret this observation as coal users halting purchase in the face of surging prices and tapping into inventory for consumption. While we do not have province-level monthly inventory data, the national inventory (Appendix Figure G.6) indeed declines sharply during the policy. Second, the quantities supplied from a province is close to, but occasionally exceeds the approved capacity.[18] We calculate an average capacity utilization factor of approximately 88%. We also note that capacity changes at the province level are small over time. Third, import is only 5.8% of the domestic shipment.

4 Reduced Form Evidence

In this section, we document two empirical patterns that inform our equilibrium model and its estimation. First, we find that the share of shipment from one province to another is remarkably

[17] Appendix D details how we calibrate the transportation costs.

[18] Prior to the April 2016, 28.4% of observations across all provinces and months are higher than their approved capacity; this share decreased to 19.6% afterwards.

stable over time, despite significant changes in price dispersion. Second, the largest coal-producing provinces and key SOEs play a main role in reducing output during the policy.

4.1 Cross-province Shipment Shares Are Stable Over Time

Table 2 reports the mean and standard deviation (in square brackets) of the monthly shipment shares from province i to province j in the province i's supply over the sample period. We list the five largest coal-producing provinces on the row and the ten largest coal-consuming provinces across columns. The standard deviation for the majority of province pairs is negligible relative to the mean, indicating a high degree of stability in shipment shares over time.

There are two likely reasons for this stability despite substantial variation in coal prices over time. First, the government and railway operators allocate railway capacity when coal buyers and sellers enter into long-term contracts. The rail capacity allocations create stability of shipment shares within the duration of long-term contracts, as any significant rerouting of shipment across provinces could create cascading disruptions in the interconnected rail network. This constraint incentivizes coal buyers to switch between suppliers within a given province even when coal buyers procure coal from outside their long-term contracts. Second, although power plants can substitute across different grades of coal to some extent through coal-blending technology, they still tend to prefer similar coals when purchasing on the spot market, because coal blending can add to the plants' operating costs (Zhao, 2021). Since mines within the same province are more likely to produce similar grades of coal, they may supply to the same set of power plants, consistent with the stability of shipment shares across multiple years.

We also find support for these structural reasons in explaining the stability of shipment shares. Between 2014 and April 2016, the log difference between the highest and lowest coal prices across provinces gradually decreased from 1.02 to 0.93, and then increased to 1.25 after April 2016.[19] If shipment shares could change flexibly in response to prices differentials, we would expect to observe strategic shipping behavior to exploit the arbitrage opportunities, keeping price dispersion relatively constant. Instead, the observed large price differentials point to a lack of such strategic behaviors.

4.2 Major Coal Producing Provinces and Large SOEs Drive Supply Reduction

We consider two sets of regressions to examine heterogeneity in supply reductions across provinces and firm types. First, we separately estimate how much supply is reduced for top n coal producing provinces and other provinces during the policy relative to their supply in prior months. Specifically, we estimate the following regression:

$$\ln Q_{it} = \beta_1 \mathbb{1}\left(i : \text{top } n \text{ prov}\right) \times \text{policy}_{it} + \beta_2 \mathbb{1}\left(i : \text{non-top } n \text{ prov}\right) \times \text{policy}_{it} + FE_i^1 + FE_{m(t)}^1 + \epsilon_{it}^1,$$

[19] The log difference of 25th-75th price levels range from 0.19 to 0.28.

Table 2: Mean and Standard Deviation of Cross-province Shipment Shares, 2014–2016

	Inner Mongolia	Shanxi	Shandong	Hebei	Jiangsu	Shaanxi	Henan	Liaoning	Guizhou	Xinjiang
Inner Mongolia	0.392	0.011	0.049	0.017	0.064	-	0.002	0.082	-	-
	[0.014]	[0.002]	[0.008]	[0.003]	[0.010]	-	[<0.001]	[0.003]	-	-
Shanxi	0.006	0.298	0.104	0.231	0.103	0.002	0.055	0.017	-	0.001
	[0.002]	[0.013]	[0.007]	[0.029]	[0.012]	[0.001]	[0.012]	[0.002]	-	[0.001]
Shaanxi	0.004	0.148	0.086	0.039	0.101	0.411	0.059	-	0.001	-
	[0.001]	[0.020]	[0.049]	[0.010]	[0.027]	[0.070]	[0.007]	-	[0.001]	-
Guizhou	-	-	-	-	-	-	-	-	0.740	-
	-	-	-	-	-	-	-	-	[0.025]	-
Shandong	-	-	0.857	0.012	0.033	-	0.008	0.002	-	-
	-	-	[0.016]	[0.005]	[<0.001]	-	[0.001]	[<0.001]	-	-

Notes: the table reports the shipment shares of the 5 largest coal-producing provinces to 10 largest coal-consuming provinces, averaged within 36 months between 2014 and 2016. The share is calculated as a month's shipment from i to j divided by the total shipment from i in the month. The standard deviations are reported in brackets.

where top n means the largest n coal producing provinces by total output in 2014 and 2015, and we estimate the regression for $n = 2, 4$ and 10. The variable policy_{it} is an indicator equal to 1 when the policy starts in the province i and 0 otherwise. The results in panel A of Table 3 shows that β_1 decreases as n increases, which indicates that top 5 to 10 provinces reduce the output less than the top 4 provinces (Shanxi, Inner Mongolia, Shaanxi and Guizhou, in descending order) or other smaller provinces. The results thus show that the top 2 provinces and the bottom 15 provinces proportionally reduce more output relative to top 3 to 10 provinces. Using the estimates as the proportion of reduced output, we find the reductions by the top 2 and 4 provinces to account for 46% and 51% of the total reduction.

Second, we further break out the production of key SOEs. We analyze the changes in key SOE production relative to (1) other firms' production in the same provinces and (2) the production in other provinces. As explained in Section 3, key SOEs are the largest coal mines in each province. Specifically, we split the supply in a month t of each of the top n provinces into the key SOE production and other firms' production. We then estimate

$$\ln Q_{kt} = \tilde{\beta}_1 \mathbb{1}\left(k : \text{top } n \text{ prov, key SOE}\right) \times \text{policy}_{kt} + \tilde{\beta}_2 \mathbb{1}\left\{k : \text{top } n \text{ prov, not key SOE}\right\} \times \text{policy}_{kt}$$
$$+ \tilde{\beta}_3 \left\{k : \text{non-top } n \text{ prov}\right\} \times \text{policy}_{kt} + FE_k^2 + FE_{m(t)}^2 + \epsilon_{kt}^2.$$

In the above, the index k is a province-firm type pair for top n provinces or a province for each of the non-top n province. Therefore Q_{kt} refers to the output in month t of key SOEs in a top n province, other firms in the province[20] or the total output of a non-top n province. We also control for k-level and month fixed effects. Columns (1) and (2) in panel B of Table 3 show that key SOEs in top provinces significantly reduce their output when the policy starts. The effect also decreases for the key SOEs in top 5-10 provinces.

Together, these findings show that top coal-producing provinces and large SOEs in these provinces drive the supply reduction. This pattern highlights the unique institutional features of China's coal industry dominated by large SOEs. The literature on Chinese firms has characterized these firms as "messy" profit maximizers (Katou et al., 2013; Marukawa, 2013; Bei, 2014; Chen et al., 2021), which are financially independent from the government yet subject to command to implement political projects.

[20]This split slightly understates other firms' production because the supplied quantity (shipment data) is slightly lower than the tonnage of excavated raw coal. We note that the shipment data include coal that has been purified from the raw coal and other coal products, and the key SOE production data are the tonnage of excavated raw coal by these firms. See the discussion in Section 3.2.

Table 3: Output Responses to the Policy
A: Province Supply

	(1) Top 2	(2) Top 4	(3) Top 10
β_1 : Top n Prov	-0.230***	-0.138**	-0.127***
	(0.024)	(0.054)	(0.039)
β_2 : Non-Top n Prov	-0.286***	-0.310***	-0.386***
	(0.072)	(0.076)	(0.087)
Province FE		YES	
Month FE		YES	
N	897	897	897
Adjusted R^2	0.965	0.965	0.966

B: Key SOE and Other Firms' Production

	(1) Top 2	(2) Top 4	(3) Top 10
β_1 : Top n Prov, Key SOE	-0.289***	-0.217***	-0.194***
	(0.076)	(0.066)	(0.04)
β_2 : Top n Prov, Not Key SOE	-0.142**	-0.042	0.116
	(0.053)	(0.069)	(0.168)
β_3: Non-top n Prov	-0.281***	-0.306***	-0.381***
	(0.071)	(0.074)	(0.085)
Province-Firm Type FE for Top n Provinces,		YES	
Province FE for non-Top n Provinces		YES	
Month FE		YES	
N	969	1,041	1,182
Adjusted R^2	0.965	0.96	0.917

Notes: the dependent variable in panel A is $\ln(\text{supply})$ every month of each province. Panel B dependent variable is natural log of output by (1) key SOEs in each of the top n provinces, (2) other firms in each of the top n provinces and (3) each of the other provinces. Top 10 coal producing provinces are Inner Mongolia, Shanxi, Shaanxi, Guizhou, Shandong, Xinjiang, Henan, Anhui, Ningxia and Hebei. Standard errors are clustered at the province level in panel A and at the k level (k is a province-firm type pair for the top n provinces, and then it is a province for each non-top n province) in panel B.

5 Coal Demand

We specify coal demand in province j and month t as

$$\ln q_{jt}\left(p_{jt}\right) = \alpha \ln p_{jt} + FE_j^{\text{demand}} + FE_{m(t)}^{\text{demand}} + \varepsilon_{jt} \tag{1}$$

where the quantity demanded q_{jt} corresponds with the shipment of coal purchased by buyers in j and p_{jt} represents the composite coal price in the province. The parameter α has the straightforward interpretation of price elasticity. We also include fixed effects for the province and the month of the year. The term ε_{jt} captures the unobserved demand shock.

Interpretation In theory, the coal purchase decision modeled above and the consumption decision are joint (dynamic) decisions that potentially depend on past shipment and consumption, expectations of future prices, and existing inventory (Jha, 2023). We do not explicitly model these intertemporal factors driving the coal demand. Instead, equation (1) captures the resulting decision rules aggregated to the province level in a reduced form.

We argue that this parsimonious demand model still provides meaningful estimates to capture the first-order effects of a price change on quantity demanded and consumer surplus. For an exogenous reduction in equilibrium quantity, the demand function is useful for measuring the welfare effect that includes the surplus change in t and the change in the expected future value, including the opportunity costs of reduced inventory and, in the case of power plants, the increased possibility of a blackout.

5.1 Identification

The equilibrium price may be correlated with the unobservable ε_{jt}. Building on the findings in Section 4, we construct instruments that exploit provinces' different exposures to supply reductions. Specifically, a coal-consuming province that historically relied more on SOE coal mines in top coal producing province, which are more significantly affected by the policy, may face a greater coal shortage. Our instruments thus have two components: a proxy for shares of a province's demand from top 4 provinces' SOEs,[21] which are key drivers of the supply reduction as explained in Section 4.2, and an indicator for the start of the supply reduction policy. Our first instrument is

$$Z_{jt}^1 = \sum_i w_{ij}^{2012-2013} \times o_i^{\text{SOE, 2012-2013}} \times \mathbb{1}\left(i \in \text{Top 4 Prov}\right) \times \text{policy}_{it}, \tag{2}$$

where $w_{ij}^{2012-2013}$ is the coal shipped from i to j divided by the total shipment to j , averaged across months from 2012 and 2013 (before the estimation sample), and $o_i^{\text{SOE, 2012-2013}}$ is the output share of key SOE in province i, also averaged across months from 2012 and 2013. The ratios w_{ij} capture j's historical dependence on coal from i, and the interaction with o_i captures the historical dependence on SOE coal from i.

[21] Our results are robust to using the top 2 provinces' SOE output for the instruments.

Our second instrument is

$$Z_{jt}^2 = \sum_i w_{ij}^{2012-2013} \times \mathbb{1}\left(i \notin \text{Top 4 Prov}\right) \times \text{policy}_{it}. \tag{3}$$

The instrument captures the dependence on coal from non-top 4 coal producing provinces.

The assumptions underlying the validity of the instruments are as follows. First, to satisfy the exclusion restriction, the unobserved demand during the policy periods must be uncorrelated with the historical shipment shares. We find that the shares of shipment from a province, w_{ij}, just like the shares of shipment to a province in Section 4.1 and are stable over time during our sample. We argue in Section 4.1 that structural reasons not due to changing prices are likely responsible for the stability.

Secondly, the exclusion restriction also requires any change in demand due to other policies at the same time (Section 2.2.2) to be uncorrelated these shares. We note that the 2015-2016 economic stimulus plan is a nation-wide policy that generally eases the borrowing constraints for transportation projects (such as the national network of high-speed rails). A correlation with our instruments may rise if provinces more dependent on coal from, say Shanxi, systematically see more or less buildout of railways. This seems unlikely, because the expansion during this period is concentrated in western China (Xinhua, 2016a), a region that receives a small share of coal from the top 4 producing provinces. Moreover, shipment shares have larger variations across provinces on the eastern coast. We also expect the steel plant closure to have a negligible effect on coal demand. In our data, coal used for steel production accounts for less than 20% of the total consumption and declines by less than 5% from 2015 to 2016.

Third, policy timing may be endogenous if coal buyers anticipated the policy and stockpiled coal in advance. However, interviews with an industry insider[22] suggest that, although the industry had expected a policy action to bolster coal prices since early 2015 when the coal prices fell by more than one third from the 2014 level, there had been a number of ineffective attempts at the province government levels to reduce production, and few industry participants expected the intensity of the 2016 supply reduction policy. In addition, national coal inventory data from NBS shows that the inventory actually declined before the policy, supporting the view that coal buyers either did not anticipate the impact of the policy, or that they were unable to further increase the inventory (Appendix Figure G.6).

Finally, the policy may have changed coal buyers' expectation of future coal prices and altered their decision rules. The implication is that the policy also changes the parameters in (1). We believe that any such effect is limited. Appendix Figure G.5 plots the steam coal prices in China from 2006 to 2020 and shows that the price increase following the policy was not unprecedented; in fact, the price after the supply reduction policy was still below the pre-2014 level and eventually returned to the pre-policy 2016 price.[23] The supply reduction policy itself was phased out at the

[22] We spoke with a provider of mining equipment who works closely with coal mine owners.

[23] We find that the coal prices remained elevated in 2017, but the economic stimulus policies likely also contributed to the increased demand.

end of 2016. The high frequency and short-lived nature of government policy interventions during our study periods further suggest that the 2016 policy is a temporary surprise and likely does not change coal buyers' decision rules in the short run.

5.2 Estimation

We report the GMM-IV estimates of equation (1) in Table 4, with standard errors clustered at the province level. The first-stage estimates are reasonable, which shows that coal-consuming provinces that source more coal from key SOEs in large coal-producing provinces experience a larger price increase during the policy periods. The demand elasticity estimate is -1.47.[24]

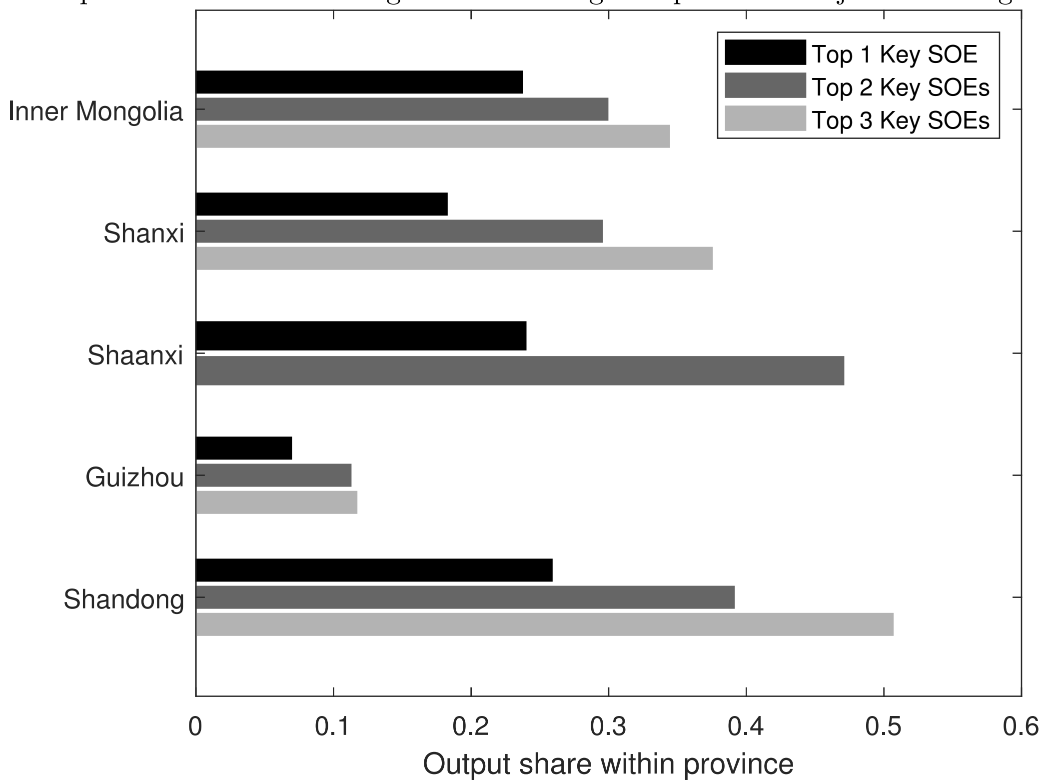
Table 4: Estimation of Demand

	OLS	IV: First Stage	IV: Second Stage
ln(price)	0.124		-1.472***
	(0.083)		(0.474)
Z^1_{jt}		0.271***	
		(0.045)	
Z^2_{jt}		0.11***	
		(0.020)	
Province FE		YES	
Month FE		YES	
Kleibergen-Paap F Statistic			59.316
N	1080	1080	1080

Notes: the table reports OLS and IV estimates of the demand model. The dependent variable is the log of demand (shipment into a province). Standard errors are clustered at the province level. We use two instruments for log(price). The first is calculated in (2) and captures the historical dependency on SOEs in top 4 coal-producing provinces. The second is given in (3), which reflects the dependence on other coal-producing provinces.

[24] In comparison, prior work has estimated elasticity for coal consumption (as opposed to purchase) (Burke and Liao, 2015) to be between -0.3 to -0.7.

Figure 2: Output Shares of Three Largest Coal Mining Companies in Major Producing Provinces



Notes: the figure shows the cumulative output shares of the three largest key SOEs, which are also the largest coal mining companies, in each of the five largest coal-producing provinces. The output shares are calculated using data before the implementation of the 2016 policy and determine the firm ranking. For Shaanxi, our data include only two key state-owned coal-producing firms, which account for a total of 50% of the production share.

6 Coal Supply

Our supply model incorporates two key institutional features of China's coal industry. First, the coal market is not concentrated. Figure 2 plots the combined output shares of the three largest coal-mining firms (based on the output in the key SOE production data) in each of the top five coal-producing provinces. No single firm in a province has more than 30% of the output share in a province, and the share of the third largest firm is often below 11%. Second, as we show in Section 5.1, the share of supply from one province to another is highly stable over time.

Motivated by these two observations, we specify a parsimonious supply curve where the output Q_{it} in province i and month t responds to an "effective price" based on the destination shares of the output. We use the uppercase Q for supply (shipment out of a province) and distinguish from demand q (shipment into a province). Specifically, we assume that

$$\frac{Q_{it}\left(P_{it}\right)}{K_{it}} = \gamma \ln P_{it} + FE_{i}^{\text{supply}} + FE_{m(t)}^{\text{supply}} + \eta_{it}. \tag{4}$$

In the above, K_{it} is the capacity in province i and month t,[25] and the effective price is $P_{it} = \sum_j s_{ij}(p_{jt} - \tau_{ij})$, where s_{ij} is the share of coal shipped from i to j in the total shipment from i,[26] p_{jt} is the price in the destination province j and τ_{ij} is the transportation costs calibrated following the procedure in Appendix D.

6.1 Behavioral Foundation for the Supply Function

There are two ways to justify this supply curve specification based on the effective price P_{it}. First, the provincial government often facilitates the coordination of production. Specifically, the provincial government may directly set production targets (NDRC, 2021) and help to organize a coalition of long-term contracts to sell coal to buyers across the country (China Internet Information Center, 2016). They also coordinate with railroad authorities to transport coal. Furthermore, profit maximization is likely a goal shared by both firms and the provincial government. Coal mines are central to local economies and can generate up to half of the total tax revenues of a province (Han and Zhang, 2022). The government heavily depends on these revenues to provide public services (Gao, 2015). Therefore, we can specify a province level profit maximization problem given exogenous output share shipped to different provinces, where province i choose output Q_{it} to maximize the profit

$$\max_{Q_{it}} \sum_{j \in \mathcal{J}} Q_{it} s_{ij} (p_{jt} - \tau_{ij}) - C_{it}(Q_{it}, \eta_{it}).$$

given the cost function

$$C_{it}(Q_{it}, \eta_{it}) = c\left(\gamma^{-1} \cdot \frac{Q_{it}}{K_{it}} + W_i + W_{m(t)} + \eta_{it}\right),$$

where the cost depends on the ratio of output to capacity, $\frac{Q_{it}}{K_{it}}$, and other components specific to the province and month of the year in addition to a shock. The capacity K_{it} is a useful cost shifter, because it reflects both the physical and regulatory constraints on production. We also find that a province's capacity change over time is small and uncorrelated with prices conditional on province fixed effects. The first order condition given a exponential function for c yields the form in (4).

Alternatively, we can microfound the supply curve by aggregating the supply decisions of many atomistic mines. Suppose each producer in province i sells a share s_{ij} to province j. The cost function is given by $c(q;\theta)$, where the cost parameter θ differs across mines and follows the distribution G_i. The total mass of the mines is $\mathcal{M}$. Slightly abusing notation, we use $a_{\theta t}$ to denote this producer's output decision, which satisfies the first order condition $P_{it} = c'(a_{\theta t};\theta)$. Under the assumptions that the marginal cost function c' is strictly monotonic in $a_{\theta t}$ for any θ, we can then invert the production decision as $a_{\theta t} = c'^{-1}(P_{it};\theta)$. Integrating both sides with respect to $G_i(\theta)$

[25] We fix capacity in a province as observed in the data. We note that these capacities are adjusted every six months, and the changes within a province over time are small, although capacities are different across provinces.

[26] We use the average shares as in Table 2, and the results are similar if we use just any one year's data (like the early year 2014) to construct the shares.

and multiplying the total mass of the mines $\mathcal{M}$ yield an aggregate supply curve as a function of P_{it}, and appropriate choices of c and G_i would give the specific exponential form.

A caveat of our specification in (4) is that the effective price P_{it} would no longer be a sufficient statistic for all relevant prices if the output decision is fully decentralized across small firms within a province and the output share s_{ij} is heterogeneous across individual mines. In the extreme case, each mine may supply coal to only one destination province, as opposed to splitting its output across provinces. Although we do not have mine-level data on output and shipment, we can rule out this extreme case based on news reports where large mines routinely supply to buyers in multiple provinces (Xinhua, 2016b; China Securities Journal, 2017; Xinhua, 2018). Furthermore, the supply in a province is not fully decentralized, and the effective price is a useful first order approximation of how government directives on coal production responds to price signals. In particular, as explained in Section 2.1.3, coal buyers and sellers explicitly use destination average prices to adjust their own transaction prices.

Interpretation We interpret the supply curve parameters as invariant to policies such as quotas and taxes. According to our interviews with industry practitioners, mine owners plan production based on current prices, and dynamic factors such as the amount of unexcavated coal or interest rates do not appear to be first-order drivers of their production decisions. For context, the coal reserve in China is close to 150 billion tons, while the annual production varies between 3 and 4 billion tons, with a similar amount of new reserves discovered every year.

However, (4) does not capture the supply during the policy periods. The policy significantly changed the supply through the closings of small mines and output reductions at many large mines, and the compliance is heterogeneous across firm types and locations. We therefore estimate the supply curve using only pre-policy data. We discuss how we use the estimates for counterfactual simulations in Section 8.

Functional Form We adopt an exponential functional form in (4) given that we work with data from just 25 provinces. We present the estimation and simulation results based on the alternative functional form $\ln(Q_{it}/K_{it}) = \gamma \ln P_{it} + FE_i + FE_{m(t)} + \eta_{it}$, which fits the pre-policy data less well but implies similar welfare results in simulations. Appendix F provides the details. We use a log-log functional form for estimating the supply of foreign imports (Appendix E).

6.2 Identification

As in the case of demand, the price may be correlated with the unobserved shock η_{it}. The standard approach to addressing this endogeneity issue is to use demand shifters as instruments (Wright, 1928). We propose using residual demand, which reflects downstream demand for electricity and cement, as an instrument for the price in the supply function, because these downstream demand shocks are arguably uncorrelated with unobserved shocks to coal excavation. This approach is similar to the covariance restriction used in MacKay and Miller (2024) and Döpper et al. (2024), where supply residuals are used to identify demand. Specifically, we define the following instrument for the effective price:

$$Z_{it}^{p} = \sum_{j} w_{ij} \exp\left(\ln q_{jt} - \hat{\beta} \ln p_{jt}\right), \tag{5}$$

where $\hat{\beta}$ is the estimated price coefficient in demand.

6.3 Estimation

Table 5 reports the supply estimates. We use the estimates to construct the average costs of coal production for each province and compare them with costs reported in financial statements of publicly listed coal mining firms in Appendix Figure G.2. The estimated and reported costs are well aligned across provinces, with a correlation coefficient of 0.64. For example, we find that Xinjiang and Inner Mongolia have the lowest production costs, consistent with more open-pit mining in these provinces.

Table 5: Estimation of Domestic Supply

	OLS	IV
ln(price)	0.466**	0.769***
	(0.190)	(0.262)
Province FE	YES	YES
Month FE	YES	YES
Kleibergen-Paap F Statistic		81.469
N	723	723

Notes: the table reports the OLS and GMM estimates of the supply model. The dependent variable is the ratio between output and capacity. Prices faced by domestic producers in a province are calculated as the average of destination prices weighted by the share of each destination in all shipment from the province as in (5). We restrict the estimation sample to the period before the policy. Standard errors are clustered at the province level. For the correct standard errors, demand and supply functions are jointly estimated.

7 Coal Consumption and Aerial Pollution

To quantify the environmental impact of reducing coal production, we model three additional outcomes: (1) coal consumption as a function of equilibrium demand, (2) the effects of coal consumption on aerial pollution, and (3) health benefits from changes in pollution levels.

7.1 Coal Consumption

We model the coal consumption, C_{it}, in province j and period t as a function of past demand and consumption:

Table 6: Estimation of Coal Consumption

	$\ln C_{jt}$
$\ln C_{jt-1}$	0.566***
	(0.067)
$\ln q_{jt}$	0.075***
	(0.024)
$\ln q_{jt-1}$	0.013
	(0.017)
Province FE	Y
Month FE	Y
Adjusted R^2	0.988
N	780

Notes: the table presents the estimation result for the predictive model for coal consumption.The dependent variable is the logarithm of coal consumption. The independent variables include the logarithm of current coal shipment, the logarithm of lagged coal consumption in and lagged shipments to the province, controlling for province and month fixed effects. The model is estimated using the pre-policy sample before April 2016. Data from January 2014 are excluded due to a lack of lagged information.

$$\ln C_{jt} = \theta_1 \ln C_{j,t-1} + \theta_2 \ln q_{j,t-1} + \theta_3 \ln q_{j,t} + FE_j^{\text{consumption}} + FE_{m(t)}^{\text{consumption}} + \nu_{it}. \tag{6}$$

where the shock ν_{it} captures unobserved factors such as deviations of energy demand from the monthly average in a province.

Interpretation We use this simple predictive model to approximate consumption decisions. Like coal demand, consumption is ultimately a dynamic decision. The model here can be interpreted as a reduced-form parameterization of the dynamic decision rule of the coal users. As such, the model can be used to inform consumption changes in response to temporary policy shocks. We do not explicitly include coal prices for two reasons: (1) the model fits the data extremely well and exhibits strong out-of-sample prediction performance; (2) the current and lagged equilibrium quantities q_{jt} and q_{jt-1} already embed relevant price information.

Table 6 reports the estimation results. The results indicate that both lagged consumption and current period demand influence coal consumption, although the impact of previous shipments is limited. We find an R^2 close to 1. Estimating the model on the subsample of the 18 months from 2014 to June 2015 and predicting consumption on the second 18 months yields a mean squared error of 0.78 million tons per province per month, compared to an average consumption of 10.06 million tons per province per month.

7.2 Aerial Pollution

We next specify the mapping from coal consumption to aerial pollution. We estimate the effects of coal consumption on monthly PM2.5 or PM10 concentrations within a province.[27] We focus on one pollutant because concentrations of pollutants such as PM2.5, PM10 and SO_x are highly correlated. The estimation equation for PM2.5 is

$$\ln \text{PM2.5}_{jt} = \psi_C \ln \tilde{C}_{jt} + \psi_X X_{jt} + FE_j^{\text{pollution}} + FE_{m(t)}^{\text{pollution}} + \omega_{it}. \tag{7}$$

To account for spillover effects (Fu et al., 2022), we define the variable $\tilde{C}_{jt}$ as the total coal consumption in province j and all of its neighboring provinces in period t.[28] The variable X_{jt} includes meteorological conditions, including temperature, dew point temperature, sea level pressure, wind speed, sky condition total coverage code, liquid precipitation duration depth dimension. Additionally, we control for fixed effects at the province and month of the year levels.

We note that coal consumption and the unobservable ω_{it} may be correlated. Specifically, the coal consumption could be correlated with other economic activities that also contribute to pollution, but also correlated with heightened monitoring and regulation that reduces pollution. We therefore use the same IVs as the demand estimation for coal consumption.[29]

Table 7 indicates that a 1% increase in coal consumption in a province and its neighbors raises local PM2.5 concentration by about 1.9%. Had we used just the consumption in province j, the estimate would fall to 1.2%. The effect is similar if we instead use PM10 concentration as the outcome variable.[30]

[27] We use the average of all monitoring stations' concentration readings in a province.

[28] We do not further normalize the variables by the province's size because both the pollution measure and the consumption are logged, and we control for province fixed effects.

[29] We construct instruments for $\tilde{C}$ by summing the instruments across neighboring provinces.

[30] Ito and Zhang (2020) estimates the elasticity of PM10 concentration with respect to coal usage to be 0.5 using a RD design exploiting the Huai-River heating policy and by OLS applied to an annual province panel data. This is similar to the OLS estimates of our province by month panel data, but smaller than the IV estimates.

Table 7: The Effects of Coal Consumption on Aerial Pollutants

	(1) ln(PM2.5) OLS	(2) ln(PM 10) OLS	(3) ln(PM2.5) IV	(4) ln(PM 10) IV
$\ln \tilde{C}_{jt}$	0.772***	0.723***	1.907***	1.739***
	(0.108)	(0.079)	(0.309)	(0.284)
Province FE	YES	YES	YES	YES
Month FE	YES	YES	YES	YES
Meteorological Controls	YES	YES	YES	YES
Observations	1,080	1,080	1,080	1,080
Adjusted R^2	0.673	0.636	0.571	0.520
Kleibergen-Paap F Statistic			16.77	16.77

Notes: the table reports estimates of the effects of coal consumption on PM2.5 and PM10 concentration by OLS and IV. All estimates control for meteorological conditions, including air temperature, dew point, sea level pressure, wind speed, sky condition coverage, and liquid precipitation duration and depth. The instruments used are the same as those in estimating demand. Standard errors are clustered at the province level.

7.3 Health Effects

We use three approaches to monetize changes in pollutant concentration levels, drawing on estimates from the environmental economics literature.

1. Health Care Expenditures. Barwick et al. (2021) estimates a saved 9.2 billion dollars in health-care spending per year per 10 $\mu g/m^3$ decrease in PM2.5 based on data from 2013 to 2015.

2. Willingness to Pay (WTP). Ito and Zhang (2020) estimate a household's willingness to pay of 1.34 dollars per year for 1 $\mu g/m^3$ decrease in PM10 based on data from 2006 to 2014. They also derive a income-dependent willingness to pay based on their estimates of random-coefficient logit model for air purifiers.

3. Value of Statistical Life (VSL). Barwick et al. (2021) combine Ashenfelter and Greenstone (2004) and Murphy and Topel (2006)'s estimated VSL and convert the mortality effect estimated in Ebenstein et al. (2017) (with data from 2004 to 2012) to a cost of 13.4 billion dollars per year per 10 $\mu g/m^3$ increase of PM10.

In the simulations, we first convert these estimate to a per person per month 2016 RMB basis and adjust for income whenever the estimates are available,[31] and then calculate the province level health effects proportional to the population and pollution changes.

[31] The national health benefit of 9.2 billion per 10 $\mu g/m^3$ PM2.5, as estimated by Barwick et al. (2021), is in 2015 US dollars. We convert this to 45.08 RMB per capita in 2016, assuming a 2015 exchange rate of 6.5 between US dollar and RMB in 2015 , a national population of 1.375 billion in China, and CPIs of 637.5 in 2016 and 615.2 in 2015. Similarly, the 13.4 billion USD estimate by Barwick et al. (2021), based on Ebenstein et al. (2017), converts to 65.66 RMB per capita. Ito and Zhang (2020) estimate a random coefficient logit model to derive income-dependent

This approach likely understates the health benefits from reducing coal production by focusing solely on aerial pollution attributed to the resulting decrease in coal consumption. Other environmental damages associated with coal production (Chu et al., 2023), transportation, and storage of coal (Jha and Muller, 2018), such as air pollution from the excavation process, water contamination and land degradation, are not quantified here. Nevertheless, addressing aerial pollution from coal consumption likely would have the greatest welfare impact given the large affected population and is a high priority goal of the supply reduction policy (Feng et al., 2019).

8 Counterfactual Simulation

8.1 No-Policy Equilibrium

Our first simulation compares the equilibrium outcome without the supply reduction policy with the status quo. We begin by defining the equilibrium. Let $\mathcal{J}$ denote the set of coal-consuming provinces and $\mathcal{I}$ for the coal-producing provinces.

Definition. In period t, an equilibrium consists of a set of delivery prices $\{p_{jt}\}_{j\in\mathcal{J}}$ and production quantities $\{Q_{it}\}_{i\in\mathcal{I}}$ that satisfy (1) and (4), where a province j's demand is given by $q_{jt} = \sum_{i\in\mathcal{I}} s_{ij} Q_{it}$.

Given that the demand and supply functions are continuous, strictly monotonic in prices, and map to the ranges of $[0, \infty)$, an equilibrium exists based on an application of Brouwer fixed point theorem.[32] To simulate the no-policy equilibrium during the policy period, we fix demand shocks as estimated[33] and simulate supply shocks. Specifically, we estimate an AR1 process for the supply shocks and simulate multiple paths of the shocks. We then report the 2.5%-97.5% range of the equilibrium outcomes in each period across simulations.

Figure 3 compares the average equilibrium prices and total quantities under the no-policy simulation with observed outcomes under the policy. Before the policy, the simulations align closely with the data. Appendix Figure G.3 compares the output from major producing provinces between the data and simulations and shows that, despite the model's parsimonious specification, the model fits the data well even at the province level. Appendix Figure G.4 similarly shows strong

willingness to pay. We collect disposable income per capita by province in 2016 RMB from the NBS and convert it to household income in 2005 US dollars to estimate province-specific per capita health benefits for a 10 µg/m³ decrease in PM 10.

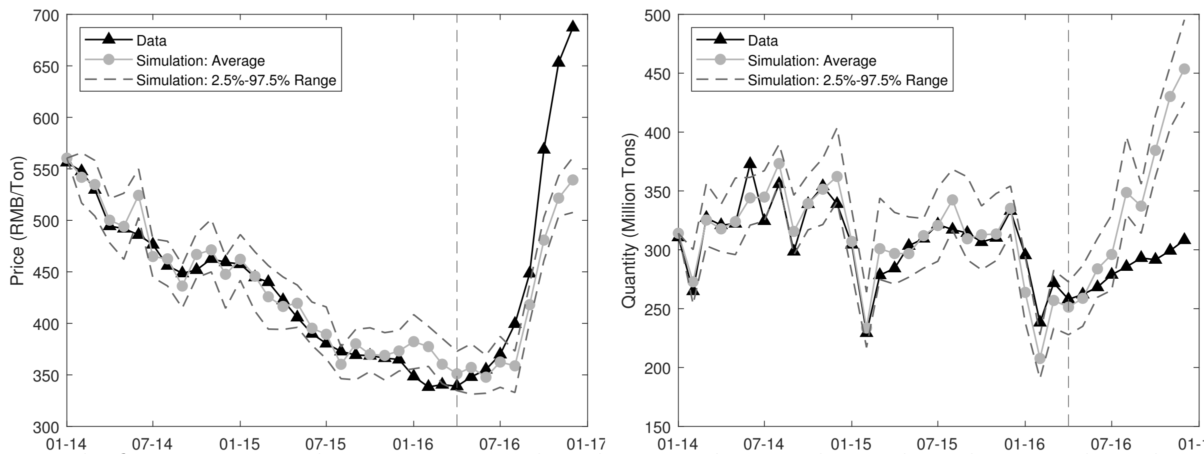
[32]Given these properties of the model primitives, we can define a compact set for prices where each price $p_{jt} \in \left[\underline{p}_j, \overline{p}_j\right]$, the quantities supplied at $\left(\underline{p}_1, \underline{p}_2, \ldots\right)$ are strictly smaller than the quantities demanded for each j, and vice versa at $(\overline{p}_1, \overline{p}_2, \ldots)$. We can then apply the Brouwer fixed point theorem to this compact set to obtain existence. For uniqueness, we solve for the equilibrium prices given the system of nonlinear equations, and we do not find multiple equilibria in our numerical experiments.

[33]A potential concern with using estimated demand residuals is that they may be a function of inventory and could change under different policies. To assess the potential effect of inventory, we regress the demand residuals on variables that proxy inventories, including lagged shipment and consumption. The R^2 is 0.01, which suggests that lagged shipment and consumption explain very little variation in demand residuals and that inventory only accounts for a small share of the residuals.

performance in predicting consumption. We find that, without the policy, prices would have been 550 RMB/ton in December 2016 as opposed to 700 RMB/ton in the data. The equilibrium quantity would have been 50% higher.

Figure 3: Price and Shipment With and Without the Policy

(A) Average Price (B) Shipment



Notes: the figures compares the average price and total quantity between data and simulations without the 2016 policy. We plot the average and the 2.5%-97.5% range across all simulations.

We next assess how the policy affects welfare. This exercise requires assumptions on how the policy alters the supply function. Consistent with the policy's stated objective to close small mines that may lack scale economies, we assume that the supply function during the policy is $Q^{\star}_{it}(P) = \min\left(\overline{Q}_{it}, Q_{it}(P)\right)$, where $\overline{Q}_{it}$ is the observed production in t. In other words, we assume that the quantity during the policy is supplied by the most efficient mines in a province up to those with marginal costs equal to the observed price. Mines with higher marginal costs are assumed to be inactive due to the policy constraint. Under this formulation, our estimate of the total surplus increase is a lower bound, which does not take into account the possibility that the closed mines may have lower marginal costs than active mines. Furthermore, compliance with the policy may have imposed additional costs on coal producers, which are also not captured in our surplus calculation.

Table 8: The Effects of Supply Reduction Policy and Production Tax

	(1) Supply Reduction Policy	(2) Output Equivalent Tax (160 RMB/ton)	(3) Optimal Tax (42 RMB/ton)
Price (RMB/ton)	64.7	78.3	17.6
	[58.8,76.3]	[77.5,79]	[17.3,17.7]
Output (Million Tons)	-531.8	-531.8	-139.7
	[-657.3,-458]	[-571.4,-506.5]	[-149.1,-133.9]
Consumption (Million Tons)	-102.1	-98.1	-23.9
	[-152.8,-50.5]	[-102.3,-94.7]	[-24.7,-23.2]
Economic Surplus (Billion RMB)	-97.1	-35.2	-0.2
	[-125.5,-76.8]	[-38.7,-33]	[-0.5,-0.1]
Consumer Surplus	-170.7	-166.2	-41.2
	[-204,-152.5]	[-171.7,-162.8]	[-42.3,-40.6]
Producer Surplus	73.6	-186.1	-59.2
	[60,89.9]	[-197.6,-179.1]	[-63.2,-56.8]
Tax Revenue		317	100.2
		[309.1,330.6]	[97.4,105]
Surplus with PM2.5	-79.2	-21.5	3.2
	[-105.7,-58.8]	[-24.6,-19.4]	[3,3.4]
Surplus with PM2.5 and Carbon	152.5	201	57.4
	[32,276.3]	[194.2,209.5]	[55.8,59.3]

Notes: the interval in the square brackets is the 2.5%-97.5% range across simulations. Column (1) compares the policy's effects relative to a no-policy equilibrium. The estimates are aggregate effects from June to December 2016. Column (2) considers the effects of a production tax that generates the same output reduction as the policy relative to the no-policy equilibrium. Column (3) calculates the optimal production tax that takes into account health costs from aerial pollutants. Health costs are calculated based on an estimated annual health cost of $9.2 billion from a 10 μg/m³ increase in PM2.5 concentration (Barwick et al., 2023). The social cost of carbon is set at $185/ton (Rennert et al., 2022), and we assume that one ton of consumed coal generates 2.64 tons of CO_2.

Column (1) of Table 8 presents the welfare impact of the policy. We focus on the months from June to December 2016. Relative to the no-policy scenario, the policy costs about 100 billion RMB in economic surplus, which is about 0.1% of China's GDP. The increase in producer surplus is large, consistent with the policy objective of improving the profitability of the coal industry. Given that the shipment data combines a variety of raw coal and coal products, we interpret the surplus as accruing not only to coal mines but also to secondary coal processing industries. Aerial pollution reduction (based on estimates from PM2.5 reduction in Barwick et al. (2021) and apportioned to each province based on population)[34] is not sufficient to offset the economic cost of the policy. However, the policy yields a positive net effect if we take into account the social cost of carbon.[35] We obtain similar estimates using other measures of pollution damages (Appendix Table G.2). There may be two reasons for the small effect from the reduced pollution. First, the health impact is proportional to health care spending, which in turn is based on local income. The benefits from reducing coal production and consumption would likely be higher if we re-examine the health costs of pollution in later years. Second, inventory is a short-run stopgap for coal consumption, which

[34]We choose this estimate as the baseline where the underlying data are closest to our sample period. Results based on alternative health cost measures, including income-adjusted measures from Ito and Zhang (2020) based on PM10, are reported in Appendix G.2.

[35]The social cost of carbon is set at $185/ton (Rennert et al., 2022), and we assume that one ton of consumed coal generates 2.64 tons of CO_2.

allows buyers to use more coal than shipped. We implicitly capture the effect of inventory in the coal consumption prediction model in (6) through lagged consumption and shipment. We would expect greater impacts on consumption and thus aerial pollution had the policy lasted longer and exhausted inventory.[36]

We next investigate the heterogeneous effects of the policy across provinces. Panels A and B of Figure 4 plot the changes in consumer and producer surplus by province, respectively. Notably, Shanxi experiences the largest decrease in consumer surplus due to its significant coal consumption (the darkest region in panel A), but this loss is more than offset by a substantial increase in its producer surplus, resulting in a positive net surplus change. In contrast, other major coal-consuming provinces, primarily coastal provinces, experience large decreases in both consumer surplus and total economic surplus. Panel C further shows that, even after accounting for improvements in air quality, the net surplus changes in these provinces are negative and large.

8.2 Pigouvian Taxes

There are two main motivations for considering a Pigouvian tax as an alternative to achieve the same policy goals. First, a Pigouvian tax is conceptually simple and straightforward to implement as a means of correcting environmental externalities. Second, as shown in Section 4.2, output is reduced more in provinces like Shanxi that have lower marginal coal excavation costs. This outcome would be inefficient unless high cost provinces supply to provinces with high marginal damages from pollution. A Pigouvian tax reduces output more evenly and may cause less deadweight loss.

We start by showing evidence of inefficiency due to the uneven supply reduction across provinces. Specifically, we conduct a simulation of a production tax designed to reduce national output by the same amount as the supply reduction policy (output-equivalent tax). Column (2) of Table 8 shows that there is substantial distortion. Compared with a no-policy equilibrium, a tax at 160 RMB/ton would achieve a similar national quantity reduction but have a smaller economic surplus loss of 35.2 billion RMB, about one third of the loss under the original policy. Figure 5 shows that both consumer and producer surplus changes (with tax revenues) are more evenly distributed across provinces under this tax. In particular, Shanxi sees reductions in consumer surplus loss as well as further gains in producer surplus.

We also calculate the optimal national Pigouvian tax[37] that maximizes the social surplus, which includes both the economic surplus and health effects from aerial pollution. We find an optimal tax of 42 RMB/ton, which would increase prices by 17.6 RMB/ton, only about one quarter of the supply reduction policy's effects. The optimal tax has similar but smaller effects than the output-equivalent tax on other dimensions.

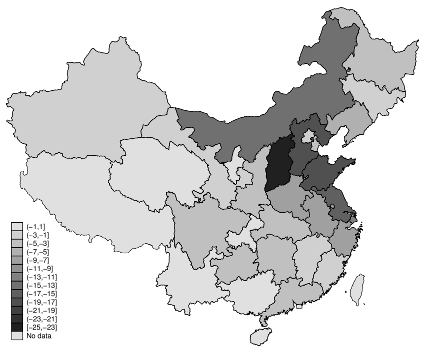
We do not calculate the optimal tax that takes into account the social cost of carbons (SSC).

[36]A caveat is that we also expect behavioral changes, i.e., changes in the demand function and its parameters, if the policy lasts long.

[37]A tax that achieves the first best would target shipment between each pair of provinces but would also be harder to implement and cause shippers to divert coal shipment, which can create unmeasured surplus losses such as forcing coal power plants to use coal-blending techniques more often and incur higher costs.

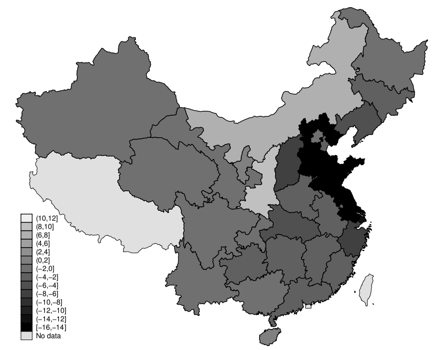
Figure 4: The Effects of 2016 Supply Reduction Policy (Billion RMB)

(A) CS Changes



(B) PS Changes

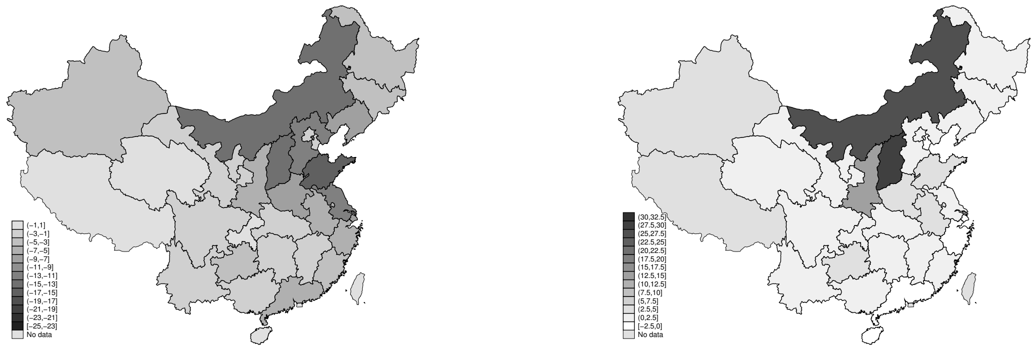
(C) Surplus Changes and Health Effects



Notes: panels A and B show consumer and producer surplus changes due to the supply reduction policy relative to a baseline of no-policy scenario. Panel C reports the total surplus changes including the health effects from air pollution. All changes are based on June to December 2016. Shanxi is the province with the largest decrease in CS as shown in panel A.

Figure 5: Effects of An Output-Equivalent Tax (Billion RMB)

(A) CS Changes (B) PS Changes



Notes: panels A and B show the consumer and producer surplus changes given a production tax that reduces the total quantity by the same amount as the policy. The PS changes include the tax revenue. All changes are based on June to December 2016.

Commonly used SSC estimates such as Rennert et al. (2022) imply a tax that is three times the highest price we see in the data. Our model likely would have poor extrapolation properties when such a tax is imposed. Nevertheless, our estimates show that the saved carbon costs from the supply reduction policy are large and more than offset the economic surplus losses. This result implies that an optimal carbon tax would cause a larger quantity reduction than in the data.

9 Conclusion

We present an empirical model of China's coal demand and supply and use it to evaluate the impact of the 2016 supply reduction policy. Our analysis reveals substantial losses in economic surplus as a result of the policy due to both the level of output reduction and the regional misallocation of reduction. An optimal Pigouvian tax taking into account the economic surplus and air pollution costs would reduce the output less. However, we caution that our analysis does not fully account for all negative externalities associated with coal production and consumption. Additional considerations, such as long-term benefits of reducing reliance on coal, could potentially justify the policy on other grounds.

The results also underscore the challenges of transitioning to carbon-free energy production with current technologies. While the benefits of reducing carbon emissions are substantial, the significant losses of economic surpluses and the lack of mechanisms for coal buyers to capture the environmental benefits make such policies unsustainable. Consistent with this observation, China has made massive investments in renewable energy, and the demand for coal has shifted considerably. In 2024, for the first time, the share of coal in electricity generation fell below 60%. Complementing these structural shifts, market-based mechanisms such as the European Union Emissions Trading System can also incentivize innovation in low-carbon technologies (Calel and Dechezleprêtre, 2016; Colmer et al., 2024).

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A Policy Documents

Figure A.1 provides a snapshot of the original government document for the supply reduction policy. We provide an English translation of this document in this section.

In order to implement the *"Opinions of the State Council on Resolving Overcapacity in the Coal Industry and Achieving Sustainable Development"* (Guo Fa [2016] No. 7, hereinafter referred to as the "Opinions"), and to further regulate and improve the coal production and management order, effectively resolve overcapacity, and promote the sustainable development of coal enterprises, the following notice is issued regarding related issues:

1. **Fully understand the importance of standardizing and improving the order of coal production and operation**

   Currently, the coal industry is in a serious predicament. Especially since last year, some coal enterprises have resorted to measures such as overcapacity production, compensating for price through volume, and low-price dumping to maintain production operations in an effort to seize market share. These actions have not only severely disrupted the normal order of coal production and operation but have also exacerbated the imbalance between supply and demand in the market, intensifying the difficulties faced by the industry. If these issues are not promptly curbed, the national goals and tasks related to the development of the coal industry will be difficult to achieve. All regions and enterprises must adopt a strategic perspective that promotes supply-side structural reform and effectively addresses capacity reduction tasks. It is essential to enhance overall awareness and fully recognize the importance of standardizing and improving the order of coal production and operation for facilitating the recovery and development of the coal industry. This requires unifying thought and action with the spirit of the "Opinions", taking effective measures to ensure the implementation of regulations concerning the control of overcapacity production, reduction of production volume, suspension of production during holidays, and maintenance of fair competition.

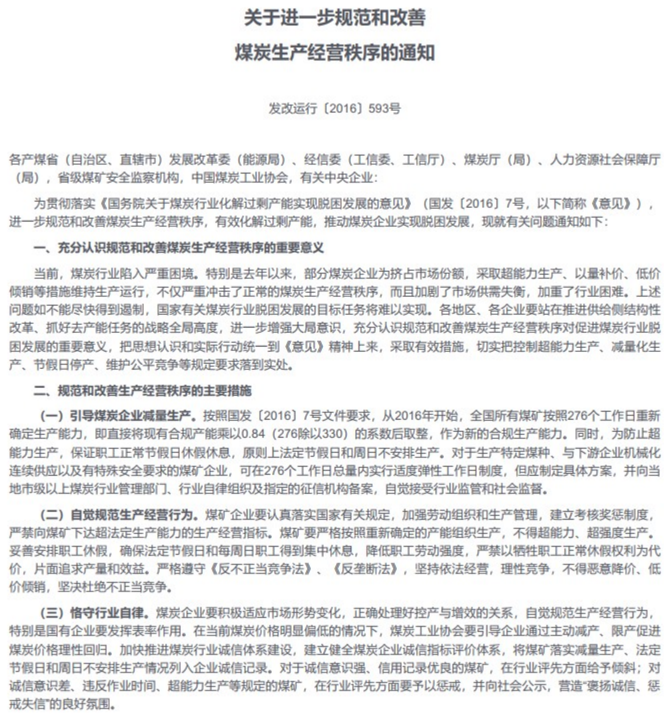
2. **Main Measures to Standardize and Improve Production and Operation Order**

   (a) **Guiding Coal Enterprises to Reduce Production Volume:** In accordance with the requirements of the State Council Document [2016] No. 7, starting from 2016, all coal mines nationwide are to re-determine their production capacity based on 276 working days. This means directly multiplying the existing compliant capacity by a coefficient of 0.84 (276 divided by 330) and rounding to the nearest whole number to establish the new compliant production capacity. Additionally, to prevent overcapacity production and ensure employees can take their normal holidays, no production should be scheduled on statutory holidays and Sundays. For coal mines producing specific coal types, providing mechanized continuous supply to downstream enterprises, or with special safety requirements, a moderately flexible working day system may be implemented within the total of 276 working days, provided that a specific plan is developed and filed with local coal industry management departments at or above the municipal level, industry self-regulatory organizations, and designated credit institutions, and that these enterprises consciously accept industry regulation and social supervision.

(b) **Consciously Standardizing Production and Operation Behavior:** Coal mines must earnestly implement national regulations, strengthen labor organization and production management, and establish a performance assessment and reward-punishment system. It is strictly prohibited to set production and operation targets that exceed the legal production capacity for coal mines. Production must be organized strictly according to the re-determined capacity, and overcapacity or excessively intense production is not allowed. Employee leave must be properly arranged to ensure that staff can rest during statutory holidays and every Sunday, thereby reducing labor intensity. It is forbidden to sacrifice employees' normal leave rights in order to pursue output and efficiency. Coal mines must strictly adhere to the "Anti-Unfair Competition Law" and the "Anti-Monopoly Law," operate in accordance with the law, engage in rational competition, refrain from malicious price cuts, and eliminate unfair competition.

(c) **Upholding Industry Self-Regulation:** Coal enterprises must actively adapt to changes in market conditions, correctly balance production control and efficiency enhancement, and consciously regulate their production and operation behavior, especially state-owned enterprises which should set a leading example. In the current context of notably low coal prices, the coal industry association should guide enterprises to promote rational price recovery through proactive production reduction and output limitations. The construction of an integrity system in the coal industry should be accelerated, establishing and improving an integrity index evaluation system for coal enterprises. Compliance with production reduction, as well as not scheduling production on statutory holidays and Sundays, should be included in the integrity records of enterprises. Coal mines with strong integrity awareness and good credit records should receive favorable treatment in industry evaluations, while those with poor integrity awareness, violations of operational times, and overcapacity production should face penalties in industry evaluations and be publicly disclosed to create a positive atmosphere of "rewarding integrity and punishing dishonesty."

Figure A.1: Policy Document: Supply Reduction Policy



关于进一步规范和改善
煤炭生产经营秩序的通知

发改运行〔2016〕593号

各产煤省（自治区、直辖市）发展改革委（能源局）、经信委（工信委、工信厅）、煤炭厅（局）、人力资源社会保障厅（局），省级煤矿安全监察机构，中国煤炭工业协会，有关中央企业：

为贯彻落实《国务院关于煤炭行业化解过剩产能实现脱困发展的意见》（国发〔2016〕7号，以下简称《意见》），进一步规范和改善煤炭生产经营秩序，有效化解过剩产能，推动煤炭企业实现脱困发展，现就有关问题通知如下：

一、充分认识规范和改善煤炭生产经营秩序的重要意义

当前，煤炭行业陷入严重困境。特别是去年以来，部分煤炭企业为挤占市场份额，采取超能力生产、以量补价、低价倾销等措施维持生产运行，不仅严重冲击了正常的煤炭生产经营秩序，而且加剧了市场供需失衡，加重了行业困难。上述问题如不能尽快得到遏制，国家有关煤炭行业脱困发展的目标任务将难以实现。各地区、各企业要站在推进供给侧结构性改革、抓好去产能任务的战略全局高度，进一步增强大局意识，充分认识规范和改善煤炭生产经营秩序对促进煤炭行业脱困发展的重要意义，把思想认识和实际行动统一到《意见》精神上来，采取有效措施，切实把控制超能力生产、减量化生产、节假日停产、维护公平竞争等规定要求落到实处。

二、规范和改善生产经营秩序的主要措施

（一）引导煤炭企业减量生产。 按照国发〔2016〕7号文件要求，从2016年开始，全国所有煤矿按照276个工作日重新确定生产能力，即直接将现有合规产能乘以0.84（276除以330）的系数后取整，作为新的合规生产能力。同时，为防止超能力生产，保证职工正常节假日休假休息，原则上法定节假日和周日不安排生产。对于生产特定煤种、与下游企业机械化连续供应以及有特殊安全要求的煤矿企业，可在276个工作日总量内实行适度弹性工作日制度，但应制定具体方案，并向当地市级以上煤炭行业管理部门、行业自律组织及指定的征信机构备案，自觉接受行业监管和社会监督。

（二）自觉规范生产经营行为。 煤矿企业要认真落实国家有关规定，加强劳动组织和生产管理，建立考核奖惩制度，严禁向煤矿下达超法定生产能力的生产经营指标。煤矿要严格按照重新确定的产能组织生产，不得超能力、超强度生产。妥善安排职工休假，确保法定节假日和每周日职工得到集中休息，降低职工劳动强度，严禁以牺牲职工正常休假权利为代价，片面追求产量和效益。严格遵守《反不正当竞争法》、《反垄断法》，坚持依法经营，理性竞争，不得恶意降价、低价倾销，坚决杜绝不正当竞争。

（三）恪守行业自律。 煤炭企业要积极适应市场形势变化，正确处理好控产与增效的关系，自觉规范生产经营行为，特别是国有企业要发挥表率作用。在当前煤炭价格明显偏低的情况下，煤炭工业协会要引导企业通过主动减产、限产促进煤炭价格理性回归。加快推进煤炭行业诚信体系建设，建立健全煤炭企业诚信指标评价体系，将煤矿落实减量生产、法定节假日和周日不安排生产情况列入企业诚信记录。对于诚信意识强、信用记录优良的煤矿，在行业评先方面给予倾斜；对诚信意识差、违反作业时间、超能力生产等规定的煤矿，在行业评先方面要予以惩戒，并向社会公示，营造"褒扬诚信、惩戒失信"的良好氛围。

B Data Comparison

To validate the provincial and monthly dataset we compiled from various sources, we compare the statistics based on our data and those from National Bureau of Statistics of China in Table B.1. The first column displays the national values aggregated from our main dataset, the second column is derived from the NBS Coal Balance Table for all provinces, and the third column represents the national statistics in the NBS National Coal Balance Table.

Overall, the national statistics derived from our main dataset are reasonably close to those in NBS, supporting the overall validity of our data. For instance, both datasets show declining output and consumption between 2014 and 2016, and a decrease in imports in 2015 followed by a rebound in 2016. These trends are consistently reflected in both the NBS and our dataset.

We validate our data at the province-year level. Figure B.1 compares the shipment out of and into a province in year with the annual coal production and consumption data by province in the provincial coal balance tables from NBS. Overall, they align closely, with the imputed consumption data being slightly lower than those reported by the NBS. This difference is expected because NBS data explicitly states that they do not remove certain instances of double-counting at the province level.[38]

[38] For example, coal transported to province A for washing and burned at power plants in B are both counted as consumption in provinces A and B. Our shipment data only count the final consumption in B.

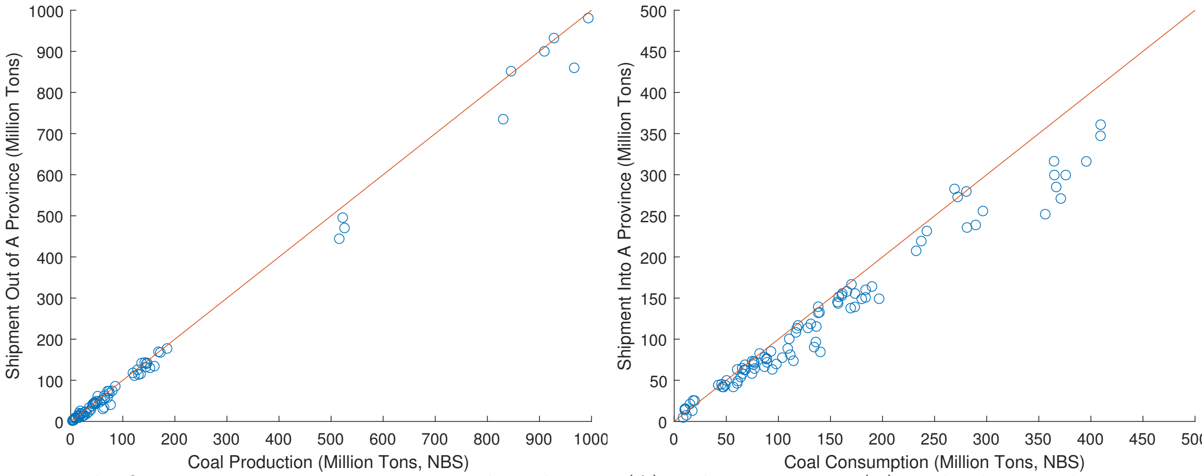
Table B.1: Data Comparison of Coal Output and Consumption (million tons)

	2014			2015			2016		
	Main	NBS (Prov)	NBS (Nat)	Main	NBS (Prov)	NBS (Nat)	Main	NBS (Prov)	NBS (Nat)
Output	3703	3876	3874	3457	3747	3747	3135	3411	3411
Consumption	3860	4317	4136	3662	4255	3998	3574	4249	3888
Thermal power	1974	1823	1895	1872	1792	1796	1908	1818	1827
Heating supply	181	306	224	204	323	241	222	345	266
Coking Coal	563	667	639	530	625	609	536	626	606

Notes: the table compares the data used in the empirical analysis (under main columns) with the annual numbers reported by the National Bureau of Statistics of China. The column NBS (Prov) are data collected from province coal balances tables and aggregated to national numbers, and the column NBS (Nat) are statistics reported in the national coal balance tables. The sum of coal consumption across provinces exceed the national total because of the potential double counting according to the official Q&A from China NBS (See `https://www.stats.gov.cn/hd/cjwtjd/202302/t20230207_1902276.html`). Under the main column, the output is calculated as total shipment and the monthly consumption is constructed based on monthly by-sector coal consumption and the output of main downstream output in different provinces, detailed in Appendix C. We then aggregate province-month production and consumption to the national level.

Figure B.1: Data Comparison of Shipment, Coal Output and Consumption at Province Levels (Million Tons)

(A) Shipment Out of A Province vs Production (B) Shipment into A Province vs Consumption



Notes: the figures compare province-year coal production (A) and consumption (B) in the data used in our empirical analysis with those reported by province coal balance tables. One dot in the figures represents one province-year pair. The y-axis is calculated by aggregating monthly total shipment out of and into a province within a year.

C Coal Consumption

We collected monthly steam coal consumption data from 2014 to 2016 across six sectors: electricity, heating supply, construction, steel, chemistry, others, and the coking sector. Table C.1 displays annual consumption in these sectors. Electricity is the largest coal consumer, accounting for over 50% of total consumption. Other major users include coking and cement plants, each accounting for 15%. The consumption breakdown is stable during our sample period. The "others" sector, which mainly includes residential demand and small-scale industrial processes, accounted for 7% in 2014 and declined to 3% in 2016.

Table C.1: Consumption Shares by Sectors

Year	2014	2015	2016
Electricity	0.51	0.51	0.53
Coking	0.15	0.14	0.15
Construction	0.15	0.15	0.14
Heating Supply	0.05	0.06	0.06
Steel (steam coal only)	0.04	0.04	0.04
Chemistry	0.04	0.04	0.04
Others	0.07	0.06	0.03

Note: The table shows annual coal consumption shares by sector. We collected monthly coal consumption by sector from China Coal Resource, and then aggregated them annually to calculate those shares.

To allocate coal consumption by sector across provinces, we further collect the monthly output of primary products in each sector by province from the NBS and converted it into coal consumption.

For the electricity sector, we use thermal electricity output as the main product. Although thermal electricity generation includes both coal and natural gas, natural gas contributes to only about 4.5% of total thermal generation, making its impact negligible.[39] We use cement as the representative product for the construction sector, as it accounts for 83.7% of coal consumption there. In the chemistry sector, fertilizers serve as the primary product.

Provincial coal balance tables provide annual coal consumption for thermal electricity generation and coking. We aggregate thermal and coke output to the province-year level and calculate coal consumption per 1 MWh of electricity and per ton of coke for each province and year. We assume these ratios remain constant across months within a province and year, converting thermal electricity generation and coke into coal consumption for the electricity and coking sectors. For cement, steel, and fertilizers, we aggregate their output by month across provinces and calculate the coal-to-output ratio. Assuming this ratio is constant across provinces within a month, we compute coal consumption in the construction, steel, and chemistry sectors based on their province-month output. Table C.2 shows that producing 1 MWh of electricity uses less coal, reflecting the gradual improvement in power plant energy efficiency. The conversion ratios are also consistent with engineering estimates by industry experts.[40]

Table C.2: Coal-to-End Product Output Ratio by Sectors

Year	2014	2015	2016
Electricity (1,000 tons of coal/MWh)	4.7	4.4	4.3
Cement (1 ton of coal/ton)	0.2	0.2	0.2
Steel (1 ton of coal/ton)	0.1	0.1	0.1
Coke (1 ton of coal/ton)	1.2	1.2	1.2
Fertilizer (1 ton of coal/ton)	2.0	1.8	2.0

Note: The table reports the conversion ratios used to estimate coal consumption for the production of key downstream products in each sector. Monthly data on the output of thermal electricity, cement, steel, coke, and fertilizers by province is collected from the NBS. The provincial coal balance tables provide annual coal consumption for thermal electricity generation and coking. We aggregate thermal and coke output to the province-year level to calculate the coal consumption per 1 MWh of electricity and per ton of coke. The table shows the average across provinces for each year. For cement, steel, and fertilizers, we calculate national output annually and match it with coal consumption data for the construction, steel (steam coal only), and chemical sectors from China Coal Resource, resulting in an annual conversion rate applied uniformly across all provinces.

To impute monthly coal consumption by province, we first calculate the annual shares for each province, then allocate the monthly consumption by sector accordingly. We collect annual coal consumption data for heating supply from provincial coal balance tables. We calculated annual consumption in "others" sector as the residual of total coal consumption after accounting for usage in electricity, heating supply, the industrial sector, and the construction sector. The left panel of

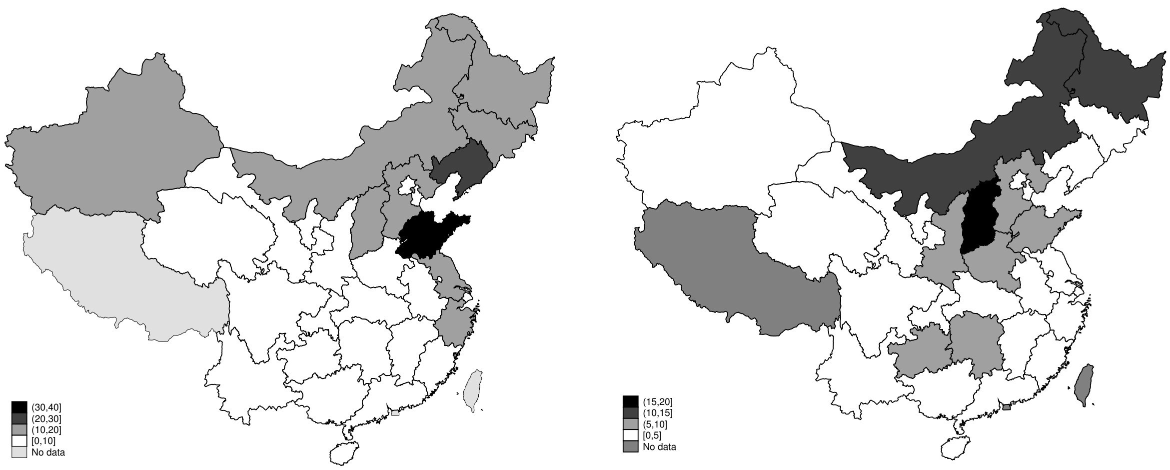
[39]https://chinaenergyportal.org/en/2016-detailed-electricity-statistics-updated/

[40]For example, producing 1 ton of cement requires 0.011 ton of standard coal, equivalent to a conversion ratio of 0.15 between coal and cement, given that 1 ton of raw coal equals 0.7143 ton of standard coal. See https://www.chinanews.com.cn/cj/2011/05-03/3011403.shtml.

Figure C.1 shows the geographical distribution of coal consumption for heating supply, highlighting higher demand in northern China due to centralized winter heating. The right panel depicts the distribution of coal consumption in the others sector. [41]

Figure C.1: Distribution of Coal Consumption in the Heating and Others Sectors (Million Tons)

A: Heating Sector B: Others Sector



Notes: the two figures show the annual coal consumption (million tons) for heating supply (A) and in others sector (B) in 2016.

D Coal Transportation

Integrated railroad and coastal marine shipping is the primary mode of coal transportation in China, accounting for 65.2% of total coal transport in 2017.[42] The transportation costs typically include the direct expenses associated with freight charges, which are influenced by the distance to be traveled, the mode of transportation (such as rail, truck, or barge), and the specific logistics involved. While shipping fares for waterway transport are influenced by market forces, railroad transportation fares are typically regulated.[43] Additionally, loading and unloading fees, terminal charges, and any necessary handling costs contribute to the total transportation expenditure. Other factors, such as fuel prices, maintenance of transportation vehicles, and labor costs, also play a significant role in shaping these costs.

Due to the limited variation in transportation shares, directly estimating transportation costs

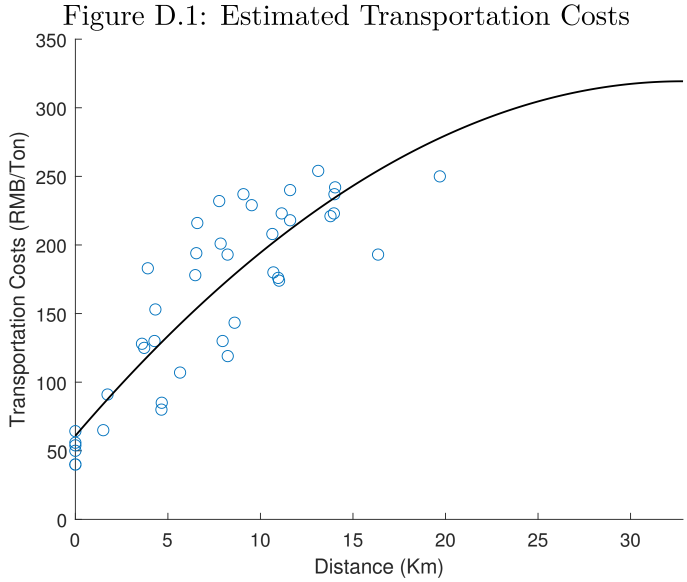
[41] Provinces north of the Huai River may rely more heavily on coal for centralized heating in the winter than those south of the river (Chen et al., 2013). As a result, northern provinces use more coal for heating than the south. To account for the differences, we categorize all provinces into two groups—northern and southern—based on whether they have centralized heating from 2014 to 2016. We also divide the months into heating seasons (November to March) and non-heating seasons (April to October). During the heating season, we increase coal demand by 20% for northern provinces and reduce it by 20% for southern provinces. Non-heating season coal consumption for heating are adjusted accordingly to ensure that the annual consumption in the heating sector match the NBS data for each province.

[42] See `http://pdf.dfcfw.com/pdf/H3_AP201811151246522585_1.PDF`.

[43] For more details about the composition of regulated fares for transporting coal by railroad, please refer to `http://www.gov.cn/xinwen/2017-12/26/5250421/files/5a71188c4fd34d1d9f05ef5e16690d2e.pdf`.

through shipping choices via a behavioral model is challenging. Instead, we manually collected estimated transportation costs between major coal producers and consumers from an authoritative industry report (Cao and Feng, 2017) published by China Bond Rating Co., Ltd., a leading agency that investigates and collects industry information to assess default risks of bonds across various sectors, including coal. Then we fit a quadratic relationship between the transportation costs and the distance between any two provinces, restricting that transportation costs increase with distance up to the maximum distance between any two provinces in China. Figure D.1 shows the transportation costs of province pairs estimated by the industry report, along with the estimated relationship between interprovincial distance and transportation costs. The intercept represents the costs of transporting coal within a province, estimated to be 60.9 RMB/ton. The cost also shows slight discounts as shipping distances increase.

Figure D.1: Estimated Transportation Costs



Notes: the figure shows transportation costs (RMB/ton) between major coal-producing and coal-consuming provinces, plotted against the distance between their capital cities (km), based on an authoritative industry report (Cao and Feng, 2017) published by China Bond Rating Co., Ltd. We then approximate the relationship between transportation costs and distance using a quadratic function. The black curve shows the estimated transportation costs for the province pairs not in the industry report.

E Foreign Import Supply Function

Our shipment data shows that the share of import to each province is also stable over time and allows us to construct a similar effective price for imports. We estimate the import supply elasticity in a log-log specification. An OLS regression based on data from 2014 to 2016 (36 months) yields an estimate of 1.16, with a robust standard error of 0.15. A similar IV estimation yields an estimate of 1.40 with a standard error of 0.07. We use the OLS results for our results given concerns about

IV estimates' bias in small samples,[44] but all of our results are similar using either estimate.

F Alternative Specification of Supply

As a robustness, we estimate a the following specification of the domestic supply

$$\ln Q_{it} = \gamma \ln P_{it} + FE_i^{\text{supply}} + FE_{m(t)}^{\text{supply}} + \eta_{it}.$$

Table F.1 report the estimation results and Table F.2 shows the counterfactual outcomes. They are similar to our baseline specification.

Table F.1: Estimation of Domestic Supply: Log-Log Specification

<table>
<tr><th></th><th>OLS</th><th>2SLS-GMM</th></tr>
<tr><td>ln(price)</td><td>0.428***</td><td>0.686***</td></tr>
<tr><td></td><td>(0.155)</td><td>(0.188)</td></tr>
<tr><td>Province FE</td><td colspan="2">YES</td></tr>
<tr><td>Month FE</td><td colspan="2">YES</td></tr>
<tr><td>Kleibergen-Paap F Statistic</td><td></td><td>81.469</td></tr>
<tr><td>N</td><td>723</td><td>723</td></tr>
</table>

Notes: the table reports the OLS and GMM estimates of the domestic supply model with log-log specification. The dependent variable is the logarithm of the output (tonnage) over capacity. All other variables and instruments are the same as 5.

[44] The endogeneity issue is also of a less concern given the small size of the import.

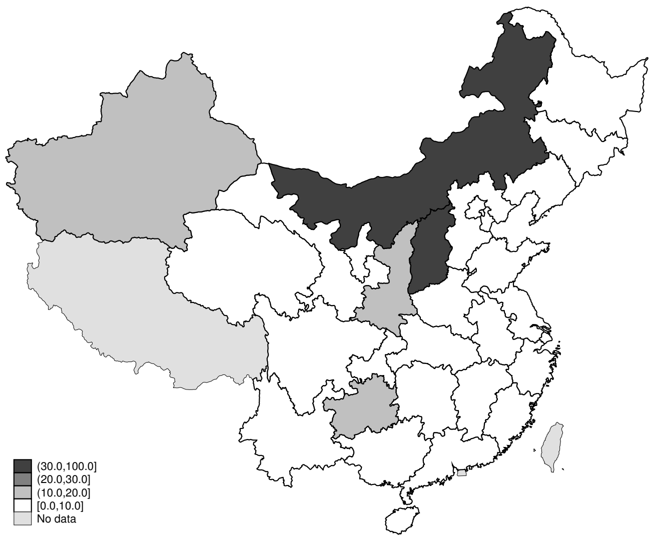
Table F.2: Counterfactual Results: Alternative Specification

	(1) Supply Reduction Policy	(2) Output Equivalent Tax (103 RMB/Ton)	(3) Optimal Tax (22 RMB/Ton)
Price (RMB/Ton)	82.1	28.8	6.6
	[75.2,91.7]	[26,31.9]	[5.7,7.6]
Output (Million Tons)	-467.6	-467.6	-92.2
	[-586.6,-400.8]	[-492,-451.7]	[-99.2,-87.7]
Consumption (Million Tons)	-151.6	-33.6	-8.4
	[-204.9,-100.4]	[-40.3,-28.3]	[-10.5,-6.6]
Economic Surplus (Billion RMB)	-119.1	-22	-0.1
	[-194,-91.8]	[-23.7,-20.2]	[-0.4,0.3]
Consumer Surplus	-213.5	-73.4	-17.4
	[-242.8,-192.7]	[-80.8,-65.5]	[-19.7,-14.9]
Producer Surplus	94.4	-151.4	-34.8
	[30.7,121.6]	[-156.2,-148.2]	[-36.6,-33.8]
Tax Revenue		202.9	52.1
		[197,212.3]	[50.7,54.5]
Surplus with PM2.5	-94.4	-16.7	1.2
	[-169.3,-66.8]	[-17.8,-15.3]	[1,1.3]
Surplus with PM2.5 and Carbon	249.3	59.6	20.3
	[116.6,383.2]	[48.4,73.7]	[16.2,24.8]

Notes: the table reports the counterfactual results based on estimates from the log-log specification of the supply model. The interval in the square brackets is the 2.5%-97.5% range across simulations. Column (1) compares the policy's effects relative to a no-policy equilibrium. The estimates are aggregate effects from June to December 2016. Column (2) considers the effects of a production tax that generates the same output reduction as the policy relative to the no-policy equilibrium. Column (3) calculates the optimal production tax that takes into account health costs from aerial pollutants. Health costs are calculated based on an estimated annual health cost of $9.2 billion from a 10 µg/m3 increase in PM2.5 concentration (Barwick et al., 2023). The social cost of carbon is set at $185/ton (Rennert et al., 2022), and we assume that one ton of consumed coal generates 2.64 tons of CO_2.

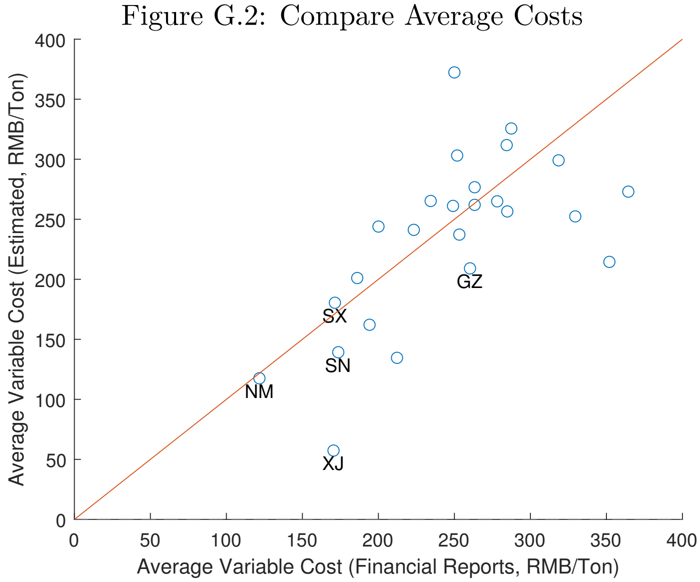
G Additional Figures and Tables

Figure G.1: Coal Reserves in 2016



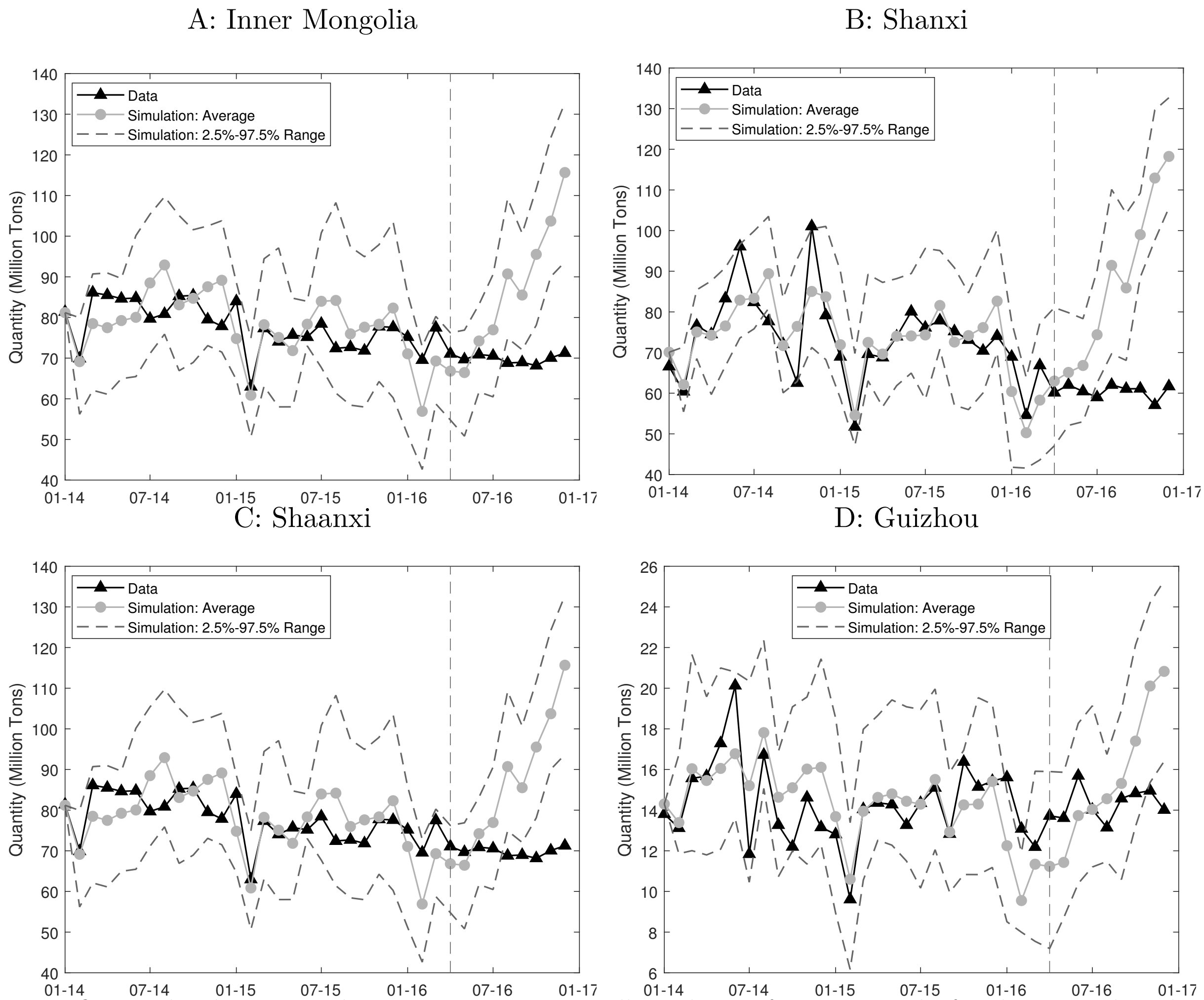
Notes: reserves are coal resources that have been surveyed and feasible for excavation based on NBS data.

Figure G.2: Compare Average Costs



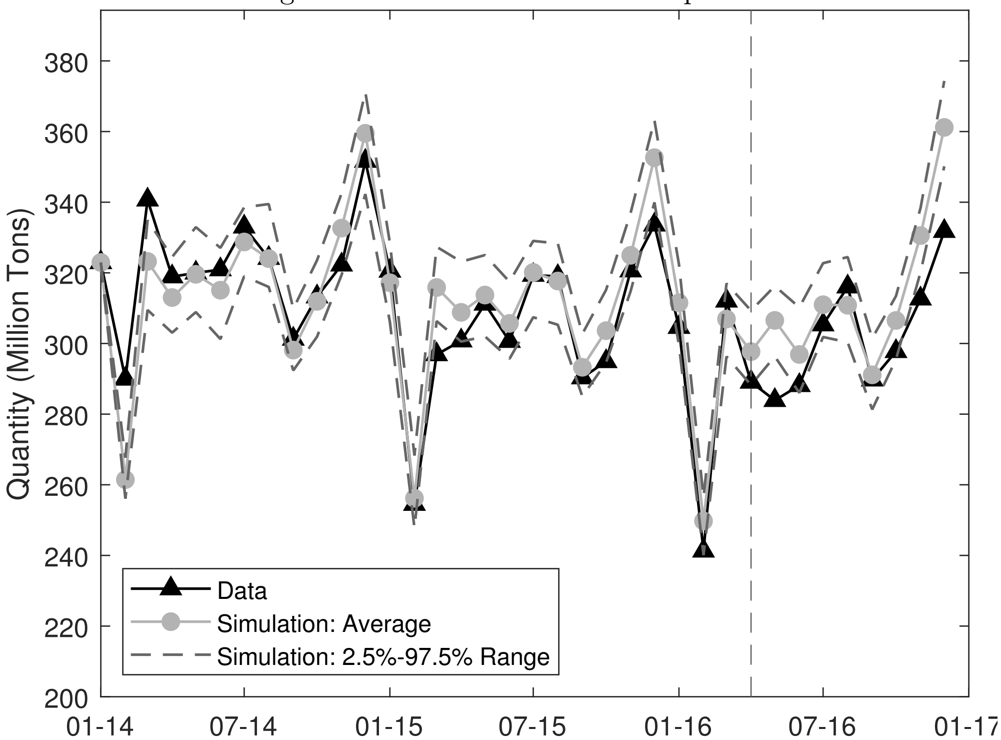
Notes: the figure compares average costs by province from the estimated model with the average costs from financial reports. The model's estimated average costs are calculated at the observed quantity and averaged over 27 months before the policy. The unit costs are collected from financial reports and bond prospectuses of major coal companies in each province, then averaged across all companies over three years in the sample.

Figure G.3: Simulations: Output by Provinces



Notes: figures plot the mean and 2.5%-97.5% range across all simulations for output in the four largest coal-producing provinces: Inner Mongolia, Shanxi and Shaanxi and Guizhou.

Figure G.4: Simulations: Consumption



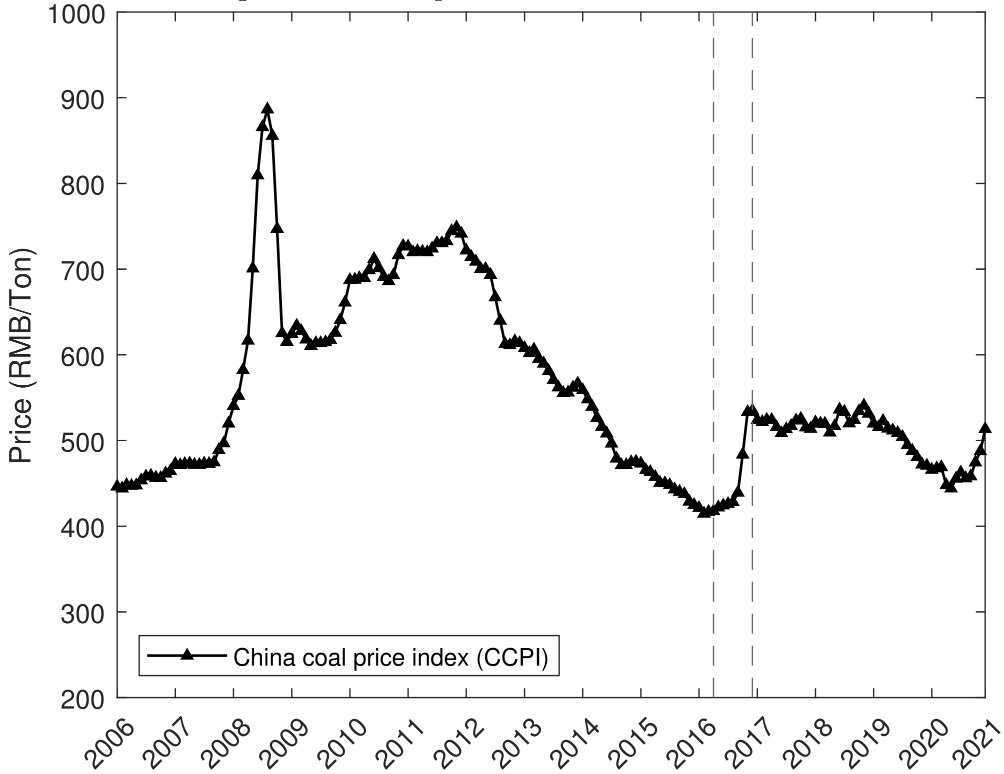
Notes: the figure shows the mean and 2.5%-97.5% range across all simulations for coal consumption. Coal consumption is simulated based on the predictive model described in 7.1.

Table G.1: Estimation of Foreign Import Supply

	OLS		IV
ln(price)	1.222***		1.314***
	(0.137)		(0.148)
Constant	-0.157		-0.727
	(0.852)		(0.926)
Province FE		YES	
Month FE		YES	
N	36		36

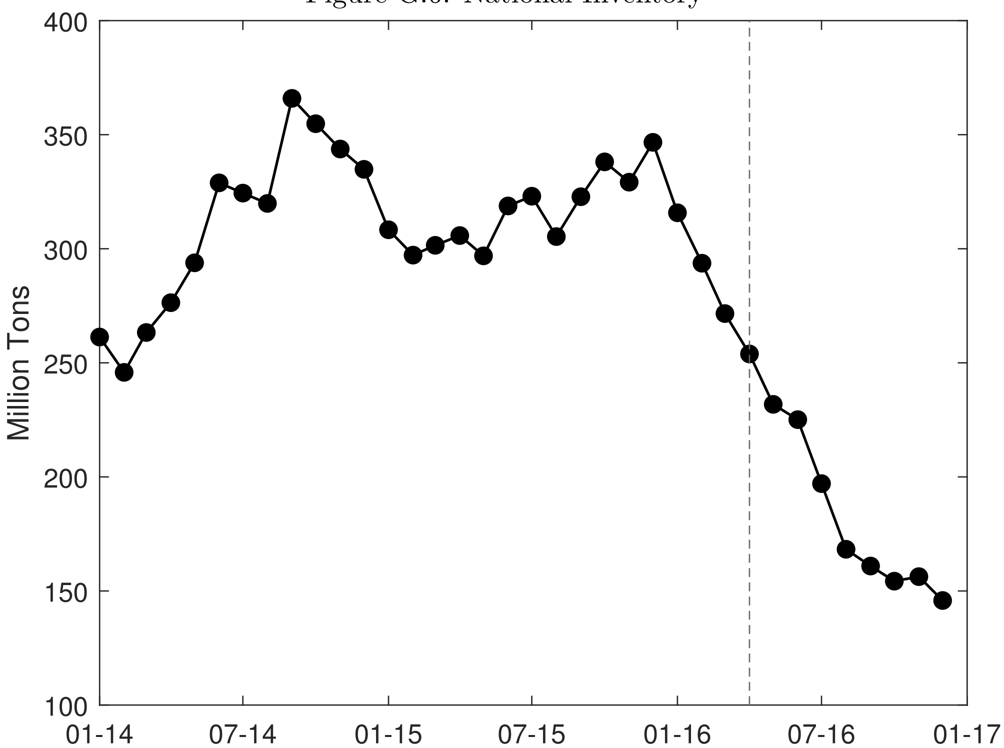
Notes: the table presents the OLS and IV estimates of the foreign import supply. The dependent variable is the logarithm of import tonnage. Prices faced by foreign producers are calculated as the weighted average of destination prices, based on each destination's share of the national total. We instrument for ln(price) using the weighted average of the exponential of residual demand at the destinations based on demand estimation, similar to the approach used in the supply estimation.

Figure G.5: Coal price between 2006 and 2020



Notes: the figure displays the China Coal Price Index (CCPI) from 2006 to 2018. The CCPI is a national index that includes all types of coal across all regions in China. It uses the coal price in January 2006 as a baseline of 100, reflecting changes relative to that date. We convert the CCPI into RMB per ton using January 2016 as the reference point.

Figure G.6: National Inventory



Notes: the figure plots the national coal stock (million tons) between January 2014 and December 2016. The data are from the consulting firm International Coal.

Table G.2: Welfare Estimates Using Other Measures of Health Costs from Aerial Pollutants

	(1) Ito and Zhang (2020)	(2) Ebenstein (2017)	(3) Ito and Zhang (2020)	(4) Ebenstein (2017)	(5) Ito and Zhang (2020)	(6) Ebenstein (2017)
	Policy	Policy	Output Equivalent Tax (160 RMB/ton)	Output Equivalent Tax (160 RMB/ton)	Pigouvian Tax (116 RMB/ton)	Pigouvian Tax (70 RMB/ton)
Price (RMB/Ton)	64.7	64.7	78.3	78.3	53.6	30.4
	[58.8,76.3]	[58.8,76.3]	[77.5,79]	[77.5,79]	[52.9,54]	[30,30.7]
Output (Million Tons)	-531.8	-531.8	-531.8	-531.8	-387.3	-233.6
	[-657.3,-458]	[-657.3,-458]	[-571.4,-506.5]	[-571.4,-506.5]	[-415.6,-369.3]	[-250,-223.4]
Consumption (Million Tons	-102.1	-102.1	-98.1	-98.1	-69.4	-40.6
	[-152.8,-50.5]	[-152.8,-50.5]	[-102.3,-94.7]	[-102.3,-94.7]	[-72.2,-67.1]	[-42.2,-39.4]
Economic Surplus (Billion RMB)	-97.1	-97.1	-35.2	-35.2	-16.5	-4
	[-125.5,-76.8]	[-125.5,-76.8]	[-38.7,-33]	[-38.7,-33]	[-18.4,-15.3]	[-4.7,-3.6]
Consumer Surplus	-170.7	-170.7	-166.2	-166.2	-118.2	-69.8
	[-204,-152.5]	[-204,-152.5]	[-171.7,-162.8]	[-171.7,-162.8]	[-121.9,-116]	[-71.7,-68.6]
Producer Surplus	73.6	73.6	-186.1	-186.1	-145	-94.4
	[60,89.9]	[60,89.9]	[-197.6,-179.1]	[-197.6,-179.1]	[-154.3,-139.4]	[-100.7,-90.6]
Tax Revenue			317	317	246.8	160.2
			[309.1,330.6]	[309.1,330.6]	[240.3,257.9]	[155.7,167.7]
Surplus with PM 10	-27.6	-60.1	19.2	-4.7	22.2	8.8
	[-62,7.7]	[-88.1,-35.1]	[17.1,21.6]	[-7.4,-2.6]	[21,23.9]	[8.3,9.4]
Surplus with PM 10 and Carbon	204	171.5	241.7	217.8	179.6	101
	[63.3,352.2]	[41.9,303.4]	[233.4,251.7]	[210.3,227]	[173.9,186.7]	[98,104.5]

Notes: the table calculates the policy effects and production tax using two alternative estimates of health costs from PM10. We use these two estimates to calculate the health cost savings from reduced air pollutants. Columns (1) and (2) report the policy effects and columns (3) and (4) report the welfare effects from the output-equivalent production tax to the policy, and (5) and (6) calculate the optimal production tax for the objective of economic surplus and aerial pollution. We adjust the estimates based on Ito and Zhang (2020) for income heterogeneity across provinces using their random coefficient estimation results.