Imperfect (Re)allocation in Imperfect Markets: Evidence from China's Pilot Carbon ETS*

Johannes Van Biesebroeck and Honghao Zheng

September 18, 2025

Abstract

We evaluate the effectiveness of the carbon emission trading scheme (ETS) pilots that China established in 2013-2014. The coexistence of two types of emissions regulation within a single energy market—with either an absolute or an intensity cap—provides a unique opportunity to study their differential effects. We employ a difference-in-differences estimation strategy at several units of analysis—provinces, industrial firms, and power plants—to examine the effects on several margins of adjustment, including energy consumption, industrial output, the energy input mix, electricity trade, and substitution between power generation sources. Both types of regulation induce carbon mitigation, but they come with distinct tradeoffs.

Keywords: Emissions trading scheme, climate change mitigation.

*Van Biesebroeck: KU Leuven and CEPR, jo.vanbiesebroeck@kuleuven.be. Zheng: KU Leuven, honghao.zheng@kuleuven.be. We thank Jan De Loecker, Frank Verboven, Sebastian Fleitas, Charlotte De Cannière, and seminar participants at Copenhagen Business School, IMT Lucca, Glasgow, PSE, Liaoning, HKU, IIOC 2023, EARIE 2023, APIOC 2023, BEED 2024, NBB-CEPR 2024, RIDGE 2024, Kiel-Göttingen-CEPR 2024, CEPR STEG 2025, and Gerzensee 2025 for their valuable comments and suggestions. Financial support from the Flemish Research Foundation (FWO) and Methusalem project METH/21/01 is gratefully acknowledged.

1 Introduction

Reducing CO_2 emissions to combat climate change is costly not only because alternative energy sources are often more expensive, but also because it makes energy-intensive economic activities less viable. Developing countries in particular face a difficult tradeoff between mitigating climate change and sustaining economic growth. However, as the share of global emissions accounted for by developing countries continues to rise, their participation in emission reduction becomes indispensable. Two solutions are often advanced.[1] Developed countries could subsidize the cost of abatement initiatives in poorer countries. Alternatively, developed countries could target *absolute* reductions in emissions, while developing countries focus on reducing their emissions *intensity* (Shapiro and Walker, 2018).

As the world's largest CO_2 emitter and an emerging economy pursuing a high growth rate, China faces this tradeoff more than most. Between 2013 and 2014, it established seven regional carbon emissions trading scheme (ETS) pilots. Each had limited discretion to tailor the rules to its industrial structure and level of development. Four 'city-ETS' cover the relatively prosperous province-level cities of Beijing, Shanghai, Tianjin, as well as Shenzhen in Guangdong province, the richest city in the country. They cap absolute emissions of industrial firms, similarly as in the EU ETS. The three 'province-ETS' in Chongqing, Guangdong, and Hubei were established in larger and less developed regions. They target the emissions intensity to avoid incentives for output reductions. The coexistence of these two types of emissions-reduction schemes within the same energy market provides a unique setting to study their differential effects.[2]

While the direction of change induced by an ETS is straightforward, the extent of adjustment is highly uncertain for several reasons. The pass-through of emission certificate costs into energy prices is imperfect as energy markets are far from perfectly competitive, especially in developing countries. Prices are often regulated and even when they are allowed to adjust, local monopolies and scale economies convey market power. The limited scope for substitution in energy production and consumption in the short run leads to low demand and supply elasticities. All these factors reduce pass-through. Incomplete regulation and carbon leakages from regional pilots can further weaken the impact of an

[1]See, for example, https://www.oecd.org/newsroom/statement-from-oecd-secretary-general-mathias-cormann-on-climate-finance-in-2019.htm and https://about.bnef.com/turner-the-case-for-intensity-based-targets-to-curb-climate-change.

[2]All pilot ETS adopted the intensity-type regulation for the power generation sector, as will be discussed in Section 2.

ETS. Finally, the many non-market aspects of the Chinese economy and the discretionary influence of authorities make it difficult to predict how effective the ETS regulation will be.

In principle, there are several possible margins of adjustment along the energy value chain when market participants are confronted with a fluctuating cost of carbon. Energy consumers can simply scale back consumption. Industrial firms can alter their energy input mix when relative prices change, but they can also evade regulation by shifting production to exempt firms or outside the pilot areas. While adjusting electricity generation is more difficult for individual power generators, it is certainly possible for provincial power systems. Local authorities can change the dispatch priority of existing power plants, import power from other provinces, or take emissions into account when approving new investments.

We investigate each of these potential adjustment mechanisms using a difference-in-differences (DID) research design. By estimating specifications with different dependent variables and at different levels of aggregation, we learn how different market participants adjust and obtain an overall impression about the effectiveness of the ETS pilots. In particular, we study equilibrium energy use at the provincial level, distinguishing between electric power and fossil fuel, and also look at interprovincial power trade. We study adjustments of industrial firms in total energy use, mix of energy inputs, output level, industry affiliation, and exit. Finally, we look at differential effects on the dispatching of power plants by fuel type and their capacity investment.

On most dimensions, we find effects in the expected direction that are stronger in city-ETS with absolute emission caps than in province-ETS with intensity regulation. This consistency is somewhat surprising because both retail and wholesale electricity prices are regulated and do not fluctuate with the cost of carbon. Moreover, decisions are often made in opaque ways by government agencies or state-owned companies that do not necessarily maximize profits or even minimize costs. Some effects show intended adjustments to the regulation, but some imply carbon leakage. The absence of higher investment in clean power capacity in pilot ETS is one dimension where the expected effect did not materialize. The (relative) lack of suitable land in more densely populated ETS areas is a possible explanation, but our DID strategy is also less suited to study long-term investment decisions, as all provinces might anticipate a national ETS.[3]

[3]In 2021, China implemented a national ETS based on the experiences from the pilot ETS. See Wang and Yang (2025) for an overview of China's long-standing practice of conducting policy experiments before rolling out a policy nationwide.

Our work contributes to at least three literatures. First, the literature on the tradeoff between environmental gains and economic outcomes has considered various environmental regulations in developed countries (Greenstone, 2002; Bushnell et al., 2013; Walker, 2013; Shapiro and Walker, 2018), but only a few in developing countries (He et al., 2020). Whether an ETS targets a reduction in *absolute* emissions or only the emissions *intensity* is likely to affect this tradeoff. An absolute cap provides stronger incentives to reduce energy consumption and economic growth, but also to engage in evasive actions (Chen et al., 2025). Our results on total energy use, on the output of regulated, industrial firms, and on exit rates speak to this issue.

Second, energy markets are highly imperfect (Cicala, 2022), especially in developing countries. Because of their efficiency in distributing abatement efforts, permit trading on an ETS has been adopted in various contexts (Fowlie, 2009). Nevertheless, Fowlie et al. (2016) shows that preexisting distortions in production markets may reduce the efficiency. The existence of command-and-control dispatch policies and opaque entry restrictions, both of which are important in China (Ren et al., 2021), might further reduce the effectiveness. Some studies evaluate the carbon market in China by simulating its effects in an explicit model, see for example Fan et al. (2016) and Goulder et al. (2022, 2025). Given the difficulty of knowing exactly the decision process and how markets clear in China, we examine adjustments in a reduced-form way, even if this requires some caveats on the interpretation of effects.

Third, empirical studies of China's ETS policy have focused on one specific margin of adjustment. Cao et al. (2021) shows that emission reductions by coal-fired power plants are achieved entirely by reducing electricity production, finding no effect on emissions intensity. In contrast, Cui et al. (2021) finds that the reduction in energy inputs by industrial firms is mainly achieved by reducing energy intensity and switching to low-carbon fuel. These are interesting findings, but provide only a partial picture of the overall effects of the ETS policy. We study both demand and supply side responses of various actors and take unexpected or unintended effects into account, including carbon leakage to unregulated firms, as in He and Chen (2023).

The remainder of the paper is organized as follows. Background information on the industry and ETS pilots is in Section 2. The data is described in Section 3, the empirical strategy in Section 4, and the results in Section 5. Section 6 concludes.

2 Policy and industry background

2.1 Pilot emissions trading schemes

To reduce its carbon emissions, China established seven regional pilot ETS between 2013 and 2014 in provinces with a combined population of 215 million. The pilots of Beijing, Shanghai, and Tianjin, which we call 'city-ETS', put an absolute cap on CO_2 emissions.[4] Regulated firms are allocated free allowances according to an emissions-based grandfathering rule, to which a reduction factor is applied. This approach is also known as a mass-based system or cap-and-trade ETS (Salant, 2016)—hereafter referred to as an absolute-type ETS.[5]

The pilots in Chongqing, Guangdong and Hubei, the 'prov-ETS', only regulate the emissions intensity. The intensity targets for each regulated sector, which are expressed in CO_2 per unit of output (tons), are lowered over time. Individual firms receive free allowances based on their lagged output, but they are adjusted during the year in function of current production. As such, the total amount of carbon certificates issued in a year scales with total output and there is no absolute cap.[6] This feature makes carbon markets more compatible with high-growth developing economies, but it diminishes incentives for emissions mitigation. If the intensity target is binding, regulated firms receive an implicit output subsidy (Goulder et al., 2022).

The designation of the two types of regulation is not random. All three city-ETS are in municipalities with relatively advanced economies, but limited resource endowments and space. Their average GDP per capita was $13,688 USD in 2013 and the level of economic development of these large, urbanized areas is by now ahead of the bottom third of OECD countries. The prov-ETS are in provinces with an average GDP per capita of $7,401 USD in 2013 and a level of development more comparable to upper-middle income countries, like Ukraine or Algeria.[7]

Firms in regulated industries need to participate in the ETS if their total energy consumption exceeds the applicable ETS threshold. Most pilots set a threshold of 10,000

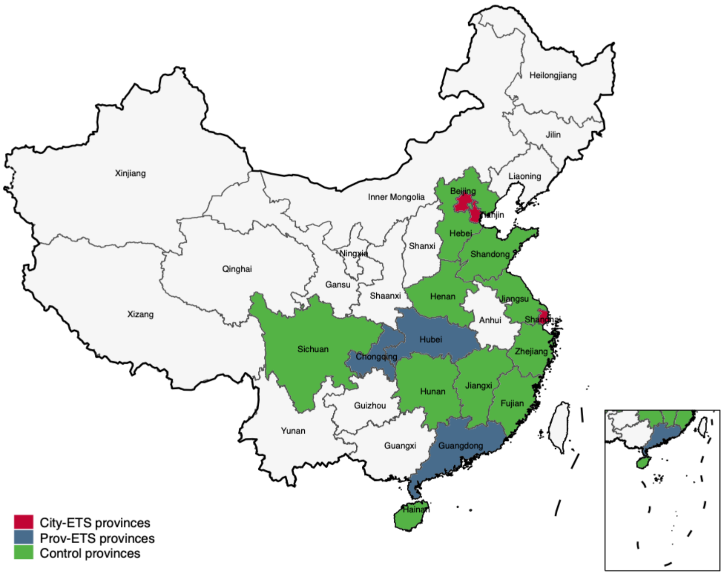
[4]Shenzhen is a special economic zone in Guangdong province and it is also subject to an absolute emissions cap. However, because economic statistics are not available for Shenzhen separately, we have to include it with Guangdong in our analysis.

[5]The European carbon ETS started in the same way, but in Phase III (2013) the allocation rule changed to 'fixed historical production benchmarking', a variant of the mass-based system.

[6]If the emissions benchmark in an absolute-type ETS adjusts over time, i.e., updates dynamically, the number of allowances is also output-based (Fowlie et al., 2016), as in the Chinese prov-ETS.

[7]Chongqing is also a municipality with provincial status, but its geographic size and level of development make it more alike Guangdong and Hubei.

Figure 1: Pilot and control provinces



Notes: City-ETS provinces (red) are Beijing, Shanghai, and Tianjin; Prov-ETS provinces (blue) are Chongqing, Guangdong, and Hubei. Control provinces (green) are in the same geographic and power-grid region as at least one of the ETS provinces.

tons of standard coal equivalent, although Chongqing and Beijing set it at 5,000 tons and Hubei at 60,000 tons.[8] Energy-intensive industries are the main participants, but the specific industries vary somewhat across pilots. Electric power generation is always included, but even in city-ETS it is subject to intensity regulation. The petrochemical, cement, aluminum, and iron and steel industries are included in most pilots.[9] To remain in compliance, regulated firms must hold permits to offset their uncontrolled emissions. They receive free emission permits every year according to the allowance allocation rules discussed above. These permits are then traded freely in the seven separate carbon marketplaces.

A unique feature of the Chinese pilots is that they cover direct as well as indirect emissions. Industrial firms need to hold permits to cover not only their own combustion of fossil fuels (direct emissions), but also their consumption of purchased electricity (indirect emissions) even though these are already counted under power plants' direct emissions (Cui et al., 2021).[10] It does not imply double-counting, because electricity prices are regulated and do not increase with the cost of carbon. Rather, it amounts to full pass-

[8] Table A.1 in the Online Appendix provides an overview of the thresholds for all pilots.

[9] Zhang et al. (2017) provides an overview of the covered industries for all pilots.

[10] Firms use the average emission factor of their regional grid, listed in Table A.2.

through of the carbon cost associated with electricity production, providing industrial firms with the appropriate price signal (Fabra and Reguant, 2014).[11]

While the pilot ETS are still operational, China's national carbon ETS market launched in mid-2021.[12] Initially, it only covered the power generation sector, i.e., 2,225 fossil fuel-fired power plants that account for more than 50% of China's industrial CO_2 emissions (Cao et al., 2021). The sectoral coverage was expanded to include cement, steel, and aluminum smelter industries in 2024.

2.2 China's electricity sector

China's electricity sector has been deregulated to some extent, but it is still a highly imperfect market featuring entry regulation in generation, government-run dispatch, and regulated wholesale and retail prices (Zheng et al., 2021).

In 2011, before the pilots were announced, fossil fuel-fired power plants accounted for 82% of total generation. Between 2011 and 2020, total generation capacity of solar and wind power increased more than tenfold, growing from 49 GW to 535 GW (from 4.6% to 24.3% of total installed capacity). Due to its intermittent nature, and initially also because of limited interregional transmission capacity, the fraction of electricity generated by solar and wind power increased less dramatically, from 1.6% to 9.5%. In 2020, fossil fuel-fired power still accounted for 68% of total electricity generation.

Power plants receive dispatch orders from monopolized local power grid companies. To avoid potential conflicts of interest, they were forced to divest all generation assets in 2002 (Gao and Van Biesebroeck, 2014). There were no interregional spot electricity markets in China during our study period. To establish interprovincial power transmission orders, the local *Economy and Information Commission* (EIC) decides an annual generation plan for each local power plant following specific allocation rules (Ho et al., 2017). The 'equal share' rule requires EICs to allocate the same operating time to plants with the same capacity (Ren et al., 2021). The 'energy conservation' rule gives priority to renewable and clean energy (Kahrl et al., 2013). The power grid company flexibly arranges monthly and daily plans with each power plant to balance and ensure the completion of the aggregate annual plan.

[11] Electricity price regulation makes it necessary to use intensity-type regulation for the power sector, even in city-ETS. However, including indirect emissions of industrial firms still imposes an absolute cap.

[12] See https://www.ndrc.gov.cn/xxgk/zcfb/ghxwj/201712/t20171220_960930.html. The National Development and Reform Commission had initially planned to roll it out in 2017, but it was postponed several times.

When companies sell power to the grid, they are paid predetermined on-grid electricity prices. These are set by the *National Development and Reform Commission* (NDRC) at the provincial level and vary by power plant type. Wind and solar power typically receive the highest price to promote the adoption of renewable energy, while hydropower receives the lowest price due to its low marginal cost. The price for coal-fired power is based on the cost of advanced power units, but plants receive markups if they implement desulfurization, denitrification, dust removal, and ultra-low emissions. Base prices occasionally adjust through the 'coal-electricity price linkage mechanism' to safeguard power plants' profitability when coal prices fluctuate (Li et al., 2015).

Retail electricity prices are also regulated by the NDRC and vary by province. Non-government power consumers are categorized in three groups facing different price schedules that each follow a step function that rises with consumption. Industry and commerce accounted for 86% of the total in 2011, residential consumers for 12%, and agriculture 2%. From 2017 onward, power plants are allowed to sign contracts directly with large power-purchasing entities. Delivery can be scheduled independently of dispatch orders and prices can vary. The fraction of electricity generation covered by these contracts is negligible during our sample period, accounting for less than 30% of the total in 2018 (Cao et al., 2021).

3 Data

We use information from several data sources, which we discuss by unit of observation.

Provincial Electricity and Energy Data. From the *China Electricity Council* (CEC), we obtain province-level information on electricity consumption and interprovincial power transmission for the period 2007 to 2019.[13] They also provide information on the length and capacity of the power transmission network which are used as control variables. We obtain provincial fossil fuel consumption from the *China Energy Statistics Yearbook*. This covers all sectors, residential and commercial, except for the power generation sector itself. *China's Statistical Yearbook* contains population and GDP per capita statistics for all provinces.

Firm Energy Consumption Data. We use firm-level data for the period 2007 to 2016 from the National Tax Survey Database, collected by the *Chinese State Administration of*

[13]Production information is available separately, but it equals consumption plus net exports.

Tax. It contains information on output and inputs, including energy consumption, separately for electricity and fossil fuel. To obtain a composite energy consumption measure, we convert both types of energy use into a 'standard coal' metric using conversion factors from the *China Energy Statistics Yearbook*. Firms in the top and bottom percentile (calculated by year) in terms of energy intensity and consumption of electricity, fossil fuel, or composite energy are eliminated from the sample.[14]

The sample includes 1,212,742 firm-year observations. Firms in ETS provinces with annual composite energy consumption above the relevant threshold in any of the years between 2009 and 2012, prior to the ETS start, are classified as above-threshold firms. The thresholds vary slightly across ETS as shown in Table A.1 in the Online Appendix. The most common standard is 10,000 tons of standard coal equivalent, which is the threshold we apply for firms in non-ETS provinces.

Power Generation Data. We use information from CEC on annual production of electricity by all electric power plants with a capacity above 6 MW that operated between 2007 and 2017.[15] The unit of observation is a 'plant',the same units that receive electricity generation dispatch orders from power grid companies. The sample consists of 53,244 plant-year observations, but data for 2013 is missing.

We observe detailed plant-level information including name, capacity, annual power generation, operating hours, amount of coal (equivalent) input used, etc. The plant type, i.e. which fuel is used, is not reported, but we recover this information using the following three approaches. First, keywords in the plant's Chinese name often reveal the fuel type.[16] Second, we match power plants based on their name with firms in China's *Administrative Registration Database*. Where successful, the information on business scope generally contains the type of fuel used. Third, for the remaining plants, we identify the type by manually searching the internet and public information sources.

[14]There seems to be some measurement error as some firms report drastic changes in yearly energy consumption, e.g. increases by more than 500% or declines by more than 80%. A possible explanation are changes in reporting units for some variables in different survey years, which some firms might not have properly adjusted to, see also Cui et al. (2021).

[15]The threshold of 6 MW is fairly low, as the average capacity of a single offshore wind turbine is around 6 MW (https://www.energy.gov/eere/articles/wind-turbines-bigger-better).

[16]Words often included in the plant names are "coal-fired" (ran mei/mei dian), "gas-fired" (ran qi/ran ji), "hydro" (shui li/shui dian), "wind" (feng li/feng dian), "solar" (guang fu/tai yang neng), etc.

4 Empirical strategy

To investigate the effects on various margins of adjustment, we estimate a series of DID specifications that can all be represented by

$$Y_{it} \quad = \quad \alpha_i + \delta_{rt} + \beta D_{it} + X'_{it}\gamma + \varepsilon_{it}. \tag{1}$$

Dependent variables Y_{it} are the various outcomes that we introduce in the next section: retail electricity prices, equilibrium use of electric power and fossil fuel by residential consumers and industry, net power imports, etc. In most cases they are expressed in logarithms. The i subscript can refer to different units of observation: provinces, industrial firms, power plants, or province-fuel type combinations. We always include a cross-sectional fixed effect (FE) α_i to use only within-observation changes over time for identification.

Control variables X_{it} are provincial per capita GDP, total capacity of power generation and high-voltage power transmission lines. In addition, δ_{rt} represents two sets of interaction FE that define the control provinces. Region-year FE absorb variations in regional growth or demand shocks related to industrial structure. Regional power grid-year FE capture variation in local policies regarding power dispatch and investments in transmission, generation capacity and infrastructure.[17] As a result, the change in a dependent variable in an ETS province is compared to the corresponding change in neighboring provinces within the same geographic and power grid regions. Firm-level regressions additionally contain 2-digit industry-year FE to control for technological evolutions in energy use.

The coefficient of interest β is applied to the ETS pilot dummy which switches to one for regulated provinces in 2013 or 2014. To examine whether effects are heterogeneous for absolute versus intensity regulation, we focus on specifications where the βD_{it} term in (1) is replaced with two terms that interact the treatment indicator with ETS type: $\beta_1\, D_{it} \times \text{Prov-ETS}_i + \beta_2\, D_{it} \times \text{City-ETS}_i$.

For a DID estimate to have a causal interpretation, the treated observations should have experienced the same evolution as control observations absent treatment. One check to assess the plausibility of this assumption is a parallel trend test on the pre-treatment period. In that case, the βD_{it} term in (1) is replaced by a full set of pre- and post-

[17] Regions are East, West, and Central; power grids follow the six regional companies created in the 2002 reform that eliminated interprovincial transmission barriers: North, Northeast, East, Central, Northwest, and South. Five of them deregistered in 2016, but the transmission structure was preserved.

treatment dummies: $\sum_{\tau=\underline{T}}^{\overline{T}} \beta_\tau D_i \times \mathbb{1}[t = \tau]$, where D_i is a time-invariant indicator for an ETS pilot province. Given that the sample period is relatively short, we use all years, i.e., $\underline{T} = 0$ and $\overline{T} = T$.

5 Results

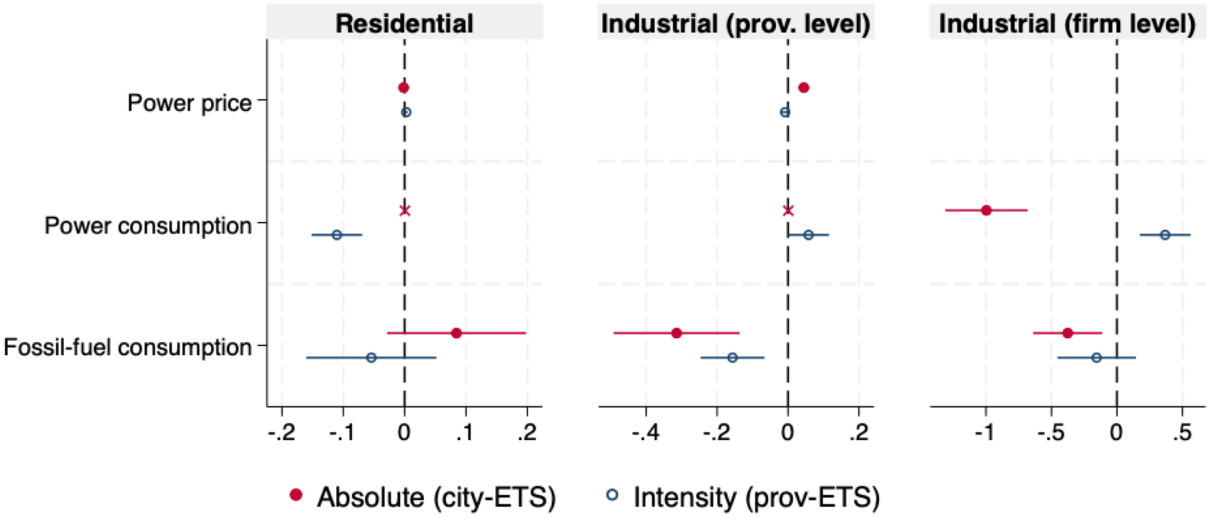
In a competitive market, economic agents can adjustment to a higher cost of carbon in several ways. Dirty power plants can bid more conservatively into the wholesale electricity market, which moves them down in the dispatch merit order, reduces capacity utilization and reallocates demand to less carbon-intensive operators. It encourages investment in cleaner technology and the grid operator may even try to import power. Higher prices push electricity consumers up their demand curve, but the short-run elasticity is generally low for residential consumers. Industrial clients may be more responsive as they can reduce the energy intensity of their production process, substitute between alternative energy inputs, change the type of products they produce, or reduce output altogether.

However, energy markets in China are still regulated and subject to command-and-control by local authorities, making it uncertain to what extent the policy signal will reach its intended targets. Before delving into the estimation results, we first review how we expect various market participants to adjust to a carbon ETS in a competitive market. Energy markets in China are still regulated and subject to command-and-control by local authorities. It is uncertain to what extent the policy signal will reach its intended targets, but we start by outlining possible adjustment margins.

Emission-intensive power plants should raise their bids into the wholesale electricity market to pass on the cost of carbon permits to their customers. This moves them down in the dispatch merit order, reducing operating hours and capacity utilization.[18] It reallocates demand to less carbon-intensive operators and encourages investment in cleaner technology. Moreover, the grid operator might source more power from jurisdictions not covered by the ETS. A higher market clearing wholesale price raises the retail price and pushes electricity consumers higher up their demand curve. The reduction in equilibrium quantity depends on the price elasticity of demand which tends to be low for residential consumers, especially in the short run. Industrial clients might be more elastic if they can reduce the energy intensity of their production process, change the type of products they

[18] The merit order ranks available electric power generators based on ascending marginal costs, prioritizing low cost units and, in principle, minimizing the total cost of satisfying aggregate demand.

Figure 2: Effects of ETS on equilibrium energy use



Notes: Coefficient estimates from separate regressions with 95% confidence intervals. Results for power consumption by residential and industrial consumers are omitted (shown by x), because the parallel trend assumption does not hold.

produce, or reduce output altogether. Facing carbon costs on their own fossil fuel consumption, industrial firms can substitute their energy use towards electric power, which tends to be less carbon intensive.

5.1 Equilibrium energy use

We first show how the retail electricity price and the equilibrium quantity of electric power and fossil fuel consumption changed in pilot ETS provinces. The first two columns in Figure 2 show DID estimates with 95% confidence intervals at the province level, i.e., the β_1 and β_2 coefficients in equation (1).[19]

Given the price regulation in China, the lack of pass-through of the cost of carbon credits in retail prices is not surprising. However, even though residential consumers are not under the ETS and retail prices did not change, we observe a significant drop in power consumption. The city-ETS effects for power consumption by residents or industry are omitted in the first two columns because the parallel trend assumption does not hold. Already before the pilots start, power consumption is growing less rapidly in city-ETS compared to control provinces. The absolute-cap emissions regulation was only imposed on the richest province-level cities, while all other provinces are catching up in electricity

[19]Point estimates and standard errors for all coefficients shown in Figures 2, 3, and 4 are in the Online Appendix.

consumption over the sample period. There simply do not exist appropriate controls in China. This problem is limited to total power consumption estimated at the province level, no other variable that we consider shows a pre-trend (Figure A.2 in the Online Appendix).

The negative effect for residential consumers in prov-ETS is more puzzling. Here the parallel trend assumption is satisfied and there is no ETS-related reason why consumers should cut back on their electricity consumption. Somehow, they still seem to face such incentives, possibly because of the publicity given to the ETS pilots or because power companies that are subject to intensity regulation find ways to limit electricity consumption. The lack of significant effect on fossil-fuel consumption by retail consumers, mostly used for heating, is as expected as this also does not fall under the ETS.

In contrast, industrial firms require carbon credits for both their direct and indirect emissions. Even though their retail electricity price is also regulated, we find a positive coefficient of 4.5% in city-ETS. This price increase relative to control provinces is driven by the 'coal-electricity price linkage mechanism' discussed earlier and not by the cost of carbon credits.[20] The latter is an additional cost for industrial firms which ranged from 0.3% to 9.5% of the retail cost of electricity, averaging 2.7% over all pilots and years. We estimate a significant reduction in power consumption of -0.252 log points (-22%) in city-ETS, but the parallel trend assumption is also here violated. The increase in power consumption we find in prov-ETS is unexpected and explained below. The estimated decline in fossil fuel consumption is in line with ETS incentives. It is twice as high in city-ETS than in prov-ETS, at -27% and -14%, and statistically significant.

We confirm the effects for the industrial sector with a firm-level analysis, estimates are shown in the third column of Figure 2. It has the advantage of focusing on within-firm changes. The province-year and industry-year FE control for confounding factors and absorb the pre-trend differences between city-ETS and control provinces. Point estimates for power consumption have the same sign as before, but are larger in absolute value, suggesting that smaller energy users see larger adjustments. Power consumption in prov-ETS is again estimated to increase. The point estimates on the reductions in fossil fuel consumption are almost identical at the province and firm level.

[20]Starting in 2017, some firms negotiated power delivery contracts directly with generators. These prices could fluctuate with the cost of carbon, but they are not observed.

5.2 Adjustments in energy demand

As regulated firms respond to a higher cost of carbon, they can reduce their energy demand in several ways, some substitutions are intended and desirable, while other adjustments represent carbon leakage that displace emissions, but not reduce them.

One adjustment that policymakers in developing countries are concerned about is firms reducing output. In principle, this only affects firms in city-ETS with an absolute emissions cap, as the intensity-regulation in prov-ETS is specifically designed to avoid this incentive. Controlling for firm output in the previous firm-level regressions leads to virtually identical point estimates for both types of ETS.

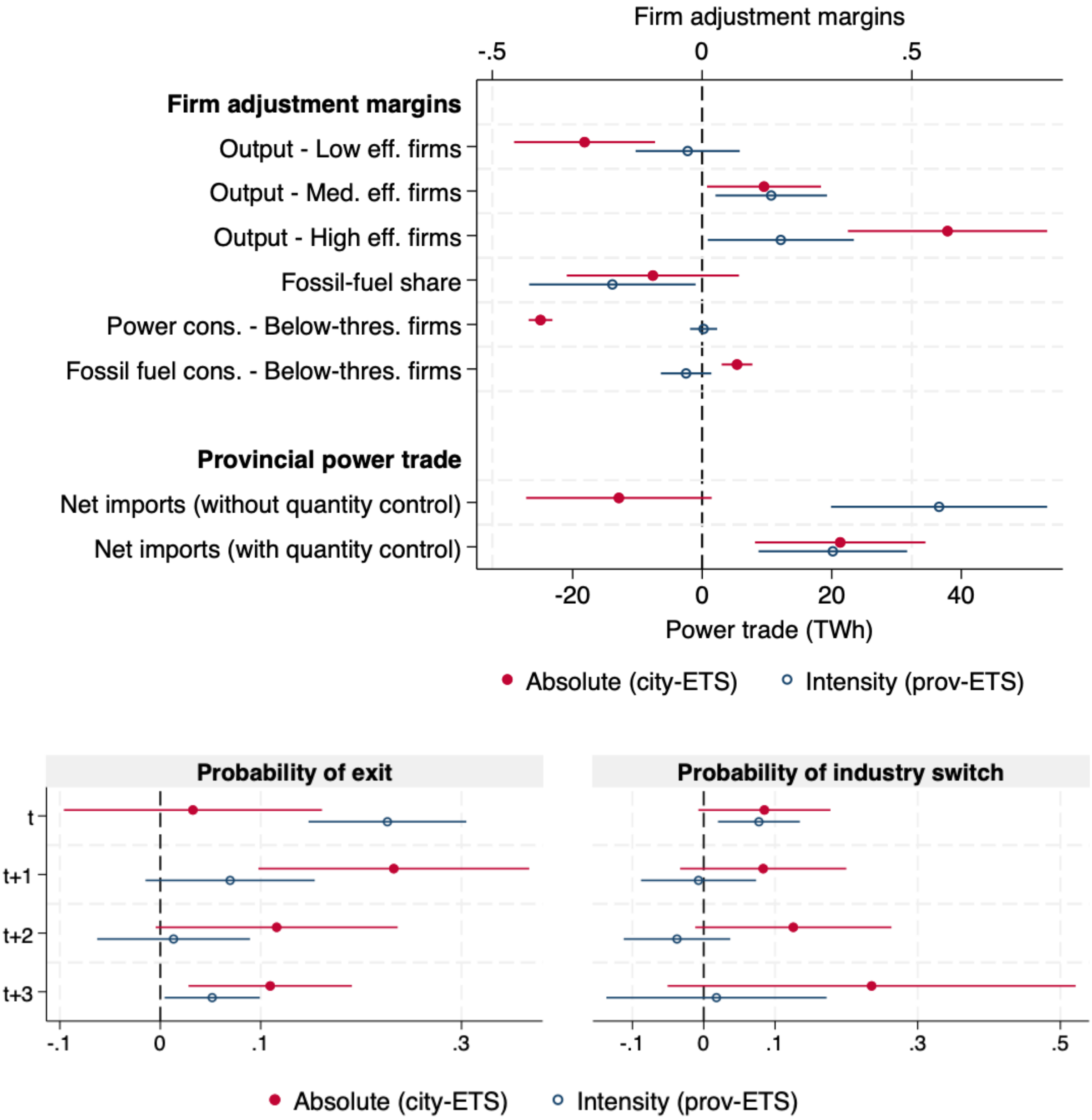
A more direct way to verify an effect is to use firm-level output directly as dependent variable. Coefficients on both types of ETS are estimated close to zero and insignificant. The pattern is more interesting when we interact the ETS dummies with indicators whether a firm is in the bottom, middle, or top tercile of the energy efficiency distribution in its industry. Output is clearly reallocated towards more energy-efficient firms, especially in the city-ETS. This shift reduces overall energy demand.

A second effect that operates in both types of ETS is to encourage and accelerate the ongoing shift in energy use by industrial firms from burning fossil fuels themselves towards purchasing electric power from utilities. Firms in the Chinese pilots need to acquire carbon certificates themselves for both inputs, while the carbon cost per unit of energy is lower for electricity. The point estimates in Figure 3 show firms reducing the share of fossil fuel in total energy use. This adjustment is especially pronounced in prov-ETS and is one reason why total power consumption increased. The point estimate has the same sign, but is not statistically significant, in the more developed city-ETS where the structural transformation towards the service sector and high-tech manufacturing happened earlier.

Regulated firms can also reduce their energy demand by changing the products they make and switching to a less energy-intensive industry. They can even exit and stop producing altogether. We start from the sample of above-threshold firms active in 2012 and define two sets of dummies. The 'exit indicators' take a value of one if a firm is no longer in the sample in year t. The 'industry switch indicators' take a value of one in year t if a firm reports a different industry than in year $t-1$. To estimate such a between-firm effect, we omit the firm FE and estimate four cross-sectional regressions, starting from the first year of carbon trading.

We find significantly elevated rates of exit, although the difference with control provinces declines over time. Firms that eventually exit, leave the sample several years

Figure 3: Adjustments in energy demand



Notes: Coefficient estimates from separate regressions with 95% confidence intervals.

sooner in ETS provinces. Three years after the start of the ETS, the likelihood of leaving the sample is 12 to 13 percentage points higher. Because the dataset is a survey and not a census, firms can disappear for various reasons, not only because of economic exit, but that is true in both ETS and control provinces. An alternative explanation for the systematic differences in exit from the sample would be firm relocation outside of the ETS. In that case, these effects represent no reduction in emissions, but merely a displacement.

Firms in ETS provinces are somewhat more likely to switch industry as well, but the pattern is more erratic. In principle, this incentive is limited to city-ETS where absolute emissions are capped. The effect in prov-ETS is indeed limited to the first year of their operation and industry switching is more common in city-ETS. Effects grow over time, but are estimated imprecisely.

The last two dependent variables in the top graph of Figure 3 capture carbon leakage, i.e., unintended effects that merely displace emissions to unregulated entities. Large energy users in city-ETS might deliberately shift output and the corresponding energy demand to unregulated firms, for example, to below-threshold affiliates in the same province (He and Chen, 2023). Such a shift might happen naturally as regulated firms reduce output or refrain from expanding output in a growing economy and below-threshold firms fill this vacuum. We find no evidence for this in the intensity-regulated prov-ETS, consistent with the lack of incentives for output reduction. In contrast, we find an increase in fossil fuel consumption by below-threshold firms in city-ETS. At -9.2% it is not negligible, but small relative to the 31.3% reduction estimated for above-threshold firms which, by definition, account for most energy use. The most likely interpretation for the estimated reduction in power consumption of below-threshold firms is a continuation of a pre-existing trend, which we also found at the provincial level.

A final way to reduce local emissions is by importing power from unregulated provinces. We investigate this possibility using net imports (exports minus imports) into each province as dependent variable. We use the level, not the logarithm, because this variable is often negative. ETS imports risk affecting control provinces which would violate the 'non-interference' assumption (Rubin, 1980). However, most imports originate not from neighboring control provinces, but from Western or Southwestern provinces with abundant renewable energy.

The results show higher imports in prov-ETS, but lower imports in city-ETS provinces even though the incentives are stronger in city-ETS. However, the point estimates become indistinguishable once we control for total provincial power consumption, which increased in prov-ETS and fell in city-ETS. In both cases, net imports—relative to the amount of power needed—strongly increase. Event study results indicate that there are no pre-trends and that it takes a few years for net imports to increase, in line with the practice of negotiating electricity transmission agreements one year in advance.

Higher net imports simply reallocate power generation and carbon emissions out of the regulated provinces. It weakens the carbon-reducing effects of the ETS policy, but there are a few positive dimensions. First, it illustrates that the ETS influence behavior, even though electricity dispatch is not market-driven. Second, it moves important sources of pollution out of densely-populated areas, conferring health benefits. Third, it provides incentives to invest in long-distance transmission infrastructure, which is necessary to bring electricity generated from clean power sources in remote provinces to population centra. In many countries, the transmission infrastructure has become a more important bottleneck than clean generation capacity.[21] Finally, this type of carbon leakage disappeared automatically when the national carbon market was introduced in 2021 and all provinces became regulated.

5.3 Adjustments in electricity generation mix

The lack of a competitive wholesale market in China means that there is no clear mechanism for more-polluting power producers to move down in the dispatch merit order. Power supply is assigned in relatively opaque ways by the monopoly grid operator (Ren et al., 2021) and the reallocation of operating hours is subject to government control. Only if local authorities in ETS provinces give priority to cleaner power sources in the dispatch will the composition of power supplied to the grid change.

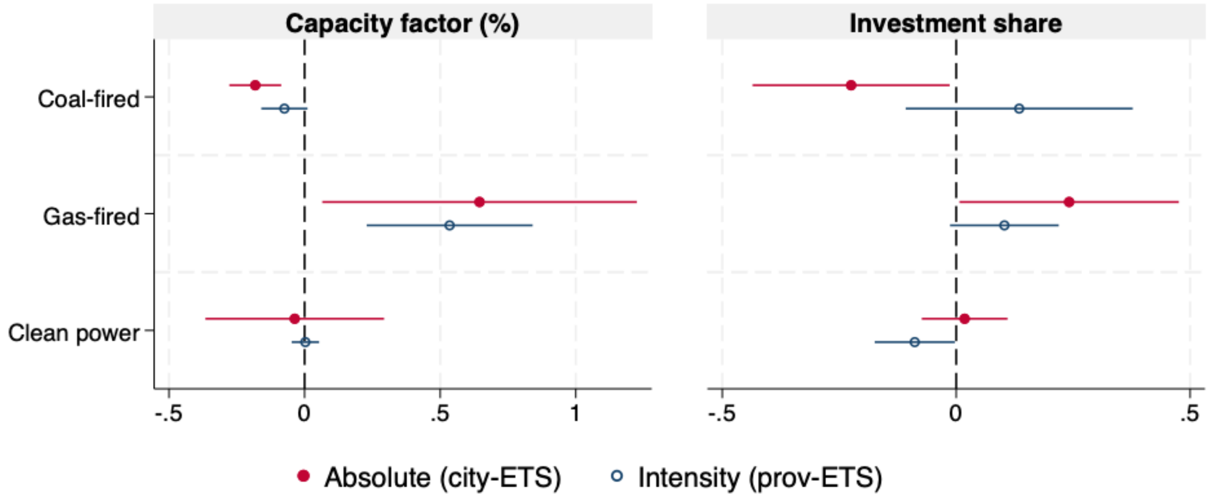
To investigate this, we use the logarithm of the capacity factor as dependent variable. This is the standard way of measuring capacity utilization in the industry and is defined as the ratio of a plant's annual power generation to its rated output capacity times the maximum number of operating hours. As explanatory variables of interest, we interact the ETS dummy with three fuel-type dummies for different generation technologies: coal, gas, and clean, which combines the renewable sources of energy (hydro, solar, and wind).[22]

Results in the first column of Figure 4 indicate that grid operators in ETS pilots are more likely to dispatch gas-fired plants and less likely to rely on coal-fired units. The

[21] See, for example, https://www.economist.com/united-states/2023/01/29/america-needs-a-new-environmentalism.

[22] Plant FE absorb any province-by-fuel-type effects.

Figure 4: Effects of ETS on power generation plants



Notes: Coefficient estimates and 95% confidence intervals from one regression for each dependent variable.

effects on the gas-fired plants—which account for a much smaller share of total generation than coal—is very large, especially in city-ETS. Recall that power generation is intensity-regulated in all pilots, but the grid operator has more flexibility to exercise discretion in city-ETS where total power consumption and average capacity utilization falls.

The capacity factor of clean power units shows no difference between regulated and unregulated provinces. That is also expected. The 'energy conservation rule' in power dispatch stipulates that clean power should always get priority on the grid, even in non-ETS provinces. There should be no room for differential treatment of clean power, and that seems to bear out.

In the long run, further adjustments require changing the composition of available generation capacity. Total energy demand in China is still growing and continuous investments are needed. An ETS provides stronger incentives to invest in clean power sources, but all investments are subject to approval by both local and central authorities. The estimated coefficient will thus combine the effects on firms' investment intentions and authorities' regulatory approval. Because these do not always coincide (Ren et al., 2021), we use actual, not planned investments.

The unit of analysis is now a province-technology combination and we include fixed effects at this level. Because annual investments for a particular province-technology are often zero, we use the share of each technology in total investment as dependent variable.

For city-ETS, results mirror those for the capacity factor: significantly lower investments in coal-fired plants, higher for gas-fired plants, and an insignificant difference for clean power. Prov-ETS only show higher investments for gas-fired plants. The increased demand for electric power might again reduce the substitution flexibility, requiring all possible capacity additions, even in dirty coal plants.

Neither of the ETS show higher investments in clean power. The negative coefficient for the prov-ETS is not a reduction in clean power capacity, but only a slower pace of investment compared to the breakneck evolution of clean power capacity in some (control) provinces.

A possible explanation is that many ETS provinces are constrained in terms of suitable land and natural conditions to develop large-scale renewable energy projects. Investments in clean power are encouraged everywhere in China, and the moderate incentives provided by the ETS might not be sufficient to overcome a comparative disadvantage.

A second possibility is that firms in non-ETS provinces anticipate the 2021 national ETS. Investment decisions are inherently forward looking. The Chinese practice of experimenting with new policies may lead them to anticipate a nationwide roll-out. Even control observations are treated to some extent and our DID estimation strategy is ill-suited to study forward-looking investments.

6 Conclusions

We have examined how market participants in China respond to the pilot carbon ETS that were initiated in 2013 and 2014. Two unique aspects of our investigation are, first, the analysis of a wide range of adjustment margins along the energy value chain and, second, the co-existence of absolute and intensity-type emission regulations within the same energy market.

We find that almost all adjustments are in the expected direction, reducing energy consumption and prioritizing cleaner sources of energy. This is in spite of many agents not facing market incentives or maximizing a well-defined profit objective. Even adjustments of unregulated residential consumers or administrative decisions by local authorities tend to support the carbon abatement efforts in regulated provinces. It makes us suspect that the ETS indicators capture not only the direct effects of ETS incentives, but the broader governmental and regulatory support for carbon abatement (actual or perceived) that likely accompanied the ETS pilots. When considering possible lessons for other developing countries, it should be taken into account that the Chinese government exercises extensive control over the economy and its directions or stated policy objectives are likely to carry unusual weight for all market participants.

We further showed that, on most dimensions, responses are most pronounced in city-ETS that face absolute-emission regulation. However, even in intensity-regulated prov-ETS, effects tend to go in the same direction and adjustments are of the same order of magnitude. The main anticipated difference in effects between the two types of regulation, namely a greater output disincentive in city-ETS, did not materialize. This is promising for developing countries which want to gradually reduce their carbon emissions, but are mindful of the economic costs involved. One caveat is that the weaker effects in prov-ETS versus city-ETS are in spite of greater scope for carbon abatement in these less-developed economies. The difference in effects for the two types of regulation might be partly muted because of different starting points.

Our analysis also shows several instances of carbon leakage. This might be a desirable design feature as it provides a temporary escape valve for firms and industries with limited substitution possibilities. The later expansion to a national ETS automatically closed some of the initial loopholes. In the meantime, starting pilot ETS in more developed and more densely-populated areas shifted pollution out of major cities, shifted energy demand to regions with more vacant land, and incentivized the constructing of long-distance transmission infrastructure. All of these adjustment mechanisms are especially valuable for regions which are ill-endowed to deploy clean-energy technologies locally.

References

Bushnell, James B., Howard Chong, and Erin T. Mansur, "Profiting from Regulation: Evidence from the European Carbon Market," *American Economic Journal: Economic Policy*, 2013, *5* (4), 78–106.

Cao, Jing, Mun S. Ho, Rong Ma, and Fei Teng, "When Carbon Emission Trading Meets a Regulated Industry: Evidence from the Electricity Sector of China," *Journal of Public Economics*, 2021, *200*, 104470.

Chen, Qiaoyi, Zhao Chen, Zhikuo Liu, Juan Carlos Suárez Serrato, and Daniel Yi Xu, "Regulating Conglomerates: Evidence from an Energy Conservation Program in China," *American Economic Review*, 2025, *115* (2), 408–447.

Cicala, Steve, "Imperfect Markets versus Imperfect Regulation in US Electricity Generation," *American Economic Review*, 2022, *112* (2), 409–41.

Cui, Jingbo, Chunhua Wang, Junjie Zhang, and Yang Zheng, "The Effectiveness of China's Regional Carbon Market Pilots in Reducing Firm Emissions," *Proceedings of the National Academy of Sciences*, 2021, *118* (52), e2109912118.

Fabra, Natalia and Mar Reguant, "Pass-through of Emissions Costs in Electricity Markets," *American Economic Review*, 2014, *104* (9), 2872–2899.

Fan, Ying, Jie Wu, Yan Xia, and Jing-Yu Liu, "How Will a Nationwide Carbon Market Affect Regional Economies and Efficiency of CO2 Emission Reduction in China?," *China Economic Review*, 2016, *38*, 151–166.

Fowlie, Meredith, "Incomplete Environmental Regulation, Imperfect Competition, and Emissions Leakage," *American Economic Journal: Economic Policy*, 2009, *1* (2), 72–112.

_ , Mar Reguant, and Stephen P. Ryan, "Market-based Emissions Regulation and Industry Dynamics," *Journal of Political Economy*, 2016, *124* (1), 249–302.

Gao, Hang and Johannes Van Biesebroeck, "Effects of Deregulation and Vertical Unbundling on the Performance of China's Electricity Generation Sector," *Journal of Industrial Economics*, 2014, *62* (1), 41–76.

Goulder, Lawrence H., Xianling Long, Chenfei Qu, and Da Zhang, "China's Nationwide CO2 Emissions Trading System: A general Equilibrium Assessment," *American Economic Journal: Economic Policy*, 2025, *forthcoming.*

_ , _ , Jieyi Lu, and Richard D. Morgenstern, "China's Unconventional Nationwide CO2 Emissions Trading System: Cost-effectiveness and Distributional Impacts," *Journal of Environmental Economics and Management*, 2022, *111*, 102561.

Greenstone, Michael, "The Impacts of Environmental Regulations on Industrial Activity: Evidence from the 1970 and 1977 Clean Air Act Amendments and the Census of Manufactures," *Journal of Political Economy*, 2002, *110* (6), 1175–1219.

He, Guojun, Shaoda Wang, and Bing Zhang, "Watering Down Environmental Regulation in China," *Quarterly Journal of Economics*, 2020, *135* (4), 2135–2185.

He, Ling-Yun and Kun-Xian Chen, "Does China's Regional Emission Trading Scheme Lead to Carbon Leakage? Evidence from Conglomerates," *Energy Policy*, 2023, *175*, 113481.

Ho, Mun S., Zhongmin Wang, and Zichao Yu, "China's power generation dispatch," 2017. Resources for the Future (RFF): Washington, DC.

Kahrl, Fredrich, James H. Williams, and Junfeng Hu, "The political economy of electricity dispatch reform in China," *Energy Policy*, 2013, *53*, 361–369.

Li, Hong-Zhou, Xian-Liang Tian, and Tao Zou, "Impact analysis of coal-electricity pricing linkage scheme in China based on stochastic frontier cost function," *Applied Energy*, 2015, *151*, 296–305.

Ren, Mengjia, Lee G. Branstetter, Brian K. Kovak, Daniel Erian Armanios, and Jiahai Yuan, "Why Has China Overinvested in Coal Power?," *Energy Journal*, 2021, *42* (2), 113–133.

Rubin, Donald B., "Randomization Analysis of Experimental Data: The Fisher Randomization Test. Comment," *Journal of the American Statistical Association*, 1980, *75* (371), 591–593.

Salant, Stephen W., "What Ails the European Union's Emissions Trading System?," *Journal of Environmental Economics and Management*, 2016, *80*, 6–19.

Shapiro, Joseph S. and Reed Walker, "Why is Pollution from US Manufacturing Declining? The Roles of Environmental Regulation, Productivity, and Trade," *American Economic Review*, 2018, *108* (12), 3814–3854.

Walker, W Reed, "The Transitional Costs of Sectoral Reallocation: Evidence from the Clean Air Act and the Workforce," *Quarterly Journal of Economics*, 2013, *128* (4), 1787–1835.

Wang, Shaoda and David Y. Yang, "Policy Experimentation in China: The Political Economy of Policy Learning," *Journal of Political Economy*, 2025, *133* (7), 2180–2228.

Zhang, Junjie, Zhenxuan Wang, and Xinming Du, "Lessons Learned from China's Regional Carbon Market Pilots," *Economics of Energy & Environmental Policy*, 2017, *6* (2), 19–38.

Zheng, Xuemei, Flavio Menezes, and Rabindra Nepal, "In between the state and the market: An empirical assessment of the early achievements of China's 2015 electricity reform," *Energy Economics*, 2021, *93*, 105003.

Online Appendix

Table A.1 shows the energy consumption thresholds that are used in the different ETS pilots to define regulated firms. For consistency, we apply a uniform threshold of 10,000 tons (of standard coal equivalent) on the pre-ETS period 2009-2012 to classify firms as regulated or not, and we use the same threshold to define a control group of firms in non-ETS provinces.

Table A.1: Total energy consumption thresholds for inclusion in the ETS pilots

ETS pilot	Established	Threshold of total energy consumption (tons of standard coal)
Beijing	Nov. 2013	>5,000 tons (2013-2014)
		>2,500 tons (from 2015 onward)
Shanghai	Nov. 2013	> 10,000 tons
Tianjin	Dec. 2013	> 10,000 tons
Guangdong	Dec. 2013	> 10,000 tons
Hubei	Apr. 2014	> 60,000 tons
Chongqing	Jun. 2014	> 10,000 tons

Notes: Chongqing is the only ETS pilot that includes other greenhouse gases than CO_2 emissions. It stipulates a threshold of CO_2 equivalent of 20,000 tons, which is much higher than the corresponding standard coal equivalent threshold of 5,000 tons.

Table A.2 shows the average carbon intensity for the six regional power grids in China for 2012. Differences are mostly due to different compositions of generation capacity, in particular the importance of hydro and clean sources of power (wind and solar). These averages decline gradually over time. When firms count indirect emissions coming from their electricity consumption, they need to use the applicable factor based on their location.

Table A.2: Average emission factors of China's regional power grids

Regional power grids	Emission factor (kg CO_2/kWh)
Northern	0.884
Northeastern	0.777
Eastern	0.704
Northwestern	0.667
Southern	0.527
Central	0.526

Source: National Development and Reform Commission, data for 2012.

Table A.3 presents summary statistics for the sample of industrial firms. It shows that energy input consumption by above-threshold firms is on average more than twenty times as high as for below-threshold firms. They are also considerably more energy intensive, as they only show a five-fold (average) difference for output.

Table A.3: Summary statistics on the sample of industrial firms

	All Firms	**Above-threshold**	**Below-threshold**
Electricity use	3,072	28,801	2,053
(MWh)	(10,021)	(29,309)	(5,076)
Fossil fuel use	750	9,838	295
(ton)	(4,288)	(12,845)	(1,315)
Composite energy use	1,504	17,057	790
(ton)	(5,430)	(13,949)	(1,921)
Output	76	327	66
(million RMB)	(188)	(390)	(156)
Observations	1,212,742	42,122	884,628

Notes: Electricity use is converted into 'standard coal equivalence' to calculate the composite energy use. The statistics represent unweighted means and standard deviations in parentheses.

Table A.4 presents summary statistics for the sample of power plants, shown separately by fuel type.[23] Fossil fuel-fired power plants still dominate the sector in terms of installed capacity and even more so in terms of power generated. Clean power, in particular solar and wind power, tends to have lower operating hours compared to thermal power, due to the intermittent nature of their operation.

Table A.4: Summary statistics on the sample of power plants

	Hydro	**Coal-fired**	**Gas-fired**	**Solar & Wind**
Capacity	50	358	309	59
(MW)	(107)	(517)	(393)	(64)
Power generation	162	1,649	796	92
(GWh)	(335)	(2,494)	(1,156)	(130)
Operating hours	3,503	4,406	3,256	1,589
(Hours)	(1,516)	(1,948)	(2,083)	(851)
Observations	22,233	18,198	1,191	15,139

Notes: The sample includes all power plants with a generation capacity above 6 MW. The statistics are unweighted means and standard deviations in parentheses.

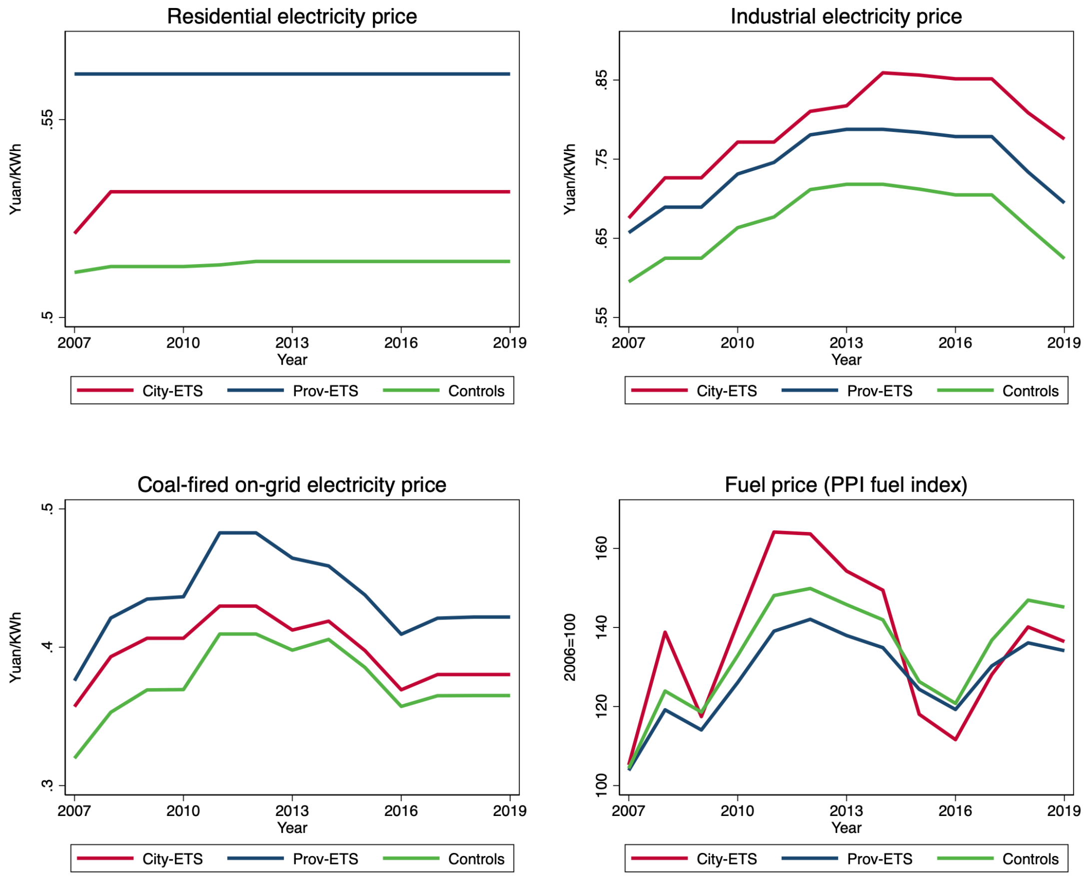
The two graphs in the top row of Figure A.1 show the evolution of the base retail electricity price, i.e., for the first block of power consumption, for residential and small

[23] Nuclear power plants, biomass power plants, garbage power plants, and pumped-storage power plants are omitted. With the exception of nuclear power plants, which are regulated entirely differently, they account for only a trivial portion of total electricity generation.

industrial consumers. The three lines show the average prices in the different types of provinces: intensity-regulated prov-ETS (in blue), absolute-cap regulated city-ETS (in red), and control provinces (in green). The bottom-left graph shows the evolution of the on-grid, wholesale price that coal-fired power plants receive. The bottom-right graph shows the evolution of the price of coal, averaged over domestically mined and imported coal.

Through the 'coal-electricity price linkage mechanism' that the NRDC uses to regulate on-grid prices, coal price fluctuations are transmitted with a lag and with a reduced amplitude into the wholesale prices that generators receive. In turn, the retail electricity price for industrial consumers follows the on-grid price with another lag and a further reduced amplitude. For example, in the control provinces, the coal price increased by more than 40% between 2007 and 2011, while the on-grid price increased by only 25%. The industrial retail price increased by 18% and it took two more years to reach the new level, even longer in prov-ETS or city-ETS. The smoothing-out of the coal price fluctuations into wholesale and retail prices is even more apparent over the 2012-2019 period.

Figure A.1: Evolution of various electricity and input prices



Source: NDRC annual reports.

Results in Table A.5 correspond to those shown in Figure 2 in the main text.

To interpret the DID results causally, we check for differences in pre-trends between treatment and control provinces. Figure A.2 contains a separate graph for all province-level effects shown in panels A and B of Table A.5 that distinguish by ETS type.[24] We normalize energy use in the year before implementation (indicated by -1) to zero and there is no point estimate in that year. Carbon trading and verification started in 2013 (for four provinces) or 2014 (two provinces). The pilot ETS policy was first announced by the NDRC in October 2011, but there do not seem to be any announcement effects in years -2 or -3. The reduction in electric power use by residential consumers in both prov-ETS and city-ETS is clearly visible. The opposing changes in the two types of ETS for electric power use by industrial consumers also shows up clearly.

However, in the two city-ETS graphs, there already is a negative pre-trend in the initial years of the sample period. For residential consumers it starts in 2010, one year before the announcement and three years before the launch of the pilots. For industrial consumers it spans the entire pre-treatment period. This pattern requires caution in interpreting the results in city-ETS provinces. We experimented with several alternative time-interaction fixed effects, but the pre-trends always show up. It seems that there simply is no good control group in China for the highly developed, provincial-level cities.

It is no surprise that the government chose these jurisdictions for the absolute-emission regulation. They are the only ones in China with a sufficiently well-developed economy for such stringent form of environmental regulation. It implies, however, that the large reduction in power consumption in these provinces cannot be interpreted as a causal effect, i.e., as a prediction of the policy's effects if it would be implemented in a random province. Rather, the point estimates need to be interpreted as the joint effect of the absolute-emission regulation when applied specifically to these more developed provinces, that were already undergoing a structural transformation to less energy-intensive industries and where the housing stock is being upgraded to more energy-efficient buildings.

In contrast, there are no pre-trends in any of the four graphs for fossil fuel use. None of the pre-treatment coefficients is ever significantly different from zero. Fossil fuel use by industrial consumers in city-ETS show a negative trend in the first 2-3 years of the sample period, but this is estimated very imprecisely and the effect is no longer discernable in the years before the ETS are implemented.

[24] Data on residential fossil fuel use is missing in 2007, hence the graphs on the right of panel A show one year less in the pre-treatment period.

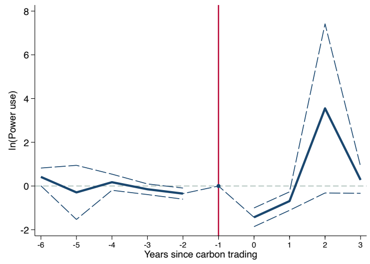
Table A.5: Effects of pilot ETS on electricity prices and equilibrium energy consumption

	Electricity price		Electricity consumption		Fossil fuel consumption	
A. Residential						
D_{pt}	0.001		-0.135***		0.012	
	(0.002)		(0.016)		(0.041)	
D_{pt} × Prov-ETS$_p$		0.003**		-0.110***		-0.054
		(0.001)		(0.021)		(0.054)
D_{pt} × City-ETS$_p$		-0.002		-0.162***		0.085
		(0.004)		(0.022)		(0.057)
Observations	390	390	390	390	390	390
B. Industrial (prov. level)						
D_{pt}	0.017***		-0.091***		-0.232***	
	(0.006)		(0.031)		(0.051)	
D_{pt} × Prov-ETS$_p$		-0.008		0.058**		-0.156***
		(0.007)		(0.029)		(0.046)
D_{pt} × City-ETS$_p$		0.045***		-0.252***		-0.314***
		(0.008)		(0.046)		(0.090)
Observations	390	390	390	390	390	390
C. Industrial (firm level)						
D_{pt}			-0.368***		-0.274***	
			(0.099)		(0.105)	
D_{pt} × Prov-ETS$_p$				0.368***		-0.155
				(0.099)		(0.153)
D_{pt} × City-ETS$_p$				-0.997***		-0.376***
				(0.161)		(0.135)
Observations			37,840	37,840	33,808	33,808
D. Industrial, with output control (firm level)						
D_{pt}			-0.375***		-0.266**	
			(0.099)		(0.104)	
D_{pt} × Prov-ETS$_p$				0.374***		-0.155
				(0.096)		(0.150)
D_{pt} × City-ETS$_p$				-1.014***		-0.360***
				(0.161)		(0.134)
Observations			37,840	37,840	33,808	33,808

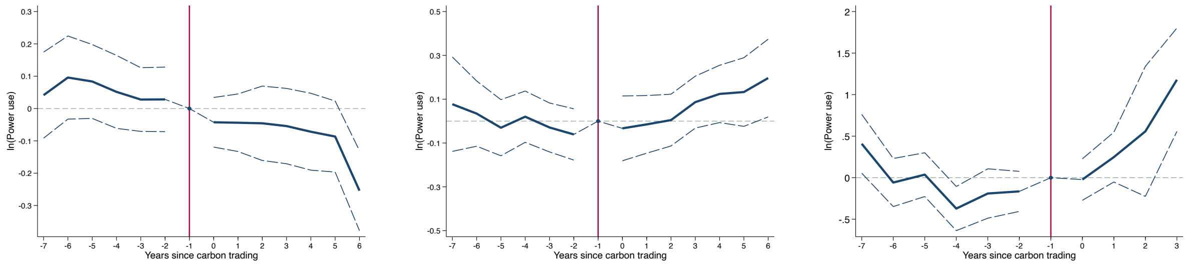
Notes: All dependent variables are in logarithms. Controls variables included, but not reported, are provincial per capita GDP, total capacity of power generation, total capacity of high-voltage power transmission lines, and province, region-year, and regional power grid-year interaction fixed effects. Robust standard errors in parentheses. In the firm-level regressions in panel C, 2-digit industry fixed effects are included and in panel D firm-level output as well. Standard errors are clustered at the firm level; significance levels are *** p<0.01, ** p<0.05, * p<0.1

Figure A.2: Event studies for changes in energy consumption

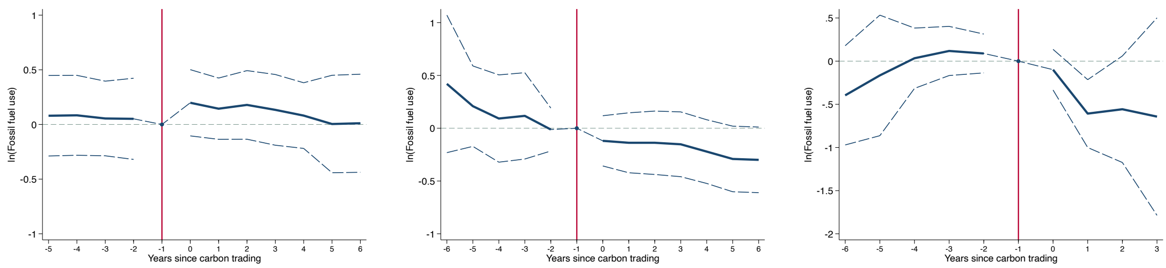
A. Power consumption city-ETS



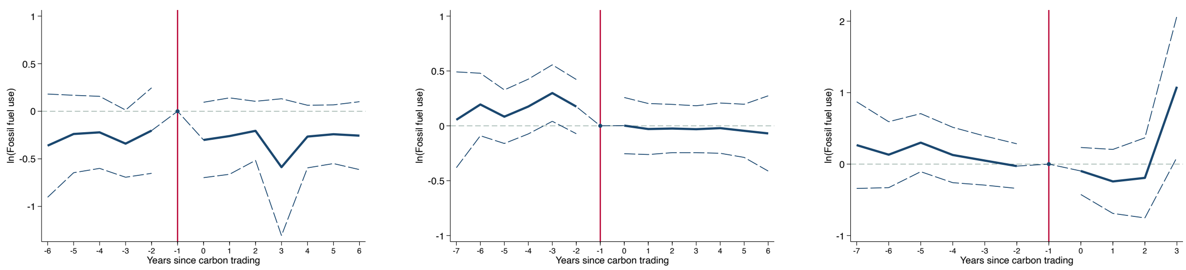
B. Power consumption prov-ETS



C. Fossil fuel consumption city-ETS



D. Fossil fuel consumption prov-ETS



(a) Residential (b) Industrial (prov. level) (c) Industrial (firm level)

Notes: The year before the implementation of the pilot ETS policy is normalized to zero and has no confidence intervals. The vertical red line indicates the start of carbon trading. Dashed lines are 95% confidence intervals.

Two more patterns are notable as well. First, the positive effect on electric power use by industrial consumers in prov-ETS is definitely not the continuation of a pre-existing trend. The patterns starts exactly when the ETS are implemented and gradually builds over time. Single-year effects become statistically significant in the last years of the sample period. Second, most of the negative effects of carbon trading on energy use take a few years to materialize. The three negative effects on electricity use, in the first, second, and fourth graphs of Figure A.2 grow gradually over time. The most pronounced negative effect on fossil fuel use, in the fourth graph of Figure A.2, also builds gradually over time. As a result, the point estimates in Table A.5 underestimate the long-term ETS effect.

Results in the following tables correspond to those shown in Figure 3 and 4 in the main text.

Table A.6: Effects of pilot ETS: Firm-level adjustment margins

(a) Effect on firm-level output

	(log) output		
D_{pt}	0.001		
	(0.046)		
$D_{pt} \times$ Prov-ETS$_p$		0.037	
		(0.061)	
$D_{pt} \times$ Prov-ETS$_p \times$ *Eff*$(t1)$			-0.034
			(0.063)
$D_{pt} \times$ Prov-ETS$_p \times$ *Eff*$(t2)$			0.165**
			(0.068)
$D_{pt} \times$ Prov-ETS$_p \times$ *Eff*$(t3)$			0.188**
			(0.089)
$D_{pt} \times$ City-ETS$_p$		-0.028	
		(0.062)	
$D_{pt} \times$ City-ETS$_p \times$ *Eff*$(t1)$			-0.280***
			(0.086)
$D_{pt} \times$ City-ETS$_p \times$ *Eff*$(t2)$			0.148**
			(0.069)
$D_{pt} \times$ City-ETS$_p \times$ *Eff*$(t3)$			0.585***
			(0.121)
Observations	40,415	40,415	40,415

(b) Effect on energy input mix

	(log) share of fossil fuel	
D_{pt}	-0.162**	
	(0.076)	
$D_{pt} \times$ Prov-ETS$_p$		-0.214**
		(0.101)
$D_{pt} \times$ City-ETS$_p$		-0.117
		(0.105)
Observations	33,808	33,808

Notes: The sample is limited to firms with input use above the ETS-threshold. *Eff*$(t1)$ is an indicator variable for firms in the lowest tercile of the energy-to-output distribution in its industry, and similarly for $t2$ and $t3$. Control variables included, but not reported, are provincial per capita GDP, total capacity of power generation, total capacity of high-voltage power transmission lines, and firm, 2-digit industry by year, region by year, and regional power grid by year fixed effects. Standard errors are clustered at the firm level; significance levels are *** p<0.01, ** p<0.05, * p<0.1

Table A.7: Effects of pilot ETS on probability of exit or industry switching

	Exit before end of year t				Industry switch between $t-1$ and t			
$t =$	τ^*	τ^*+1	τ^*+2	τ^*+3	τ^*	τ^*+1	τ^*+2	τ^*+3
$D_p \times$ Prov-ETS$_p$	0.226***	0.070	0.013	0.052**	0.077***	-0.007	-0.038	0.018
	(0.040)	(0.043)	(0.039)	(0.024)	(0.029)	(0.041)	(0.038)	(0.079)
$D_p \times$ City-ETS$_p$	0.032	0.233***	0.116*	0.109***	0.085*	0.083	0.126*	0.235
	(0.066)	(0.069)	(0.061)	(0.042)	(0.047)	(0.059)	(0.070)	(0.146)
Observations	6,406	6,406	6,406	6,406	5,063	3,260	1,985	1,018

Notes: The first year of the ETS pilot is denoted by τ^*. The sample in the first four columns is the same: above-scale industrial firms active in 2012. The sample in the last four columns is based on the above-threshold firms active in year t which declines over time. The same control variables as in Table A.6 are included, except for the firm fixed effects, but not reported. Standard errors are clustered at the firm level; significance levels are *** p<0.01, ** p<0.05, * p<0.1

Table A.8: Effects of ETS: Carbon leakage

(a) Spillover effects on energy consumption of exempt firms

	Electricity		Fossil fuel	
D_{pt}	-0.251***		0.044***	
	(0.011)		(0.017)	
$D_{pt} \times$ Prov-ETS$_p$		0.004		-0.038
		(0.016)		(0.031)
$D_{pt} \times$ City-ETS$_p$		-0.385***		0.083***
		(0.014)		(0.019)
Observations	720,001	720,001	437,346	437,346

(b) Interprovincial electricity trade

	Net imports		Net Imports	
D_{pt}	17.914***		20.590***	
	(6.522)		(4.532)	
$D_{pt} \times$ Prov-ETS$_p$		36.575***		20.168***
		(8.476)		(5.827)
$D_{pt} \times$ City-ETS$_p$		-12.862*		21.311***
		(7.272)		(6.682)
Output control			✓	✓
Observations	390	390	390	390

Notes: In panel (a), the dependent variable is in logarithms, the sample is limited to exempt firms with energy input use below the ETS-threshold, and control variables are the same as in Table A.6. Standard errors are clustered at the firm level. In panel (b), the dependent variable is in levels (TWh), and the same control variables as in Table A.5 are included, but not reported. Robust standard errors in parentheses; significance levels are *** p<0.01, ** p<0.05, * p<0.1

Table A.9: Effects of pilot ETS on power dispatch and investment

	Capacity factor (%)		Investment share (%)		Investment (TWh)
$D \times$ Coal	-0.107***		-0.044		
	(0.035)		(0.091)		
$D \times$ Coal $\times$ Prov-ETS$_p$		-0.074*		0.135	-307.8
		(0.043)		(0.124)	(502.4)
$D \times$ Coal $\times$ City-ETS$_p$		-0.182***		-0.225**	-101.0
		(0.049)		(0.107)	(341.2)
$D \times$ Gas	0.589***		0.170**		
	(0.188)		(0.066)		
$D \times$ Gas $\times$ Prov-ETS$_p$		0.535***		0.103*	394.2
		(0.156)		(0.059)	(244.4)
$D \times$ Gas $\times$ City-ETS$_p$		0.645**		0.242**	278.2
		(0.296)		(0.120)	(275.1)
$D \times$ Clean	-0.002		-0.038		
	(0.026)		(0.035)		
$D \times$ Clean $\times$ Prov-ETS$_p$		0.003		-0.089**	-305.1**
		(0.026)		(0.044)	(153.9)
$D \times$ Clean $\times$ City-ETS$_p$		-0.036		0.018	-431.4***
		(0.168)		(0.047)	(147.5)
Plant FE	✓	✓			
Province-type FE			✓	✓	✓
Observations	52,061	52,061	1,800	1,800	1,800

Notes: In addition to the fixed effect indicated in the table, the same control variables as in Table A.5 are included, but not reported. In the first two columns, the sample consists of a panel of power plants, the dependent variable is in logarithms, and standard errors are clustered at the plant level. In the last three columns, the sample consists of province-fuel type combinations and the dependent variable is in shares or levels (last column). Robust standard errors in parentheses; significance levels are *** p<0.01, ** p<0.05, * p<0.1