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

Johannes Van Biesebroeck[†] Honghao Zheng[‡]

January 8, 2025

Click here for the latest version

Abstract

We study how economies with distinct development phases can preferably curtail emissions. We exploit unique variations of heterogeneous regulations—absolute- and intensity-type emission regulations in the context of carbon emission trading schemes (ETS) in China. Using an extensive array of rich data, we employ a difference-in-differences empirical strategy to examine the behaviors of all primary margins of adjustment to ETS from the demand to the supply side of energy. We find that, under imperfect markets and incomplete regulation, both types of ETS can induce carbon mitigation but with distinct tradeoffs. Aggregate impacts suggest overall annual reductions in energy consumption by 23% and 9% of yearly energy consumption in ETS with absolute- and intensity-type emission regulations, respectively.

Keywords: Carbon Market, Emission Trading Scheme, Intensity-type Emission Regulation.

JEL Codes: D22, L23, O14, O51, O56

*We thank Jan De Loecker, Sebastian Fleitas, Frank Verboven, and participants at IIOC 2023, EARIE 2023, APIOC 2023, BEED 2024, CEPR-NBB, RIDGE 2024, Kiel-Goettingen-CEPR and seminars at Copenhagen Business School, IMT Lucca, University of Glasgow, KU Leuven IO group for their valuable comments and suggestions. All errors are our own.

[†]KU Leuven, Naamsestraat 69, 3000 Leuven, Belgium. E-mail: jo.vanbiesebroeck@kuleuven.be

[‡]KU Leuven, Naamsestraat 69, 3000 Leuven, Belgium. E-mail: honghao.zheng@kuleuven.be

1 Introduction

The tradeoff between reducing carbon emissions and sustaining economic development lies at the focus when deliberate emission-reduction initiatives (Bushnell et al., 2013; Shapiro and Walker, 2018). Especially for developing countries, which would like to reduce CO_2 emissions while minimizing output loss. Two emission mitigation alternatives in developing countries have sparked considerable debate. One option is for developed countries to subsidize **absolute** emission reductions for developing counterparts.[1] Another solution is to regulate emission **intensity** instead of absolute emission in developing economies.[2]

China provides a unique setting for studying *both* absolute- and intensity-type emission regulations. From 2013 to 2014, China established seven regional pilot carbon emission trading schemes (ETS) including Beijing, Tianjin, Shanghai, and Shenzhen, i.e., *city ETS*s, which are comparable to developed economies, and also Guangdong, Hubei, and Chongqing, i.e., *province ETS*s, which are still under development.[3] The regional pilot ETSs had the discretion to design and adopt diverse policy specifications according to their industrial structures and resource endowments, etc.[4] In practice, all city ETSs capped *absolute* emissions hence limiting output proportionally, while province ETSs regulated emission *intensity* without restricting output, provided the targeting emission intensity is binding.[5] The discrepancy between the ETS policy adopted in regions with distinct development phases offers an exceptional window to investigate how diverse phase economies can mitigate emissions preferably.

However, two critical considerations are latent. First, the pass-through of the emission reduction policy into behavior could be imperfect. Energy markets, especially electricity generation sectors in developing countries, are often not perfectly competitive but are even highly regulated. The rigid nature of energy products also induces low demand and supply elasticities. Moreover, carbon leakages deriving from incomplete regulation further weaken the effectiveness of the ETS (Fowlie and Reguant, 2022). Hence, the pass-through of the policy signal can be hindered, leading to ineffective carbon mitigation.

Second, along the entire value chain of the electricity industry, various market participants could adjust differently to confront carbon trading. Industrial firms could either alter

[1]See, for example, https://www.oecd.org/newsroom/statement-from-oecd-secretary-general-mathias-cormann-on-climate-finance-in-2019.htm.

[2]See https://about.bnef.com/turner-the-case-for-intensity-based-targets-to-curb-climate-change.

[3]In 2021, the average per capita GDP of city and province ETSs is \$25,564 and \$13,270, respectively.

[4]China rolled out the ETS nationally in 2021 based on the experience drawn from the pilot ETSs. See Wang and Yang (2021) for a detailed overview of China's long-standing convention of conducting policy experimentation before a policy rolls out nationally.

[5]All pilot regions adopted intensity-type carbon emission regulations for power generation sectors. More details about China's power generation sectors in the pilot ETS regions will be discussed in Section 2.

their energy input allocation to reduce emissions or shift production to evade regulation (Cui et al., 2022; Chen et al., 2025). In contrast, local authorities in ETS regions could approve more investment in clean power or expand local renewable power dispatching and inter-provincial net power import. All these adjustments, intertwined in conjunction with each other, challenge the effectiveness of ETS. Looking at a single margin of adjustment to ETS would be partial.

We combine multiple rich data sources to comprehensively analyze the impacts of the pilot carbon ETS policy on various outcomes along the electricity value chain. The datasets include both provincial- and firm-level energy consumption information, e.g., use of power and fossil fuels, etc., and supply-side data on electricity generation and trade. We employ a difference-in-differences (DiD) empirical strategy to examine the behaviors of all primary margins of adjustment to ETS, from energy consumption to power supply, at various dimensions. The provincial-level DiD analysis estimates the effects on residential and industrial energy consumption, interprovincial trade, and capacity investment. While we further implement firm-level examinations to study industrial firms' energy mixes and motives to circumvent regulation. Also, power plant-level analysis is employed to investigate the impact of ETS on power generation dispatch by fuel type.

We find remarkably consistent effects in the expected directions on most dimensions, but effects are more substantial for some dimensions than others, and sometimes they are entirely absent. Under carbon markets with intensity-type emission regulations, e.g., province ETSs, firms have incentives to substitute fossil fuels with electricity. In contrast, carbon markets with absolute-type emission regulations induced more effective carbon curtailment but also incurred severer carbon leakages due to the inherent stringency regarding emission mitigation, which aligns well with the literature (Meunier et al., 2014; Goulder et al., 2022, 2023).

In terms of power generation, the dispatch of gas-generated power was substantially raised in ETS regions in response to the pilot ETS policy, while the increase in clean power dispatch was absent owing to the lack of renewable endowment. Concurrently, ETS regions were consistently motivated to increase the net power import from non-ETS areas to shift power generation and consequent emissions out, which has weakened the effectiveness of the ETS. Nevertheless, trading power to avoid the ETS can still be beneficial as it raises demand for transmission infrastructure. For regions without suitable and sufficient renewable energy endowments, especially, constructing the long-distance power transmission infrastructure can help connect clean power sources to population centers and hence adopt more renewable energy.

Ultimately, combining our estimates of carbon trading on various market participants, we obtain back-of-the-envelope calculations of aggregate impacts associated with the pilot ETS policy. We find that adopting ETS has reduced the annual energy use of 7.5×10^6 and 8.7×10^6 tons of standard coal equivalent, or 9% and 23% of total energy consumption in the province and city ETSs, respectively. The curtailment of fossil fuel consumption in standard coal metric is commensurate with a decrease in CO_2 amounting to 20.8×10^6 and 24.0×10^6 tons. It suggests that the pilot ETS policy indeed induced carbon mitigation for both types of ETS markets, but with distinct tradeoffs. City ETSs with absolute emission regulation can achieve more effective carbon reductions but incur more output loss and carbon leakages. Comparatively, province ETSs with intensity-type emission regulation encounter less output fall by design but curtail fewer emissions in magnitude.

We contribute to the following literature. First, our study adds to the literature on the environmental gain versus economic loss tradeoff in developing countries. A large body of empirical literature exists on how environmental regulation affects economic outcomes in developed countries (Greenstone, 2002; Bushnell et al., 2013; Walker, 2013; Shapiro and Walker, 2018), and few have been found in developing economies (He et al., 2020). Most environmental regulations could be classified into either *absolute*- or *intensity*-target according to their environmental objectives, implying high and low environment-economy tradeoffs, respectively. Both types of regulation can work well, but the former has a lot more bite in the short-run economic growth, while the latter could be more gradual. We fill the gap by examining the policy effects of two types of ETS, i.e., province and city ETSs, which differ by regulating *absolute* emission level or emissions *intensity*. The results corroborate that intensity-type emission regulations with less economic output loss can reduce emissions effectively.

Second, we contribute to the extensive literature on ETS in imperfect markets. Emission trading has been adopted as one of the most prevalent emission reduction measures in various contexts (Fowlie, 2009, 2010; Fowlie and Muller, 2019). Nevertheless, Fowlie et al. (2016) indicate that preexisting distortions in production markets may interfere with ETS's ability to operate efficiently. In the context of the electricity industry, many countries are still conducting command-and-control-type operations with opaque entry restrictions (Ren et al., 2021). We examine how the margins of adjustment to ETS in China reacted in an imperfect electricity market combined with incomplete emission regulations. Our results suggest that with appropriate adaption, ETS can still effectively curtail emissions under such imperfect scenarios.

Third, existing empirical studies that have examined the effects of China's ETS policy either focus on the demand side, e.g., industrial firms (Cui et al., 2021, 2022), or on the supply side, e.g., coal-fired power plants (Cao et al., 2021). Each dimension's responses reflect distinct but substitutable behaviors from various market participants. Confining research on a single margin of adjustment to ETS could be ambiguous regarding the evaluation of overall effects. Hence, it is essential to consider both sides of the energy equation to draw a comprehensive picture of the overall impact of carbon trading. Preferably, our study aims to supplement existing literature by considering all these margins of adjustments to ETS without imposing explicit parametric assumptions on various market participants.

The remainder of the paper is organized as follows. In Section 2, we overview the industry background of the carbon ETS in China along with the electricity sector. We also introduce the data used in the analysis in the same section. In Section 3, we demonstrate the theoretical sources of imperfect reallocation in response to ETS in imperfect markets. An overview regarding the margins of adjustment to ETS in China and the empirical strategy utilized in the paper are outlined. Section 4 illustrates the heterogeneous effects of carbon trading on energy consumption. Section 5 presents the impacts of ETS on power trade, dispatch, and investment, and Section 6 illustrates the aggregate impacts of the pilot ETS policy. Section 7 concludes.

2 Industry Background and Data

Imperfect markets in the paper refer to incomplete carbon emission trading regulations and imperfect competitive power markets. In this section, we describe the policy and industry background of China's pilot ETS and power generation sectors, respectively. We also illustrate the rich datasets we use to conduct our various analyses.

2.1 Carbon Emission Trading Scheme in China

Heterogenous Carbon Markets To reduce carbon emissions, China established seven *regional* pilot carbon ETS in Beijing, Tianjin, Shanghai, Shenzhen, Guangdong, Hubei, and Chongqing, from 2013 to 2014, followed by the *national* ETS market in mid of 2021. The purpose of conducting pilot ETSs instead of launching national ETS directly is to gain ex-ante experience by experimenting across locations with heterogenous tradable emission mechanisms considering diverse industrial structures and resource endowments. Among the pilot ETSs, Beijing, Tianjin, and Shanghai are municipalities with relatively developed economies but limited resource endowments, which we call **city ETSs**. Chongqing is also a municipality but has the size and resource endowments of a comparable province, hence combining with Guangdong and Hubei, we classify them into **province ETSs**.[6] According

[6]Shenzhen is a special economic zone located in Guangdong. Official economic statistics usually don't report Shenzhen separately from Guangdong, so in the analysis that follows, we let Guangdong absorb

to per capita GDP, developed pilot municipalities, i.e., city ETSs, are similar to developed country participants in the European ETS, while the remaining pilot provinces are more comparable to developing countries. By piloting carbon markets in the city and province ETSs, the Chinese government expected to build a national carbon market that considers the heterogeneity of economic development across regions. In 2021, Phase I of China's national carbon ETS market had finally launched based on the last decade's experience drawn from the pilot ETSs.[7] Phase I of the national carbon ETS accounts for at least 50% of China's annual industrial CO_2 emissions (Cao et al., 2021).

Regulated Industries and Firms Energy-intensive industries are the main participants to being emission-regulated, though the specific included industries vary across the pilot ETSs. The power generation sector has been regulated in all the pilot ETSs due to its emission-intensive feature, while petrochemical, cement, iron and steel and other industries are also commonly regulated.[8] Firms in ETS-regulated industries will be regulated if their composite energy consumption exceeds the ETS threshold. A more detailed overview of the thresholds in composite energy consumption across ETSs can be found in Appendix Table A.1. In most of the pilot ETSs, such as Guangdong, Shanghai, and Tianjin, the ETS threshold is 10,000 tons of standard coal equivalent, while that of Chongqing and Beijing is 5,000 tons of standard coal equivalent.[9] Hubei has the highest ETS threshold at 60,000 tons of standard coal equivalent. In Phase I of the national ETS, only the electricity generation sector was included, which consists of 2,225 fossil fuel-fired power plants. Each of the power plants emits at least 26,000 tons of CO_2 equivalent in either year from 2013 to 2019.[10] To remain in compliance, regulated emission sources must hold permits to offset uncontrolled emissions, while a corresponding number of emission permits will be issued for the regulated firms every year according to specific allowance allocation rules. For the carbon market mechanism to work, these allowances are traded freely in the marketplace.

Allowance Allocation Rules The foundational mechanism and framework of China's carbon ETS markets draw on the experience of other existing ETSs worldwide, e.g., EU carbon ETS, but with distinct differences, especially regarding the allowance allocation rules. For example, the EU carbon ETS allocates emission allowances according to the emission-

Shenzhen.

[7]Source: https://www.ndrc.gov.cn/xxgk/zcfb/ghxwj/201712/t20171220_960930.html. The *National Development and Reform Commission* (NDRC) initially planned to roll out the carbon ETS market nationally in 2017. Since the coronavirus pandemic and so on, the launching of the national ETS was postponed until 2021.

[8]We refer to Zhang et al. (2017) for an overview of the covered sectors across pilot ETSs.

[9]To expand the carbon trading market, Beijing has lowered the ETS threshold to 2,500 tons of standard coal equivalent since 2015.

[10]Source: https://www.mee.gov.cn/xxgk2018/xxgk/xxgk03/202012/t20201230_815546.html.

based grandfathering rule with capped total emissions, by which the amount of permits depends on an *absolute* emission cap conditional on a firm's historical absolute emission level with a certain emission reduction factor, which is also known as the mass-based system or cap-and-trade ETS (Salant, 2016) — hereinafter referred to as absolute-type ETS.[11] However, China's national carbon ETS is a rate-based system that regulates emission *intensity* — hereafter called intensity-type ETS, though for experimenting and obtaining experience, the pilot ETSs also implemented absolute-type permit allocation rules in some sectors.

An intensity-type ETS system is devoid of an absolute emission cap. The number of permits allocated to a regulated emission source depends on its emission intensity, i.e., $\frac{\text{emission}}{\text{output}}$. Given the output is the denominator of the emission-output ratio, the amount of allowances allocated is output-based, which induces an implicit output subsidy (Goulder and Morgenstern, 2018; Goulder et al., 2022).[12] The implicit output subsidy allows firms with more output to have more free emission permits allocated, provided that the targeting emission intensity is binding.[13] The feature can make carbon markets more compatible with less developed economies by not capping the total emissions and hence less output fall, but it would correspondingly conduce less stringency for mitigating emissions than in a comparable absolute-type system. In practice, the electricity generation sector in all of China's pilot ETSs applied intensity-type permit allocation rules. In contrast, for the non-electricity sectors, only the province ETSs that are in developing conditions allocated emission allowances depending on the output, i.e., intensity-type ETS.

Measurement of Carbon Emissions Distinct from the EU ETS and California's greenhouse gas emissions trading program, which only takes direct carbon emissions into regulation, the carbon ETS in China covers both direct and indirect emissions. The direct emissions are derived from the combustion of fossil fuels, while the indirect emissions come from the consumption of purchased electricity (Cui et al., 2021). In general, carbon emissions from electricity consumption would be reflected on the electricity generation side, i.e., power plants' direct carbon emissions. In a market-based competitive electricity market,

[11]In Phase III of the European carbon ETS started in 2013, the allowance allocation rule changed to fixed historical production benchmarking, which is still under the mass-based system.

[12]In a mass-based system that allocates allowances according to the emission-based grandfathering rule conditional on fixed historical emission levels, e.g., the European carbon ETS, the number of permits is not output-based. However, if the benchmark of historical emission levels of a mass-based system can vary across years, i.e., dynamic updating (Fowlie et al., 2016), then the number of allowances is also output-based, e.g., the pilot ETSs of Hubei, Chongqing, and Guangdong.

[13]We can elaborate on the implicit output subsidy using a simple conceptual model. Assume there are two ETS programs S_i and S_j with the same initial conditions of the total emission of E and the emission-output ratio of β. Suppose S_i caps its next unit-time total emission on $E(1-\eta)$, where η is the emission mitigation target ($\eta < 1$). In contrast, S_j benchmarks its next unit-time emission intensity of β', where $\beta' < \beta$. For reducing the same amount of emission of $E\eta$, the next unit-time final production in two programs corresponds $\frac{E(1-\eta)}{\beta} < \frac{E(1-\eta)}{\beta'}$, and hence corresponding reductions of output $\frac{E}{\beta} - \frac{E(1-\eta)}{\beta} > \frac{E}{\beta} - \frac{E(1-\eta)}{\beta'}$.

the production cost, as well as the carbon cost of power plants, could pass through to the demand side perfectly (Fabra and Reguant, 2014), and hence the equilibrium electricity price signal would induce consumers to adjust consumption decisions accordingly. However, since China's electricity sector remains command-and-control-type operations with an imperfect market feature, fluctuated carbon cost of power plants would not perfectly be reflected and passed through to the demand side.[14] Hence, to give the electricity demand side enough incentive to adjust electricity consumption, the carbon ETS in China also includes indirect emissions. Apparently, the inclusion of indirect emissions implicitly incurs the double-counting issue. Carbon emissions associated with electricity would be counted twice, i.e., once on the electricity production side and once on the electricity consumption side, which potentially induces a higher number of emission allowances allocated than actual emissions.

2.2 China's Electricity Sector

The vertical industry structure of the electricity sector in China can be seen in Figure 1, which consists of three main parts, i.e., electricity generation, power distribution and transmission, and consumers. The power system in China has experienced progressive deregulation reform and policy changes from vertical unbundling in 2002 (Gao and Van Biesebroeck, 2014) to the latest phase of the market reform of the electricity industry in 2015 (Zheng et al., 2021). Nevertheless, China's electricity sector is still a highly imperfect market where monopolized power distributors dominate power plants. Power generation plans and electricity prices are substantially regulated by corresponding government agencies. The entry of power plants, i.e., capacity investment, also requires approval from governments.[15]

Electricity Generation China's electricity generation sector consists of all-type of power plants, in which fossil fuel-fired power plants accounted for 82.4% of the total electricity generation in 2011.[16] Hence, the power generation sector is the industry with the most carbon emissions in China, emitting more than 40% of the total CO_2 emissions nationally (Yang and Lin, 2016). To reduce CO_2 emissions and substitute for traditional coal-fired power in the long run, China adopts a battery of subsidy policies to encourage and support renewable power plants, e.g., solar and wind power, to enter the electricity generation market (Zhang et al., 2009; Liu, 2019). The total generating capacity of solar and wind power increased drastically by 1,000% from 48.5 GW in 2011 to 535.2 GW in 2020, accounting for 4.6%

[14] More details about the industry structure of China's electricity sector can be found in Section 2.2.

[15] We refer to Ren et al. (2021) for a detailed overview of China's project approval system regarding power investment.

[16] All relevant data come from the *China Electricity Council* (CEC). See Section 2.3 for more details.

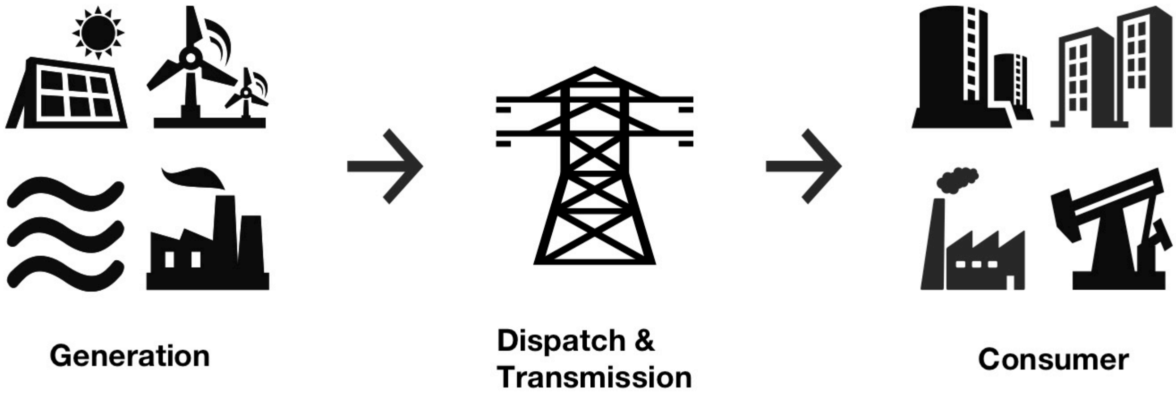


Figure 1: Vertical Structure of the Electricity Industry in China

Notes: The vertical industry structure of the electricity sector in China consists of three main parts, i.e., electricity generation, power dispatch, and consumers.

and 24.3% of total national capacity, respectively.[17] However, due to limited interregional transmission capacity and intermittent features of renewable power, the portion of solar and wind power-generated electricity only raised by around 8 percentage points from 1.6% (2011) to 9.5% (2020), while fossil fuel-fired power still accounts for 67.9% of the total electricity generation at the end of the same period.

All the power plants have to obey the dispatching orders from the monopolized local power grid companies, which are responsible for electricity dispatch and transmission.[18] By selling electricity to power grid companies to comply with the dispatched generation orders, power plants get revenue under predetermined *on-grid* electricity prices.[19] The on-grid electricity prices are regulated and determined by *National Development and Reform Commission* (NDRC) province by province. The NDRC adjusts the on-grid electricity prices aperiodically according to the profitability of power plants, especially that of coal-fired power plants, in response to the fluctuated coal prices, which is known as the *coal-electricity price linkage mechanism.*[20]

Power Trade and Dispatch There were no substantial interregional spot electricity mar-

[17]An overview of the evolution of the national installed capacity of all types of power in China can be found in Appendix Figure A.2.

[18]In 2015, the latest phase of the market reform of the electricity industry started. Power plants have been allowed to sign electricity contracts directly with large power-purchasing entities since 2017. In terms of these contracts, they can schedule the dispatching orders independently of the monopolized power grid dispatcher. However, the portion of competitive power contracts over the total is still limited, e.g., 30% in 2018 (Cao et al., 2021).

[19]The 2002-phase of the electricity market reforms did plan to deregulate prices to launch competitive wholesale markets and even trialed in a few regions, but finally decided to postpone essentially due to the electricity shortages and limited interregional transmission capacity and so on (see Gao and Van Biesebroeck (2014)).

[20]More details about the coal-electricity price linkage mechanism can be found in Li et al. (2015).

kets in China during our study period. Power trade between provinces is primarily determined by administrative orders from governments (Ho et al., 2017). To transmit power over long distances but minimize transmission losses, ultra-high-voltage and other high-voltage electricity transmissions have been deployed in China.[21]

Given the inter-province power transmission orders, the annual electricity generation plan for each of the local power plants is decided and compiled by the local *Economy and Information Commission* (EIC) according to specific allocation rules, e.g., equal share or energy conservation rules, conditional on the production capacity and forecast of electricity demand for the coming year. The equal share rule requires EIC to allocate relatively the same operating time to power plants with the same capacity level, hence the same planned generation output, while the energy conservation rule gives priority to renewable and clean energy rather than contaminative fossil fuel-fired power (Kahrl et al., 2013).

Provided the annual power generation plans, the power grid company would flexibly arrange monthly and daily plans for power plants to balance and ensure the completion of the annual plans. Of course, power grid companies can report to EIC to adjust the annual power plans when unexpected deviations from the plans happen. To avoid the potential conflicts of interest when dispatching, the power grid companies were forced to divest all their generation assets after the 2002-phase deregulation and vertical unbundling in the electricity sector (Gao and Van Biesebroeck, 2014).

Consumers There are three major categories of consumers on the electricity demand side: residents, agriculture, and industry and commerce. The industry and commerce normally account for the largest portion of the total social power consumption, e.g., 86% in 2011, while residential electricity consumption took 12% during the same period. However, unlike most other countries, the electricity rates for industry and commercial business are higher than that of residents and agricultural production, which essentially require the former to subsidize the latter (Lam, 2004; Wang et al., 2017). The levels of wholesale electricity prices of different consumer categories are also regulated and determined by NDRC province by province, just like the pricing mechanism of on-grid electricity prices.

2.3 Data

We combine multiple rich data sources to comprehensively analyze the impacts of the pilot carbon ETS policy on various outcomes. The datasets include both provincial- and firm-level energy consumption information, e.g., use of power and fossil fuels, etc., and supply-side

[21]See Appendix Figure A.1 for the evolutions of the construction of high-voltage electricity transmission in China.

data on electricity generation and trade. Due to the data availability varying across settings, provincial data generally have a longer time span than firm-level data. We use different data at the best level to conduct various specifications.

Energy Consumption Data We access the firm data from the National Tax Survey Database (NTSD) from 2007 to 2016, which is conducted by the *Chinese State Administration of Tax*. This dataset contains detailed information on firm-level energy consumption, including electricity and fossil fuels, and other production data. We convert electricity and fossil fuels into standard coal metrics by corresponding conversion factors from *China Energy Statistics Yearbook* and sum them up to obtain firm-level composite energy consumption. We eliminate all firms with electricity, fossil fuel use, and composite energy consumption in the top and bottom 1%, where the percentiles are calculated year by year.[22] Our sample includes 418,883 firm-year observations from 2007 to 2016. We classify firms into above- and below-threshold firms by comparing their average annual composite energy consumption with the ETS thresholds, e.g., 10,000 tons of standard coal.[23] We take 2009 and 2010 — the two years before the announcement of ETS — as criterion years to calculate the average energy consumption to alleviate potential announcement effects. Table 1 presents summary statistics of the industrial firms in our sample. It shows that above-threshold firms are larger than below-threshold firms in output but with disproportionately higher composite energy inputs, which suggests that the above-threshold firms are considerably more energy-intensive.

Power Generation Data We also use novel annual production data that include all types of power plants with a capacity above 6 MW in China that operated during the 2007-2017 period, which cover the sample period of our provincial- and firm-level energy consumption data.[24,25] The dataset is compiled and examined by CEC, which is the most authoritative organization in the field of electric power in China. The unit of observation in the CEC data is the 'plant', which is the level power grid companies dispatch electricity generation tasks in practice. The dataset reports detailed plant-level information about name, capacity,

[22]We detect underlying reporting issues for some firms with drastic changes (>500% or <-80%) in energy-relevant variables, e.g., energy intensity, etc. This might be because the units of these variables changed in different survey years, but these firms did not adjust correctly when reporting data. We drop relevant observations following Cui et al. (2021).

[23]The ETS thresholds vary across ETSs, as seen in Appendix Table A.1. However, the threshold of annual composite energy consumption of 10,000 tons of standard coal equivalent is the most commonly adopted standard. Hence, we consider it the cut-off for identifying the above(below)-ETS-threshold firms in non-ETS regions.

[24]The threshold of 6MW for being included in the power generation data is fairly small. In comparison, the average capacity of a typical offshore wind turbine is around 6MW. Source: https://www.energy.gov/eere/articles/wind-turbines-bigger-better.

[25]Data for 2013 is missing.

Table 1: Summary Statistics of the Industrial Firms

	All Firms	**Above-threshold Firms**	**Below-threshold Firms**
Electricity (10 MWh)	342	3,138	226
	(996)	(3,056)	(555)
Fossil fuels (ton)	870	12,523	386
	(3,872)	(13,519)	(1,471)
Total energy (ton)	1,709	20,385	934
	(5,263)	(14,688)	(2,197)
Output (million RMB)	67	283	58
	(145)	(311)	(127)
N	418,883	16,690	402,193

Notes: Means and standard deviations (in parentheses) are listed. We classify firms into above- and below-threshold firms by comparing their composite energy consumption in 2010, the year before the announcement of ETS, with the ETS threshold, e.g., 10,000 tons of standard coal.

power generation, operating hours, coal inputs, etc. However, information on specific plant types is not reported. We identify plant types following three steps as follow: First, we identify plant types by keywords (in Chinese) in their names, e.g., "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. Second, we match power plants by their names with China's Administrative Registration Database to access information on the business scope to deduce types. Third, for all the remaining unidentified power plants, we determine the type by manually searching the Internet and public information. Finally, our sample consists of 53,244 observations from 2007-2012 and 2014-2017. Table 2 shows summary statistics of all types of power plants in our sample.[26] It corroborates the market structure of China's electricity generation sector we introduced in Section 2.2 Electricity Generation, that fossil fuel-fired power dominates all other types of power with regard to capacity and power generation. Clean power, especially solar and wind power, has relatively low operating hours compared to thermal power due to the intermittent features of renewable power.

Provincial Electricity and Energy Data We supplement the above micro-level datasets with detailed provincial electricity demand and power transmission data from 2007 to 2019, collected by the CEC as well. The electricity demand dataset consists of all-sector electricity consumption data across provinces, while the provincial power transmission data report information on all cross-province electricity trade. Data regarding the length and capacity

[26]Nuclear power plants, biomass power plants, garbage power plants, and pumped-storage power plants are not included here because they only account for a trivial proportion and are not the interest of the paper. We mainly divide power plants into hydropower, wind/solar power, coal-fired power plants, and gas-fired power plants in our study.

Table 2: Summary Statistics of the Power Plants

	Hydro	Coal-fired	Gas-fired	Solar/Wind
Capaicty (MW)	64	299	315	60
	(175)	(411)	(405)	(74)
Power generation (GWh)	215	1,371	823	98
	(616)	(1,985)	(1,202)	(202)
Operating Hours (Hour)	3,526	4,408	3,349	1,607
	(1,497)	(1,939)	(2,093)	(841)
N	21,219	16,229	1,158	14,015

Notes: Means and standard deviations (in parentheses) are listed. The data cover all types of power plants with a capacity above 6 MW.

of power transmission lines are also complemented by the same source. We further obtain provincial fossil fuel consumption from China's *Energy Statistics Yearbook*, and other data from China's *Statistics Yearbook*.

3 Sources of Imperfect (Re)allocation

3.1 Theoretical Justifications

The power generation sector links the energy supply and demand sides involved in an ETS along the value chain by supplying essential electricity inputs to the industrial sector. Carbon costs from the power generation sector, acting as a component of the price signal for carbon reduction, could be passed on to the power price, impacting the abatement behavior of downstream firms. However, the electricity market structure can affect the pass-through of price signals (Fabra and Reguant, 2014), hence the effectiveness of an ETS. The incomplete regulation may further complicate the capability of effective operation of a carbon market (Fowlie et al., 2016). In practice, electricity markets are commonly not perfectly competitive but even regulated, which, combined with the context of incomplete regional ETS policy in the paper, leads to inefficiencies and imperfect (re)allocations.

Scenario I: Perfect Carbon and Power Markets To study (imperfect) (re)allocations stemming from market participants' behavior along the whole value chain following carbon trading, it is helpful to consider the particular scenario in that market participants respond to the ETS in perfect carbon and power markets. Under such a market structure, emission-intensive power plants tend to pass the carbon costs to electricity consumers through increased power prices, but accordingly would lose prior positions in the merit order of power dispatch in an economic dispatch market, compared to other less-emitting power producers.[27] Thus, carbon-intensive power plants might obtain lower operating hours and become less profitable, which encourages new investment in less carbon-intensive power plants. Simultaneously, the reduced power generation tasks would reallocate to less carbon-intensive counterparts within or outside the local power generation market.

For energy consumption, the impact of ETS on energy mixes, or energy input allocation, could be ambiguous. The increased power prices can straightway induce consumers to reduce electricity demand. However, considering the incurred carbon costs associated with direct emissions embedded in fossil fuels, the firms have incentives to substitute carbon-intensive energy with low-carbon alternatives, e.g., substituting fossil fuels with power, thereby increasing electricity demand. These two forces drive firms to adjust their energy allocation and consumption patterns.

Scenario II: Imperfect Power and Carbon Markets Nevertheless, in imperfect electricity markets, high-emitting power producers would not necessarily lose prior positions in the merit order of power dispatch in response to carbon trading, compared to their less-emitting counterparts, due to the inefficiencies of power markets. Not to mention that in power markets with command-and-control-type operations, power dispatch is determined by the dispatch agency in a potentially opaque way. The inefficient power dispatch hence hinders the reallocation of operating hours from high-emitting to low-emitting power plants in response to carbon trading. The resulting profit signals can further deviate potential reallocation of capital investment from high carbon-intensive to less carbon-intensive power plants.[28]

Furthermore, the extent of pass-through of emission costs to electricity prices also matters as the carbon cost signal would encourage demand-side consumers to adjust energy input allocation to reduce total emissions (Bushnell et al., 2013). However, in a highly imperfect power market where both on-grid and retail electricity prices could be regulated, it hardly passes any emission cost to the power demand side in the short run, which would induce firms to misuse electricity as an alternative to fossil fuels and shift (but not necessarily reduce) emissions to the power supply side.

Another potential source of imperfect reallocation is carbon leakage when the ETS is incomplete (Fowlie et al., 2016). Electricity generated in non-ETS-regulated regions would

[27]The merit order is a procedure of ranking available electrical generators based on ascending marginal production costs. Thereby, the power plants with lower marginal costs would be prioritized, theoretically minimizing the power market's total cost of power generation ultimately.

[28]Of course, many other factors are uncorrelated to the market structure but can still impact investment decisions, e.g., entry restrictions for fossil fuel-fired power supply or lack of natural resources endowment for building renewable power plants.

have comparative cost advantages, hence prior positions in the merit order of power dispatch if non-ETS-regulated power plants participate in the power trade market. Thus, more electricity trade, specifically the more net import of power from non-ETS-regulated regions, would be expected. In essence, the power trade shifts local power generation and underlying emissions to other regions. In addition, ETS-regulated firms could also reallocate their production to related but non-regulated parties to evade regulation (Cui et al., 2022). All these carbon leakages will weaken the effectiveness of carbon markets; but also note that once the regulation of ETS gets complete, though not effortless to do so, a large part of these imperfect reallocations would be gone.

3.2 Margins of Adjustment to ETS in China

As elaborated in Section 2, carbon and power markets in China are highly imperfect and regulated under command-and-control operation. The pass-through of the policy signal hence could be substantially impeded, resulting in overall ineffective carbon abatement. We break down the holistic impact into various margins of adjustment to ETS according to market participants along the value chain, e.g., residential and industrial consumers and local authorities responsible for power trade, dispatch, and investment.

We start with the energy consumption part. Residential consumers usually are not regulated by the ETS policy. But they could be incentivized to adjust consumption patterns driven by the publicity effect. In contrast, industrial firms are regulated straightway and hence tend to alter energy input allocation to minimize total cost. The treated industrial firms might also have the motive to shift production to untreated counterparts to evade regulation.

Regarding the power supply side, power trade, dispatch, and investment in China mostly need to follow orders or get approval from local authorities. The authoritative institutions, e.g., the local power dispatch agency, are never under ETS regulated directly but could adjust commands to support the smooth implementation of policies to meet the demands of higher authorities based on political intents and promotion incentives.[29] Hence, local authorities in ETS regions could expand local renewable power dispatching and inter-province net power import or approve more investment in clean power.

3.3 Empirical Strategy

Various market participants could adjust differently in response to the ETS. We will examine all the margins of adjustment to ETS in the empirical analysis to draw a holistic picture

[29]See Li and Zhou (2005) for details about the political promotion competition in China.

regarding market participants' behavior responding to the pilot ETS. Throughout the regression analysis, we utilize a consistent empirical strategy at different adjustment margins to examine the changes induced by carbon trading.

We use the potential outcome notations proposed by Rubin (1974, 1978) to illustrate. Suppose D_{it} denotes exposure status to ETS policy for a market participant i in period t, where $D_{it} = 1$ if that agent receives ETS treatment and $D_{it} = 0$ otherwise. Let $Y_{it}(0)$ be the outcome of interests for market participant i in period t if that agent has not been treated, and let $Y_{it}(1)$ denote the outcome for the same agent if she has received treatment. The outcome for the market participant i in period t in the absence of the ETS regulation can be written as

$$Y_{it}(0) = \alpha_i + \delta_t + d(X_{it}, 0) + \epsilon_{it}, \tag{1}$$

where $d(X_{it}, 0)$ indicates a time-variant behavioral function that depends on market participant i's characteristics X_{it} and policy exposure status. α_i denotes agent i's time-invariant behavioral features that are unaltered by whether exposure to ETS, and δ_t covers agent-invariant variations. Similarly, the outcome for the ETS-treated agents satisfies

$$\begin{aligned} Y_{it}(1) &= Y_{it}(0) + [d(X_{it}, 1) - d(X_{it}, 0)] \\ &= Y_{it}(0) + \tau(X_{it}), \end{aligned} \tag{2}$$

where $\tau(X_{it})$ indicates the relative outcomes between being treated and non-treated by ETS policy for agent i in period t. Let the observed outcome of market participant i in period t be Y_{it}. Note that the observed data are the triple (Y_{it}, D_{it}, X_{it}), and $Y_{it}(0)$ and $Y_{it}(1)$ are not observable simultaneously for agent i in period t. Therefore, the observed outcome of agent i in period t can be written as $Y_{it} = Y_{it}(0) + \tau(X_{it})D_{it}$.

We can construct a DiD specification to estimate the average treatment effect on the treated (ATT), $\tau = \mathbb{E}[\tau(X_{it})|D_{it} = 1]$, by regressing

$$Y_{it} = \alpha_i + \delta_t + \beta D_{it} + X_{it}'\gamma + \varepsilon_{it}, \tag{3}$$

where $\beta = \mathbb{E}[Y_{it}(1)|X_{it}, D_{it} = 1] - \mathbb{E}[Y_{it}(0)|X_{it}, D_{it} = 0]$. We rewrite β into a function of ATT (τ) by subtracting the term $\mathbb{E}[Y_{it}(0)|X_{it}, D_{it} = 1]$ first and adding it back:

$$\begin{aligned} \beta &= \big[\mathbb{E}[Y_{it}(1)|X_{it}, D_{it} = 1] - \mathbb{E}[Y_{it}(0)|X_{it}, D_{it} = 1]\big] \\ &\quad + \big[\mathbb{E}[Y_{it}(0)|X_{it}, D_{it} = 1] - \mathbb{E}[Y_{it}(0)|X_{it}, D_{it} = 0]\big] \\ &= \underbrace{\tau}_{\text{ATT}} + \underbrace{\mathbb{E}[Y_{it}(0)|X_{it}, D_{it} = 1] - \mathbb{E}[Y_{it}(0)|X_{it}, D_{it} = 0]}_{\text{Selection Bias}}. \end{aligned} \tag{4}$$

Here, the first term in Eq.(4) depicts the ATT, and the second term indicates the selection bias, i.e., the difference in the potential outcomes between treated and non-treated agents if there had never been exposed to the ETS policy. Provided the selection bias equals zero, i.e., $\mathbb{E}[Y_{it}(0)|X_{it}, D_{it} = 1] = \mathbb{E}[Y_{it}(0)|X_{it}, D_{it} = 0]$, conditional on the covariates, the potential outcomes of interest are independent of D_{it}. Hence, Eq.(4) corresponds to $\beta = \tau$, and we can obtain ATT, i.e., $\mathbb{E}[Y_{it}(1)|X_{it}, D_{it} = 1] - \mathbb{E}[Y_{it}(0)|X_{it}, D_{it} = 1]$, from the estimate of β from Eq.(3). Otherwise, the estimate of ATT would be contaminated by selection bias.

We check the existence of selection bias by conducting parallel trend tests following a general specification as

$$Y_{it} = \alpha_i + \delta_t + \sum_{\kappa=\underline{\kappa}}^{\bar{\kappa}} \beta_\kappa \times D_i \times \mathbb{1}[t = \kappa] + X_{it}'\gamma + \varepsilon_{it}, \tag{5}$$

where D_i is now an indicator of whether an agent i has ever been treated. $\bar{\kappa}$ and $\underline{\kappa}$ denote the first and last periods relative to the ETS starting years, respectively. We allow β's to vary over time relative to the ETS starting years, capturing the policy effects of ETS policy on outcome variables. We identify β's using agent-to-agent variations in the outcome of interest net of a host of agent characteristics (X_{it}), spatial or agent (α_i) and temporal (δ_t) fixed effects at the finest level, based on the assumption that the outcome of interest of non-treated agents would have evolved similarly to that of treated units in the absence of the pilot ETS policy.[30]

In practice, to examine the heterogenous effects of ETS policy, i.e., absolute- vs. intensity-emission regulations, we further augment the specification in Eq.(3) by interacting the treatment indicator D_{it} with the province and city ETS dummy variables separately:

$$Y_{it} = \alpha_i + \delta_t + \beta_1 D_{it} \times \text{ProvETS}_i + \beta_2 D_{it} \times \text{CityETS}_i + X_{it}'\gamma + \varepsilon_{it}, \tag{6}$$

where ProvETS_i equals one if agent i locates in a province ETS, e.g., Guangzhou, Hubei, and Chongqing, while CityETS_i equals one if agent i locates in a city ETS, e.g., Beijing, Tianjin, and Shanghai.

4 Heterogeneous Effects of Carbon Trading on Energy Consumption

To conduct a comprehensive study of the effects of the pilot ETSs, we examine various agents' reactive behavior to carbon trading along the whole power value chain. We start

[30] A richer set of spatial-temporal fixed effects will be discussed in the empirical sections later.

with the energy consumption side at both provincial and firm levels. The province-level investigation examines more indirect and general equilibrium consequences of the pilot ETS policy, while the firm-level analysis focuses more on direct and partial equilibrium effects.

4.1 Province-level Energy Mixes

The power generation sector, as suppliers, generally reacts passively to meet electricity demand. It is hence intuitive to start the study of the impacts of carbon trading from the demand-side consumers. To do so, we begin by focusing on the difference in the effects on the energy consumption patterns in ETS regions relative to that of other non-ETS counterparts. We use province data to estimate DiD specifications of the form:

$$\ln(\text{EnergyConsumption}_{pt}) = \alpha_p + \eta_{jt} + \delta_{kt} + \beta D_{pt} + X'_{pt}\gamma + \varepsilon_{pt}, \tag{7}$$

where the dependent variable $\ln(\text{EnergyConsumption}_{pt})$ is logged energy consumption of the industrial sector, either power or fossil fuels, in province p and year t. We examine the corresponding impacts on power and fossil fuel use for the residential and industrial sectors (excluding the utility sector) separately. D_{pt} indicates the ETS treatment, and equals one for all periods after province p starts the carbon trading. To satisfy the selection-on-observables assumption in the nicest possible way, we control province characteristics X_{pt}, e.g., provincial per capita GDP, the total capacity of power generation, and the total capacity of high-voltage power transmission lines, and province fixed effects α_p in all province-level regressions.

Furthermore, to control spatial-temporal heterogeneity and potential spillovers, we also allow region-by-year fixed effects η_{jt} as well as regional power grid-by-year fixed effects δ_{kt}, where j denotes a geographic region in China (e.g., western, middle, and eastern regions, etc.) and k represents a regional power grid.[31] The region-by-year fixed effects η_{jt} absorb time-varying within-region variations in underlying regional developmental inequalities, demand shocks, etc. In contrast, the regional power grid-by-year fixed effects δ_{kt} capture evolutions of command-and-control patterns within regional girds regarding power dispatch and transmission, power assets and infrastructures, and so on. The overlapping fixed effects generate nearby provinces into control groups. We identify β using these province-to-province variations in energy consumption patterns net of the province characteristics and spatial and temporal fixed effects.

[31] In the 2002-phase electricity market reform, six regional power grid companies, i.e., northern, northeastern, eastern, central, northwestern, and southern regional power grids, were established to break inter-provincial barriers to power transmission. Though five regional power grid companies were deregistered in 2016, the pattern of inter-provincial power transmission is still preserved. Source: https://www.thepaper.cn/newsDetail_forward_1502725.

To examine the heterogeneous effects of carbon trading across different types of ETSs (absolute- vs. intensity-emission regulations) veiled beneath the average treatment effects, we augment Eq.(7) to equations of the form:

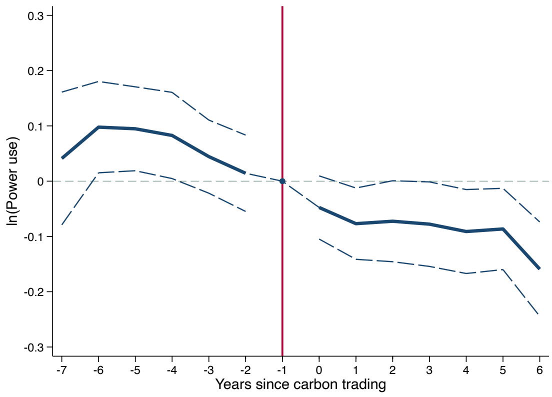
$$\begin{aligned} \ln(\text{EnergyConsumption}_{pt}) = \alpha_p + \eta_{jt} + \delta_{kt} + \beta_1 D_{pt} \times \text{ProvETS}_p \\ +\beta_2 D_{pt} \times \text{CityETS}_p + X'_{pt}\gamma + \varepsilon_{pt}. \end{aligned} \tag{8}$$

Figure 2 presents the pre-trend estimates of β_κ coefficients in different specifications of energy consumption in the spirit of Eq.(5). Note that the pilot ETS policy was first announced by the NDRC in October 2011, and the corresponding carbon trading and verification measures were released and started to implement in 2013 or 2014 for different ETS regions. We normalize the year before the implementation to zero and check potential announcement effects. The coefficient for the year prior to the ETS practice is hence omitted. The periods regarding announcement should be pre-one or pre-two periods depending on the specific starting years in different ETS regions.

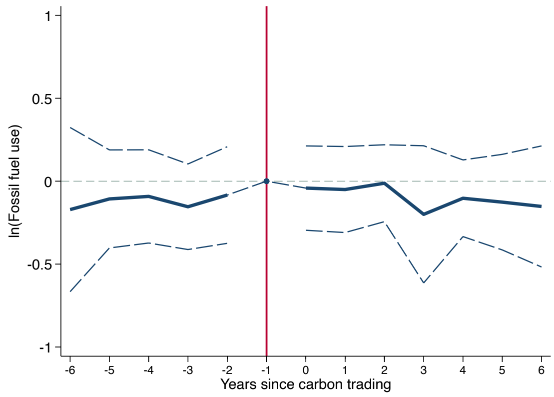
Panels A and B in Figure 2 show the event-year plots for changes in province-level energy consumption patterns of the residential sector for power and fossil fuel use, respectively. It appears that the residential sector partially responded to the ETS policy, even though most emission regulations were not specific to residents directly. A significant decline has been witnessed in power use at the provincial level, while an announcement effect was detected prior to the practice of pilot ETS. In contrast, residential fossil fuel use had no significant difference before and after carbon trading in ETS and non-ETS regions.[32] The observed change in residential electricity consumption is more likely due to the publicity effect of the pilot ETS policy and relevant energy conservation initiatives pursuing a low-carbon environment. Relatively, residential fossil fuel use consists of necessary daily household usage of coal and gas for cooking, heating, etc. A non-resident-target emission mitigation initiative such as the pilot ETS policy is not cost-effective enough to incentivize residents to find alternative substitutions.

Panels C and D display changes in power and fossil fuel use of the industrial sector at the provincial level. Three findings emerge. First, the figure shows that for both power and fossil-fuel consumption of the industrial sector, β_κ estimates are statistically indistinguishable from zero, indicating that ETS and non-ETS provinces had similar trends before the trading of carbon. Second, there is no significant announcement effect prior to the implementation of carbon trading. Finally, carbon trading took years to induce the ETS regions to reduce both types of industrial energy use, compared to that of non-ETS counterparts.

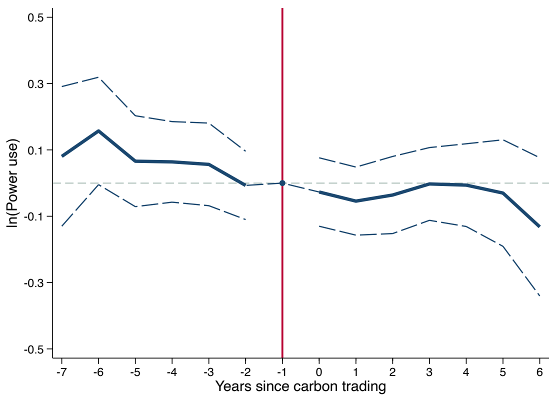
[32] Residential fossil fuel use data for 2007 are missing, thus, there is one period short in Panel B compared to other panels in Figure 2.



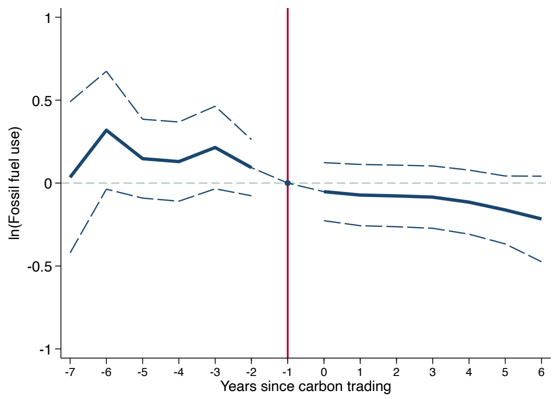
A. Residential Power Use



B. Residential Fossil Fuel Use



C. Industrial Power Use



D. Industrial Fossil Fuel Use

Figure 2: Changes in Energy Consumption Patterns: Province-Level

Notes: We normalize the year before the implementation of the pilot ETS policy to zero with omitted confidence intervals. The periods after the solid red vertical line indicate that carbon trading has started. 95% confidence intervals in dashed lines are shown.

We combine the period-by-period event-year effects into a single interaction term D_{pt} as in Eq.(7) to quantify the overall effects of carbon trading. Table 3 reports the impact of the ETS policy on energy input allocation at the provincial level. Panel A regarding residential energy consumption presents qualitatively consistent patterns, as shown in Figure 2. The residential sector decreased power use by 12.6% compared to non-ETS regions, while fossil fuel use had no significant change in response to carbon trading.[33]

In terms of the industrial sector, columns 1 and 3 in Panel B of Table 3 show that, on average, ETS regions decreased industrial power use by 8.7%, and fossil fuel use by 21.7% compared to that of non-ETS counterparts.[34] Furthermore, we interact the single interaction term D_{pt} with the province and city ETS indicators separately to disentangle the heterogeneous effects. One can find from columns 2 and 4 in Panel B of Table 3 that average treatment effects indeed conceal rich heterogenous responsive behaviors of different types of ETS markets. Estimates in column 2 show a 5.8 log-point (6.0%) increase in industrial power consumption that province ETSs have utilized relative to non-ETS regions that were similar in the trends of evolution prior to carbon trading. In contrast, city ETSs consumed 25.2 percentage points less (-22.3%) power use in the industrial sector relative to non-ETS regions. In terms of fossil fuel use, column 4 reports declines of 17.4 log points (-16.0%) and 32.1 log points (-27.5%) for province and city ETSs relative to non-ETS areas, respectively.

It appears that instead of suppressing both power and fossil fuel use in the industrial sector to comply with the ETS regulation like city ETSs have done, province ETSs are inclined to substitute fossil fuels with electricity, hence a reduction in fossil fuel use but an increase in power consumption. The heterogeneous effects of city and province ETSs on the industrial demand side are accordant with the scheme designs — output-based permit allocation rules in province ETSs are less stringent in mitigating emissions but are more compatible with conditions in developing industries and economies — for example, it enables province ETSs to shift from fossil fuels to power use gradually, rather than cutting all types of energy use promptly. City ETSs capped the total emissions and targeted the absolute emissions indeed induce more stringency and perform effectively for carbon mitigation, but also incur more prominent side effects of spillovers. Further details and discussion can be found in Section 4.2.

[33] $= 100 \times [\exp(-0.135) - 1]\% = -12.6\%$.

[34] These estimates of specifications are robust to a flexible set of spatial-temporal controls that include province fixed effects, region-year fixed effects, regional power grid-year effects, and province controls.

Table 3: Effects of the Carbon Trading on Energy Consumption Patterns: Province-Level

Variables	ln(Power Use)	ln(Power Use)	ln(Fossil Fuels)	ln(Fossil Fuels)
Panel A: Residential				
D_{pt}	-0.135***		-0.002	
	(0.016)		(0.060)	
$D_{pt} \times \text{ProvETS}_p$		-0.110***		-0.093
		(0.021)		(0.092)
$D_{pt} \times \text{CityETS}_p$		-0.162***		0.098
		(0.022)		(0.078)
Controls	✓	✓	✓	✓
FEs: province	✓	✓	✓	✓
FEs: region×year	✓	✓	✓	✓
FEs: regional power grid×year	✓	✓	✓	✓
Observations	390	390	360	360
Panel B: Industrial				
D_{pt}	-0.091***		-0.245***	
	(0.031)		(0.052)	
$D_{pt} \times \text{ProvETS}_p$		0.058**		-0.174***
		(0.029)		(0.047)
$D_{pt} \times \text{CityETS}_p$		-0.252***		-0.321***
		(0.046)		(0.093)
Controls	✓	✓	✓	✓
FEs: province	✓	✓	✓	✓
FEs: region×year	✓	✓	✓	✓
FEs: regional power grid×year	✓	✓	✓	✓
Observations	390	390	390	390

Notes: Robust standard errors in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$

4.2 Firm-level Energy Mixes

As introduced in Section 2.1, firms in ETS-regulated industries will be regulated if their composite energy consumption exceeds the ETS threshold. In response to the compliance obligation of carbon trading, industrial firms can take different measures to reduce compliance costs. Straightforward and effective measures to mitigate emissions could be adjusting energy input allocations, or reducing output directly; of course, an incentive to shift production to circumvent regulation goes hand in hand.

We first investigate the energy input allocations in response to carbon trading at the firm level using NTSD data. The NTSD data provide detailed firm profiles that allow us to distinguish firms into treated and non-treated groups to conduct a more granular study on firms' energy use choices, though covering three post-ETS years fewer than the provincial data. We identify the above-ETS-threshold firms in ETS regions as treated, based on their composite energy consumption in 2010, the year before the announcement of ETS, to further rule out potential anticipation effects. Correspondingly, above-ETS-threshold firms in non-ETS regions belong to control groups in the case.

We hence compare the above-ETS-threshold firms' behavior in ETS and non-ETS regions using firm data to estimate equations of the form:

$$\ln(\text{EnergyConsumption}_{it}) = \alpha_i + \eta_{jt} + \delta_{kt} + \varphi_{dt} + \beta D_{it} + X'_{it}\gamma + \varepsilon_{it}, \tag{9}$$

where D_{it} indicates the carbon trading treatment, and equals one for all periods after an above-ETS-threshold firm i starts carbon trading. Here, α_i now is the firm fixed effects, and η_{jt} and δ_{kt} are the same set of spatial and temporal fixed effects as before. We further include two-digit industry-by-year fixed effects φ_{dt} to account for time-variant technological evolutions of industrial energy use. We also control similar provincial characteristics as before, e.g., provincial per capita GDP, the total capacity of power generation, and the total capacity of high-voltage power transmission lines. Our baseline firm-level specifications do not control firm-level output, but we add it to the preferred specifications to detect the heterogeneous response of firms in different types of emission regulations.

We present the pre-trend plots in Figure 3. Within the same event window that spans from 2007 to 2016, the patterns shown in energy choices are qualitatively consistent for using either firm- or province-level data. The changes in fossil fuel consumption display a parallel trend prior to carbon trading that is statistically indistinguishable from zero, while power use also evolved similarly before the practice of ETS, though a one-period minor potential pre-trend due to the announcement effect is observed. The anticipation formed by ETS firms induces adjustment in power consumption before implementing carbon trading.

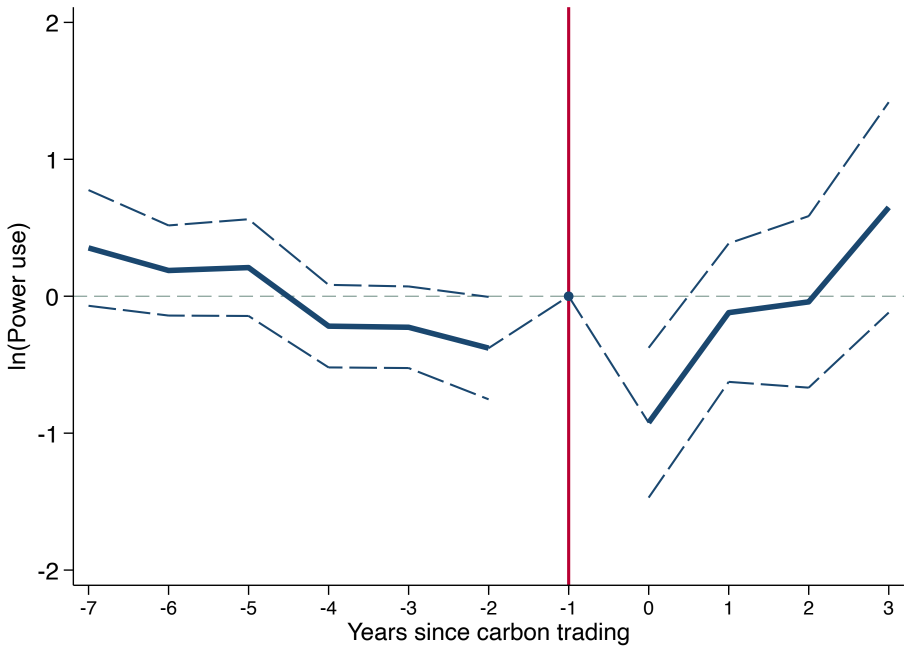
Nevertheless, the adjustment appears to be transitory, with economically small magnitudes compared to the relatively sharp changes in power consumption after the ETS practice.

After the implementation of carbon regulation, however, ETS firms saw a persistent rebound in power use, which is consistent with the pattern during the same periods in the context of provincial specifications, though it diminished gradually in the following periods, during which we are unable to examine due to the data availability. In contrast, the difference in post-ETS evolution of fossil fuel use among above-ETS-threshold firms appears to be not significantly different from zero with much broader confidence intervals. Hence, an in-depth disentanglement of heterogenous responsive behaviors of ETS firms in different ETS provinces is awaiting.

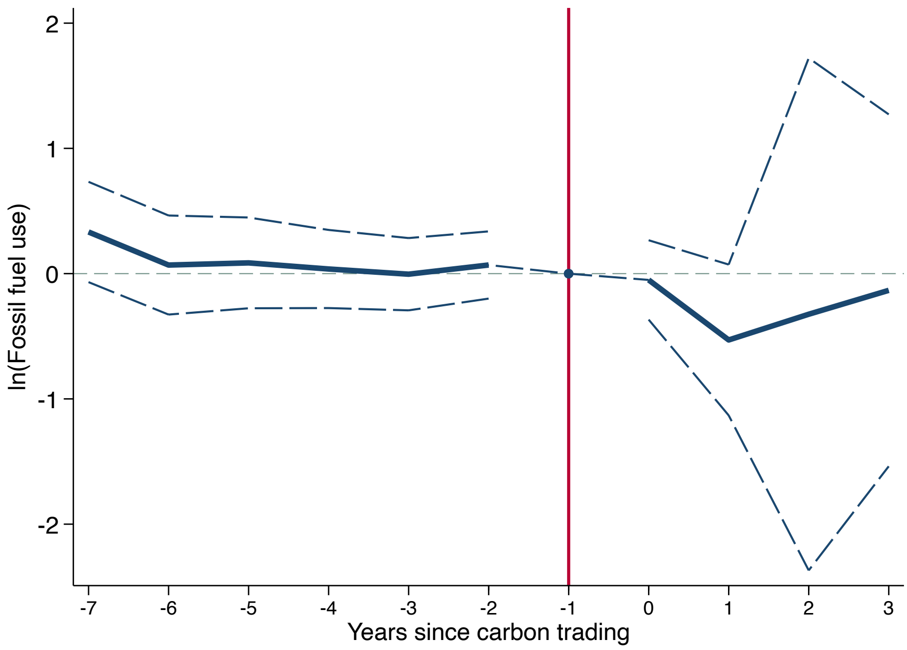
We mimic the specification of Eq.(8) by adapting subscripts to the firm level and further allowing firm and industry-by-year fixed effects to investigate the firm-level heterogeneous effects of carbon trading. We report results in Table 4. The difference between the first and last two columns in both panels is whether the firm-level output is controlled. Interesting findings regarding heterogeneous firm-level energy consumption patterns in different types of ETSs (absolute regulation in city ETSs vs. intensity regulation in province ETSs) emerge from the comparison.

Column 2 of panel A shows that above-ETS-threshold firms in province ETSs find a 55.5 log-point (74.2%) increase in electricity consumption, while ETS firms in city ETSs declined by 97.6 log points (62.3%), compared to other above-ETS-threshold firms in non-ETS regions. The intensity-emission regulation in province ETSs tends to induce implicit output subsidy. In contrast, the absolute-emission regulation in the province ETS could lead to direct output reduction for complying with the regulation. One might claim that the increase and fall in power use in province and city ETSs, respectively, are mainly due to the output variation instead of the carbon trading. We then control the firm-level output in column 4 at the same panel, and the estimates of the above-ETS-threshold firms in province ETSs regarding power consumption decrease by six percentage points to 49.5 log points (64.0%), while that of city ETSs raise by around two percentage points to -95.9 log points (-61.7%). The estimates are all still significant, as shown, while city ETSs less changed than province ETSs when controlling output. This is consistent with the scheme designs of absolute-emission regulation in city ETSs, where the total emissions are capped; given power is the primary energy input and emission accounting source, the output is relatively controlled in city ETSs' power use context already.

By comparison, in panel B of Table 4 regarding fossil fuel use, the same firms in province ETSs witnessed a 19.3 log-point (21.3%) rise, while ETS firms in city ETSs dropped 60.5 log points (45.4%), though only the estimate of city ETSs is significant. When controlling



A. Changes in Power Consumption



B. Changes in Fossil Fuel Consumption

Figure 3: Changes in Energy Consumption Patterns: Firm-Level

Notes: We normalize the year before the implementation of the pilot ETS policy to zero with omitted confidence intervals. The periods after the solid red vertical line indicate that carbon trading has started. 95% confidence intervals in dashed lines are shown.

Table 4: Effects of the Carbon Trading on Energy Consumption Patterns: Firm-Level

Variables	(1)	(2)	(3)	(4)
Panel A: ln(Power Use)				
D_{pt}	-0.375**		-0.388**	
	(0.180)		(0.178)	
D_{pt} × ProvETS$_p$		0.555***		0.495***
		(0.172)		(0.162)
D_{pt} × CityETS$_p$		-0.976***		-0.959***
		(0.274)		(0.275)
Controls: output			✓	✓
Controls: others	✓	✓	✓	✓
FEs: firm	✓	✓	✓	✓
FEs: region×year	✓	✓	✓	✓
FEs: regional power grid×year	✓	✓	✓	✓
Observations	15,260	15,260	15,260	15,260
Panel B: ln(Fossil Fuels)				
D_{pt}	-0.279		-0.293	
	(0.181)		(0.179)	
D_{pt} × ProvETS$_p$		0.193		0.140
		(0.238)		(0.227)
D_{pt} × CityETS$_p$		-0.605**		-0.594**
		(0.239)		(0.240)
Controls: output			✓	✓
Controls: others	✓	✓	✓	✓
FEs: firm	✓	✓	✓	✓
FEs: region×year	✓	✓	✓	✓
FEs: regional power grid×year	✓	✓	✓	✓
Observations	13,838	13,838	13,838	13,838

Notes: Standard errors are clustered at the firm level. *** p<0.01, ** p<0.05, * p<0.1

the firm-level output, the estimate regarding fossil fuel use in city ETSs decreases by around 1 percentage point to 59.4 log points (-44.8%), while that of province ETS decreases by more than 5 log points but is still not significant. It appears that above-ETS-threshold firms in city ETSs with absolute-emission regulation reduced both types of energy input, while regulated firms in province ETSs with intensity-emission regulation utilized power rather not fossil fuels in response to the implicit output increase during our sample periods.

Spillover Effects of Carbon Leakage To evade the (incomplete) regulation of carbon control, unregulated firms could have the motive to reduce carbon emissions to avoid being regulated, i.e., anticipation effects. In contrast, regulated firms could have the incentive to shift production to unregulated counterparts. However, the shifting behavior cannot fully offset all reductions in output and energy use due to carbon regulation (Chen et al., 2025). The residual demand hence would increase, potentially further impacting unregulated firms.

We examine the firm-level spillover effects by conducting the same set of estimation specifications used for firm-level energy mixes but using samples of below-ETS-threshold firms during the same periods instead. In contrast to the above-threshold firms located in non-ETS regions, which are—on average—more competitive, the below-threshold firms in the same region are relatively less likely to be contaminated by production shifts or equilibrium competition. We hence compare how these below-threshold firms' evolutions in outcomes of interest differ after carbon trading.

Table 5 detects the firm-level spillover effects of carbon trading. Estimates in columns 1 and 3 show opposite directions of spillover effects for power and fossil fuel use. The power use of below-threshold firms in ETS regions decreased by 37.2 log points (31.1%), suggesting the ETS policy effects spilled over to unregulated firms and induced firms to reduce electricity consumption. It could mainly boil down to the anticipation effects that led unregulated firms to reduce energy use to evade yearly rolling incorporation of regulation or the potential expansion of the carbon market, in which both situations are related to annual energy consumption. Another interpretation could be relevant to the potentially limited accessibility of power for the below-threshold firms in ETS regions, where most fossil fuel-fired power plants in the same province are regulated. The below-threshold firms have a lower priority than larger firms for being satisfied with electricity demand when the power supply is constrained.

Nevertheless, the estimate in column 3 reports that unregulated firms witnessed around a 9% rise in fossil fuel use, indicating positive production shifts from regulated to unregulated firms, which dominated the underlying anticipation effects. The shift, or reallocation, in production hence appears to be associated with fossil fuels-intensive production. On the

Table 5: Spillover Effects of the Carbon Trading on Energy Consumption Patterns: Firm-Level

Variables	ln(Power Use)	ln(Power Use)	ln(Fossil Fuels)	ln(Fossil Fuels)
D_{pt}	-0.372***		0.087***	
	(0.025)		(0.030)	
$D_{pt} \times \text{ProvETS}_p$		0.060		-0.039
		(0.039)		(0.068)
$D_{pt} \times \text{CityETS}_p$		-0.478***		0.115***
		(0.029)		(0.032)
Controls	✓	✓	✓	✓
FEs: firm	✓	✓	✓	✓
FEs: region×year	✓	✓	✓	✓
FEs: regional power grid×year	✓	✓	✓	✓
Observations	323,500	323,500	208,447	208,447

Notes: Standard errors are clustered at the firm level. *** p<0.01, ** p<0.05, * p<0.1

one hand, the high emission reduction cost of fossil fuels-intensive production could straightforwardly provoke regulated firms to reallocate production. On the other hand, it is arduous to entirely shift the reduced production in the short run due to constrained production capacity. Thus, unregulated firms could further spur production when facing a raised residual demand.

In terms of heterogeneous effects, columns 2 and 4 in Table 5 present two patterns. First, below-threshold firms in province ETSs saw no significant change in either power or fossil fuel use after the carbon trading. Second and in contrast, unregulated firms in city ETSs witnessed a difference of 47.8 log-point falls in power use and an 11.5 log-point rise in fossil fuel use relative to that of below-threshold firms in non-ETS regions.

The firm-level spillover of carbon leakage is prominent in city ETSs rather than in their province counterparts. The discrepancy in spillover effects between province and city ETSs is indeed consistent with the feature of allowance allocation rules in different types of ETSs, as seen in Section 2.1, Allowance Allocation Rules. Firms in province ETSs under intensity-emission regulations follow output-based allowance allocation rules, which incorporate output subsidies as long as the emission intensity has complied. On the contrary, the rules for allocating emission permits in city ETSs depend on absolute historical emissions. They hence conduce more stringency for carbon mitigation, which would incline firms to resort more to regulation evasion. A similar nexus between output-based allowance allocation rules and carbon leakage is conducted theoretically and numerically in Goulder et al. (2022), but we present the first empirical evidence.

5 ETS and Power Supply

We move on to the power supply side to investigate the impacts of ETS on power trade, dispatch, and investment.[35] We are interested in how the policy effects vary by supply-side agents and regions over time.

5.1 Power Trade

The supply-side reactions, passively reacting to demand-side evolutions, are also crucial to be disclosed due to their carbon-intensive nature to overview the ETS's impacts comprehensively. As detailed in Section 2.2, the inter-provincial power trade is determined by agreements negotiated between bilateral local governments at the end of the year before, and local power generators complement the residual electricity demand conditional on these power transmission agreements.

To evaluate the change in the power supply response to carbon trading, we adapt province-level specifications of Eq.(7) - (8) by first replacing the dependent variable with net imports in province p and year t. Since the value of net imports can be negative, we alter all log variables into corresponding level specifications. Our benchmark specifications do not include provincial power consumption as a covariate. Still, we introduce it to the preferred settings to draw a comprehensive picture of net power import and local power consumption.

We control the same rich set of spatial and temporal fixed effects as we discussed before at the provincial specifications. The β then captures the difference in evolutions of the net imports between ETS and non-ETS regions before and after carbon trading. The identification power of β comes from the within-fixed effects variations that bring nearby provinces into control groups. Nevertheless, the inter-province power trade, especially that of ETS regions, mainly transits from western or southwestern provinces, rich in renewable energy but located in remote power-grid areas. The specification can purge the potential bias due to violating the stable unit treatment value assumption (SUTVA). The nearby provinces that function as control units are mostly insulated from treated areas regarding power trade. The only point that needs attention when interpreting the estimates is to divide by 2 to avoid double counting.[36]

[35] The production-side emissions of fossil fuels are trivial to combustion from end users. Thus, few relevant firms have been regulated under the pilot ETS.

[36] In the context of bilateral trade, an increment in the net imports of one party is met with a concomitant decrease in the net imports of the other party, with an equal magnitude.

Figure 4 presents the evolution of the net imports of ETS regions relative to that of non-ETS counterparts before and after the implementation of carbon trading when conducting parallel trend tests. It appears that there is no statistically significant difference before the practice of ETS. The estimates exhibit a positive and prominent level shift after the carbon trading, suggesting the local government in ETS regions tended to sign more bilateral electricity transmission agreements to import more (or export less) electricity from (to) other provinces in response to the ETS policy. The rise of net import of power, in essence, reallocates local power generation and hence carbon emissions to other provinces.

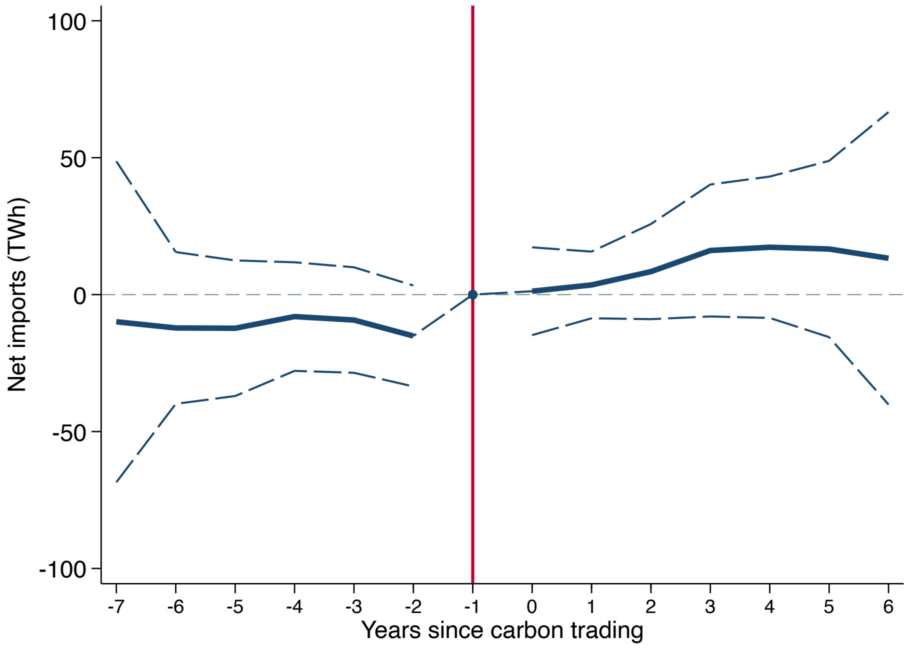


Figure 4: Changes in Electricity Trade

Notes: We normalize the year before the implementation of the pilot ETS policy to zero with omitted confidence intervals. The periods after the solid red vertical line indicate that carbon trading has started. 95% confidence intervals in dashed lines are shown.

Table 6 shows the overall change in net imports associated with carbon trading. The first and last two columns differ from each other by whether controlling the total power consumption. Note that we must divide all the estimates by 2 to avoid double counting before interpreting the results. We first focus on the benchmark specification without controlling the total power consumption, as shown in the first two columns. The ETS policy seems to increase net imports of power by 9 tWh/year per ETS region. However, if we examine the heterogeneous effects shown in column 2, the province ETSs' net power imports grew 18 tWh/year per ETS region, while the city counterparts reduced net power imports by 6 tWh/year per ETS region, compared to non-ETS areas.

In contrast, when controlling the total power consumption, the estimates of province ETSs regarding net power imports decrease by 8 tWh/year to 10 tWh/year per ETS region,

Table 6: Effects of the Carbon Trading on Electricity Trade

Variables	Net Imports	Net Imports	Net Imports	Net Imports
D_{pt}	17.914*** (6.522)		20.590*** (4.532)	
$D_{pt} \times \text{ProvETS}_p$		36.575*** (8.476)		20.168*** (5.827)
$D_{pt} \times \text{CityETS}_p$		-12.862* (7.272)		21.311*** (6.682)
Controls: total power consumption			✓	✓
Controls: others	✓	✓	✓	✓
FEs: province	✓	✓	✓	✓
FEs: region×year	✓	✓	✓	✓
FEs: regional power grid×year	✓	✓	✓	✓
Observations	390	390	390	390

Notes: Robust standard errors in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$

and that of city ETSs increase substantially by 17 tWh/year to 11 tWh/year per ETS region. The sharp changes reveal that the increase in province ETSs' net power imports in the second column partially responds to increased power consumption. Oppositely, the decline in net power imports of city ETSs in the same column is primarily due to decreased power consumption. Once conditional on the total power consumption, it appears that both the province and city ETSs increased the net power import in response to the ETS policy, which suggests that the reaction and incentive of local government to increase import or decrease export regarding electricity is common and consistent among different types of ETSs.

It suggests that to comply with carbon regulation, local governments tend to adopt electricity trade to reallocate carbon-intensive power generation to non-ETS regions, which, to a certain extent, has weakened the effectiveness of the ETS. Further, once the national carbon market gets complete, the local amelioration of carbon emissions by shifting power generation to other non-ETS regions would retrograde promptly. Nevertheless, though the net carbon mitigation nationally would be gone in this case, trading power to avoid the ETS can still be beneficial as it raises demand for transmission infrastructure. For regions without suitable and sufficient renewable energy endowments, especially, constructing the long-distance power transmission infrastructure can conduce to connect clean sources of power to population centers and hence adopt more renewable energy.[37]

[37]However, this is not as effortless as it seems. The most significant practice bottleneck in many countries

5.2 Power Dispatch and Investment

After knowing how energy consumption and power trade are affected by carbon trading, it is intuitive how the local power supply would be impacted according to the power identity, i.e., $Q_{pt}^{\text{Generation}} = Q_{pt}^{\text{Consumption}} - (Q_{pt}^{\text{Import}} - Q_{pt}^{\text{Export}})$, where Q_{pt} terms are corresponding amounts of power at province p in period t. Regarding the local power supply, we are hence more interested in the composition of power generation, which internalizes and reflects emission information, rather than the pure changes in the total amount.

To do so, we slightly augment Eq.(3) by interacting the treatment indicator D_{it} with power-type dummy variables separately to investigate deeper power-type-specific policy effects. Nevertheless, the costs associated with narrowing down control groups to additional power-type levels come with the challenge of identifying appropriate controls. The concerns turn out to be severer, especially for city ETSs, which are rich in economic development and power demand but with limited energy endowments and open lands, and hence hard to find comparable controls. Therefore, here we discreetly interpret the results as net policy results rather than causal effects.

We use detailed power plant data from the CEC to study power dispatch using the consistent empirical strategy:

$$\begin{aligned}\ln(\text{CapacityFactor}_{it}) = \alpha_i + \eta_{jt} + \delta_{kt} + \varphi_{dt} + \beta^{\text{Coal}} D_{it} \times \text{Coal}_i \\ +\beta^{\text{Gas}} D_{it} \times \text{Gas}_i + \beta^{\text{Renewable}} D_{it} \times \text{Renewable}_i + X_{it}'\gamma + \varepsilon_{it},\end{aligned} \tag{10}$$

where $\ln(\text{CapacityFactor}_{it})$ is logged capacity factor ($= \ln(\frac{\text{annual power generation}}{\text{capacity}\times\text{total hours a year}})$) of a power plant i at year t, which is commonly used to depict the situation of power dispatch and measure a power plant's utilization rate, or operating time equivalently. D_{it} is an indicator for the treatment, which equals one if the province where plant i is located is an ETS region and has started carbon trading at year t, and zero otherwise. Dummy variables Coal_i, Gas_i, and Renewable_i take the value one if plant i is a coal-fired, gas-fired, or hydro-/solar-/wind-power plant, respectively. We allow plant fixed effects α_i as well as the same set of spatial and temporal fixed effects, η_{jt} and δ_{kt}, as before. φ_{dt} now refers to power plant type-by-year fixed effects, which absorb all the unobserved time-variant technological changes of different types of power generation.

In the specifications, the set of coefficients β^{Coal}, β^{Gas}, and $\beta^{\text{Renewable}}$ indicate power plant type-specific treatment effects of carbon trading, respectively, relative to the same type

does not regard investments in clean power but in transmission. See https://www.economist.com/united-states/2023/01/29/america-needs-a-new-environmentalism for a recent debate regarding the hurdles to building transmission infrastructure in the US.

of power plants in non-ETS regions. We identify β's using variations driven by differences in capacity factor net of plant-year characteristics that include all fixed effects mentioned above. By interacting each D_{it} relevant terms with ProvETS_p and CityETS_p as in Eq.(6), we also study the heterogeneous effects of power dispatch across ETS regions.

Furthermore, provided effective carbon and power markets, the responded changes in power plants' capacity factor to the ETS tend to further deviate investment incentives from carbon-intensive power plants. We use province-sector data to examine this by estimating equations of the form:

$$\begin{aligned}\text{Investment}_{pdt} = \alpha_{pd} + \eta_{jt} + \delta_{kt} + \varphi_{dt} + \beta^{\text{Coal}} D_{pt} \times \text{Coal}_d \\ + \beta^{\text{Gas}} D_{pt} \times \text{Gas}_d + \beta^{\text{Renewable}} D_{pt} \times \text{Renewable}_d + X'_{pt}\gamma + \varepsilon_{pdt},\end{aligned} \tag{11}$$

where Investment_{pdt} is investment in capacity of d-type power generation sector in province p at year t.[38] Here, Coal_d, Gas_d, and Renewable_d equal one if power generation sector d is coal-fired, gas-fired, or hydro-/solar-/wind-power, respectively. α_{pd} is province-by-sector fixed effects absorbing unobserved provincial-power sectoral characteristics, e.g., heterogeneous distributions of provincial energy endowments, etc. Other controls are the same as before. Analogously, we examine heterogeneous effects in investment across ETS regions like previous specifications.

Table 7 presents the net policy outcome of carbon trading on power dispatch and capacity investment. Column 1 in the table shows that the implementation of the ETS policy induced the ETS regions to witness a significant 10.7 log-point (10.1%) decline in dispatching coal-generated electricity and, in contrast, a substantial rise of 58.9 percentage points (80.2%) in the utilization of gas-fired power, net of the effects on non-ETS counterparts. Meanwhile, the capacity factor of clean power almost kept stable with only a not significant minor drop (0.2%). We also investigate the heterogeneous effects regarding power dispatch, as shown in column 1 of Table 8. City ETSs decreased more in dispatching coal-generated electricity (-16.6% vs. -7.1%) but raised more in dispatching gas-generated electricity (90.6% vs. 70.7%) compared with province ETSs. In terms of renewable power dispatch, city ETSs dispatched less renewable power, while provincial counterparts utilized more in this regard, though both estimates are not statistically significant.

We further examine the changes in the provincial capacity investment of different types of power plants. 80% of the incumbent power plants have not observed any capacity reinvestment within the sample periods. The variation in province-level capacity investment hence almost entirely comes from the new entry of power plants. Column 2 of Table 7 suggests

[38] We refrain from applying the logarithmic transformation to the outcome variable as a result of the high incidence of zero investment among combinations of power type-provinces.

Table 7: Effects of the Carbon Trading on Power Dispatch and Investment

Variables	ln(Capacity Factor)	Investment
$D \times$ Coal	-0.107***	-20.126
	(0.035)	(32.707)
$D \times$ Gas	0.589***	34.171*
	(0.188)	(18.619)
$D \times$ Renewable	-0.002	-36.266***
	(0.026)	(11.555)
Controls	✓	✓
FEs: plant	✓	
FEs: province		✓
FEs: type×province		✓
FEs: type×year		✓
FEs: region×year	✓	✓
FEs: regional power grid×year	✓	✓
Observations	52,061	1,800

Notes: Standard errors are clustered at the plant level for the plant-level specifications. *** p<0.01, ** p<0.05, * p<0.1

that carbon trading inclined local governments in ETS regions to reduce investment in coal-fired power plants (though not significant) but approve more new gas-fired power projects relative to the non-ETS regions. Once we consider the heterogeneity of ETS type, as seen in column 2 of Table 8, the directions of the impacts on both coal- and gas-fired power plants' investment are still qualitatively consistent, however, the significant increase of investment in gas-fired power capacity is gone for both types of ETSs. In contrast, province ETSs witnessed a statistically significant 305 MW decline in the investment of renewable power capacity, while that of city ETSs decreased by 431 MW, compared with that of non-ETS regions. It appears that the limited renewable energy and land endowments hindered the adoption of renewable power, as revealed by comparing with non-ETS controls.

Note that, as we mentioned already, it's hard to find comparable controls at the province-power-type level for all ETS province-power-type combinations. Hence, all the β's here capture net policy effects, which are the sum of causal effects (i.e., ATT) and selection bias, as in Eq.(4). We discuss the directions of the potential selection bias to shed light on the treatment effects. The primary selection bias emerges from renewable energy for both power dispatch and investment. Comparatively, coal- and gas-fired power have no demanding requirements regarding energy endowment – coal and gas are transportable across regions. In contrast, renewable power demands specific natural endowments, e.g., wind, sunshine, or

Table 8: Effects of the Carbon Trading on Power Dispatch and Investment: Heterogeneous Effects

Variables		ln(Capacity Factor)	Investment
$D \times$ Coal	$\times$ProvETS$_p$	-0.074*	-30.779
		(0.043)	(50.240)
	$\times$CityETS$_p$	-0.182***	-10.103
		(0.049)	(34.119)
$D \times$ Gas	$\times$ProvETS$_p$	0.535***	39.416
		(0.156)	(24.440)
	$\times$CityETS$_p$	0.645**	27.823
		(0.296)	(27.509)
$D \times$ Renewable	$\times$ProvETS$_p$	0.003	-30.512**
		(0.026)	(15.392)
	$\times$CityETS$_p$	-0.036	-43.137***
		(0.168)	(14.748)
Controls		✓	✓
FEs: plant		✓	
FEs: province			✓
FEs: type×province			✓
FEs: type×year			✓
FEs: region×year		✓	✓
FEs: regional power grid×year		✓	✓
Observations		52,061	1,800

Notes: Standard errors are clustered at the plant level for the plant-level specifications. *** p<0.01, ** p<0.05, * p<0.1

hydraulic potential energy, which cannot be acquired and nurtured. ETS regions do not have the natural conditions for developing mass renewable energy relative to non-ETS areas.[39] Therefore, the selection bias of renewable power for both power dispatch and investment should be negative, i.e., the potential outcomes of ETS regions would be lower than that of non-ETS areas even if there had never been exposed to the ETS policy. This leads to underestimating the ETS treatment effects on both power dispatch and investment in renewable power.

Ultimately, by combining the local dispatch centers' behaviors regarding interprovincial power trade that we can see in Table 6, an unequivocal picture of how local authorities in ETS provinces reacted to the pilot ETS policy can be depicted. Governments in ETS

[39]The evolution of the average installed capacity of renewable power between ETS and non-ETS regions in China can be found in Appendix Figure A.3.

regions tend to reduce coal-generated electricity dispatch and increase both power dispatch and approved capacity for gas-fired power generation units, which not only reallocates coal-fired power dispatch to gas-fired counterparts but also induces more gas-generated power on top of it due to the relative unavailability of renewable energy. At the same time, local governments are prone to conduct more power imports from or fewer power exports to non-ETS regions to substitute with local power generation, which straightforwardly leads to a potential reduction in carbon emissions.

6 Aggregate Impacts of the Pilot ETS Policy

Our analyses elaborate that carbon trading has affected various market participants to conduct a range of behaviors and outcomes. Using the estimates obtained from previous sections, we can compute the economic magnitudes of the aggregate impacts, which is more informative in evaluating the policy effects, especially when the provinces' size and resource structure differ substantially.

We perform back-of-the-envelope computations of ATT into magnitudes, as presented in Table 9, focusing on all the margins of adjustment that we find have significantly reacted to the ETS policy.[40] To illustrate how salient the ETS policy accounts for the total change of the variables of interest, we first report the average change (Δ) between the prior periods before the start of the ETS ($\overline{\text{Pre}}$) and the post periods after the beginning of the ETS ($\overline{\text{Post}}$). We further decompose Δ into ATT and $\Delta-$ATT, where $\Delta-$ATT denotes the net effects of all other factors except for the impact of ETS policy. We construct a salience ratio for ATT defined as $\frac{|\text{ATT}|}{|\text{ATT}|+|\Delta-\text{ATT}|} \times 100\%$ to reflect what fraction of the total change in the outcome of interest the ETS policy accounts for, which indicates how crucial the roles of ETS have played.

Panel A presents the impacts of carbon trading on power use and fossil fuels. We use the estimates from the province- but not firm-level specifications to calculate the magnitudes of effects because the province-level specification indicates more general equilibrium consequences of the pilot ETS policy. In contrast, the firm-level setting focuses more on partial equilibrium effects and has spillover effects.[41] Our main interests are the ATT magnitudes and salience ratio, as shown in the last two columns.

It appears that the ETS policy is more salient in the industrial energy consumption rather not the residential part, given the salience ratios. This is consistent with the scheme

[40] Given the value in the chosen base year, the magnitudes of treatment effects per year are calculated by multiplying them by the relevant estimates in percent changes ($e^{\beta}-1$) in log-log regressions. In level-level regressions, the estimates illustrate the magnitudes directly.

[41] See Section 4.2, Spillover Effects of Carbon Leakage, for more discussions.

Table 9: Components of the Impacts of the Pilot ETS Policy

Components of Effects	Type	$\overline{\text{Pre}}$	$\overline{\text{Post}}$	$\Delta = \overline{\text{Pre}} - \overline{\text{Post}}$		Salience Ratio
				$\Delta-$ATT	ATT	
Panel A: Energy Consumption						
a) Residential						
Power Use (tWh)	Prov ETS	27	49	25	**-3**	10%
	City ETS	12	17	7	**-2**	20%
Fossil fuels (10^4 tons)	Prov ETS	590	635	46	**0**	0%
	City ETS	233	240	7	**0**	0%
b) Industrial						
Power Use (tWh)	Prov ETS	102	154	46	**6**	12%
	City ETS	38	42	12	**-9**	41%
Fossil fuels (10^4 tons)	Prov ETS	5,089	4,059	-217	**-813**	79%
	City ETS	2,040	1,546	65	**-560**	90%
Panel B: Power Supply						
a) Power Trade						
Net Imports (tWh)	Prov ETS	5	48	32	**10**	24%
	City ETS	28	50	11	**11**	49%
b) Power Dispatch						
Operating Hours (Hour) - Coal	Prov ETS	4,067	3,422	-207	**-438**	68%
	City ETS	4,784	3,759	107	**-1,132**	91%
Operating Hours (Hour) - Gas	Prov ETS	2,326	2,656	-1,814	**2,143**	54%
	City ETS	1,649	2,496	-782	**1,629**	68%
c) Power Investment						
Investment (MW) - Renewable	Prov ETS	929	977	353	**-305**	46%
	City ETS	32	214	613	**-431**	41%

Notes: $\overline{\text{Pre}}$ denotes the mean values of the variable of interest during the periods before the start of the ETS policy. $\overline{\text{Post}}$ indicates the mean values of the variable of interest during the periods after the beginning of the ETS policy. We define Salience Ratio= $\frac{|\text{ATT}|}{|\text{ATT}|+|\Delta-\text{ATT}|} \times 100\%$.

design of the carbon market, which is primarily specific to establishments but not households. Regarding industrial energy consumption, the province ETSs have witnessed a rise in power use by 6 tWh/year per ETS region on average, while city ETSs reduced by 9 tWh/year of power use per ETS region at the same time. In contrast, both types of ETS declined fossil fuel use substantially by 813×10^4 and 560×10^4 tons of standard coal, respectively. ETS regions responded to the ETS policy more considerably in fossil fuel use (79% and 90%) than power use (12% and 41%) in terms of the salience ratios.

Panel B of Table 9 shows the effects of ETS from the power supply side. The qualitative impacts of carbon trading on province and city ETSs are consistent in directions. As shown in sub-panel a) Power Trade, ETS regions have incentives to increase the import from or decrease power export to the non-ETS areas by around 10 tWh/year per province in response to the pilot ETS, by which they shift power generation and consequent emissions out.

Simultaneously, regarding power dispatch, ETS regions substantially utilize gas-fired power plants to substitute more emission-intensive coal-fired counterparts. The operating hours of coal-generated power declined by 438 hours/year and 1,132 hours/year in province and city ETSs, respectively. In contrast, power distributors in ETS areas dispatched more gas-generated power by 2,143 hours/year and 1,629 hours/year per ETS in the province and city ETSs, respectively, compared to non-ETS regions. The considerable salience ratios suggest that the ETS policy accounted for a nontrivial fraction of the total change in power dispatch for both coal- and gas-generated power.

In terms of renewable power, we don't find significant changes in power dispatch in both types of ETSs compared with that in non-ETS areas. Nevertheless, the investment in renewable power capacity declined by 305 MW/year and 431 MW/year in the province and city ETSs, respectively, compared to non-ETS regions. As discussed in Section 5.2, the inconsequential change in power dispatch and relative fall in the capacity investment of renewable power is partially hindered by the limited renewable energy endowments.

Furthermore, as we can see from the salience ratios from the energy consumption to the power supply, the pilot ETS accounted for a more substantial fraction of the total change in city ETSs, which adopted absolute-type carbon emission regulation, than that of province ETSs, which were under intensity-type carbon mitigation initiatives. The more stringent absolute emission regulation hence indeed induced more salient reactions from various market participants.

Magnitudes of Aggregate Impacts We compute the economic magnitudes of aggregate effects by summing up all the components of effects from the energy consumption side. The total impacts of pilot ETS aggregating from either energy consumption or supply should be the same due to the energy identity—however, two underlying reasons induce us to aggregate from the energy consumption side. First, the energy consumption specifications in our study have more extended periods than most supply-side setups, which corresponds to a more comprehensive picture. Second, the impacts of ETS on energy consumption are imputed from the provincial level with a more macro perspective, considering more general equilibrium consequences. In contrast, the specification of power dispatch in the power supply sides is conducted at the plant level, being exposed to more potential spillover effects.

We first convert the amount of electricity into carbon emissions equivalently using electricity emission factors across different power grids released by NDRC (see Table A.2). We further transfer the carbon emissions into standard coal equivalently given the emission factor of standard coal, i.e., 2.774 kg CO_2/kg. Conclusively, aggregating all the impacts corresponds to overall annual reductions in energy consumption of 751×10^4 and 866×10^4 tons of standard coal equivalent, or 9% and 23% of yearly energy consumption in the province and city ETSs, respectively.[42] The curtailment of fossil fuel consumption in standard coal metric is commensurate with a decrease in CO_2 amounting to $2{,}082 \times 10^4$ and $2{,}401 \times 10^4$ tons. It suggests that the pilot ETS policy indeed induced carbon mitigation for both types of ETS markets but with distinct tradeoffs. The city ETSs with absolute emission regulation can achieve more effective carbon reductions but with more output loss and severer potential carbon leakages. Comparatively, province ETSs with intensity-type emission regulation can incur less output fall by design but curtail emissions less substantially in magnitudes.

7 Conclusion

In this paper, we examine the behaviors of market participants in response to carbon trading along the value chain, including residential and industrial consumers and local authorities responsible for power trade, dispatch, and investment. China's pilot carbon trading practices provide a unique carbon ETS setting for studying absolute- and intensity-type emission regulations in regions with distinct economic development conditions, i.e., province- and city-ETSs. We take advantage of detailed energy use and production information for consumers (e.g., industrial firms) and producers (e.g., power plants) to comprehensively estimate the overall effects of the pilot ETS policy in China.

To this end, we implement a consistent empirical strategy to construct multiple DiD specifications to capture the policy outcomes of interest and disentangle the heterogeneous effects of distinct types of carbon markets. We utilize the variations in power and fossil fuels use, net imports, and power dispatch and investment, net of a host of spatial and temporal

[42] Take the average energy consumption during the periods before the start of the ETS policy as the base.

characteristics and fixed effects, to identify the impacts of carbon trading on various agents.

Our results suggest that the pilot ETS policy indeed reduced annual overall carbon emissions of, on average, $2{,}082 \times 10^4$ and $2{,}401 \times 10^4$ tons of CO_2 in the province and city ETSs, respectively, though the mechanisms differ a bit. We find clear evidence that under carbon markets with intensity-type emission regulations, e.g., province ETSs, firms have incentives to substitute fossil fuels with electricity, which is essential for sustainable carbon reduction. In contrast, carbon markets with absolute-type emission regulations induced more stringency regarding emission mitigation, which led to more effective carbon curtailment but also incurred severer carbon leakages.

In terms of power generation, we account for all types of power generation simultaneously to consider potential equilibrium effects among power units. The estimates indicate that, in response to the pilot ETS policy, the increases in gas-generated power generation substantially offset the declines in coal-generated power dispatch in both types of ETSs. Concurrently, ETS regions had consistent motives to increase the import or decrease power export from non-ETS areas to shift power generation and consequent emissions out.

The study has broader implications for thinking about carbon emission reductions. First, renewable energy is inherently cleaner than coal-fired power plants. However, for regions without suitable and sufficient renewable energy endowments, constructing the long-distance power transmission infrastructure is essential for connecting clean power sources to population and demand centers. Second, imperfect markets stemming from imperfectly competitive markets and/or incomplete regulation are common in developing countries. Our results show that ETS with appropriate adaptation can still be efficacious in emission mitigation under such scenarios. Notably, the presence of potential carbon leakages further elaborates that environmental regulation with intensity standards might be more appropriate for developing economies (Holland, 2012; Goulder et al., 2022, 2023).

Appendix

A Figures and Tables

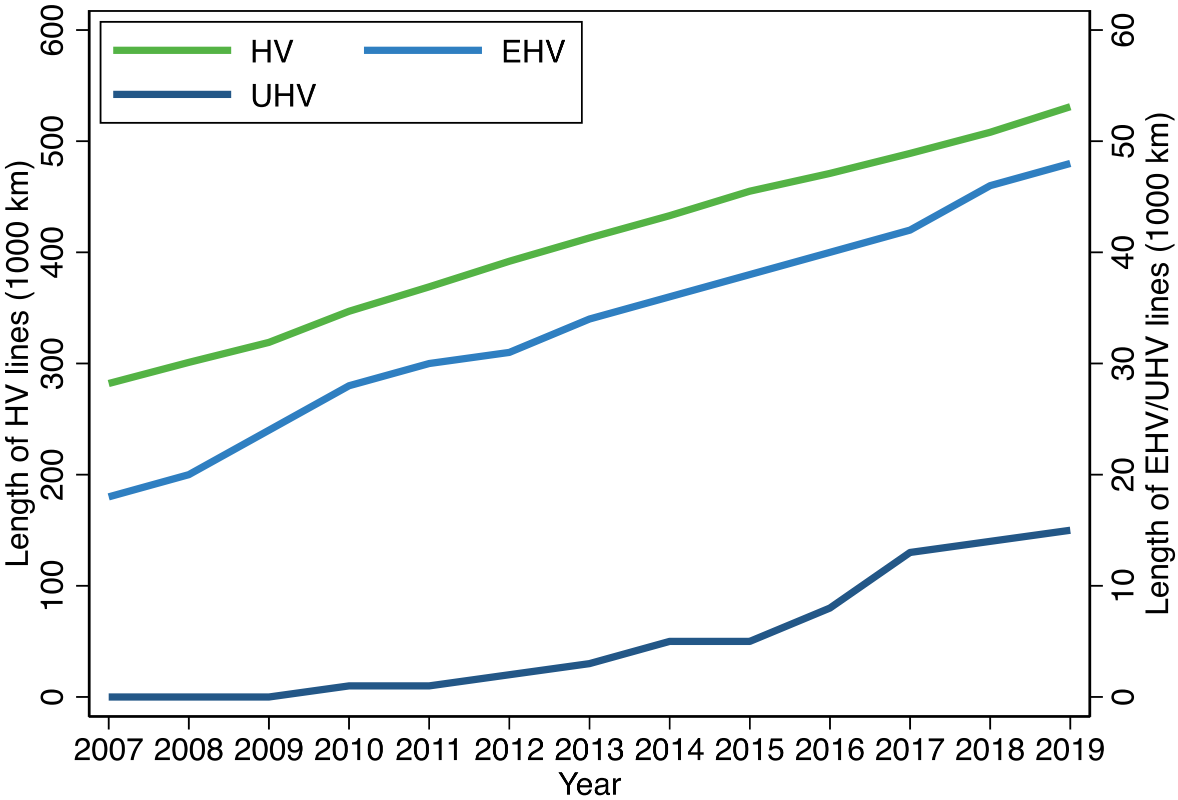


Figure A.1: Evolutions of the Construction of High-Voltage Electricity Transmission in China

Notes: HV: High-Voltage lines (e.g., 35 kV, 110 kV, and 220 kV, etc.); EHV: Extra-High-Voltage lines (e.g., 330 kV, 400 kV, 500 kV, 660 kV, and 750 kV, etc.); UHV: Ultra-High-Voltage lines (e.g., 800 kV and 1000 kV, etc.). The lengths are weighted by their designed voltage.

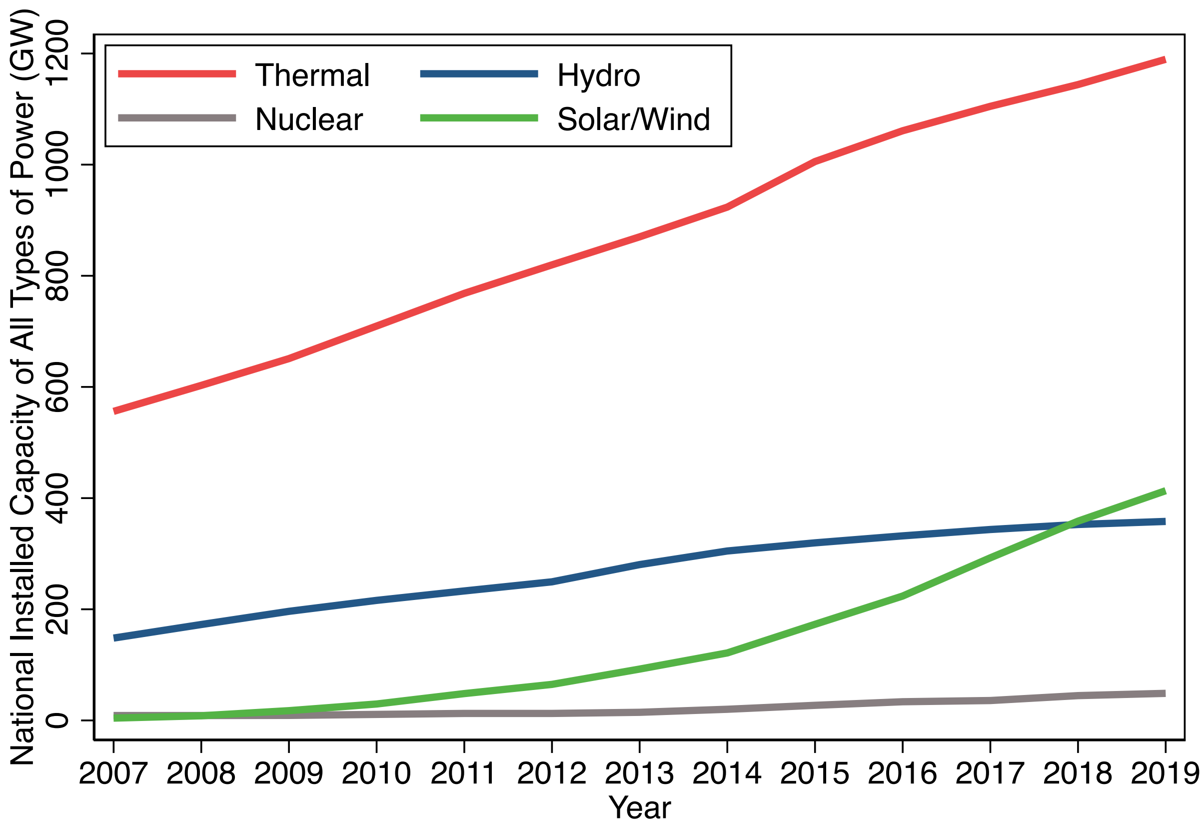


Figure A.2: Evolution of the National Installed Capacity of All Types of Power in China

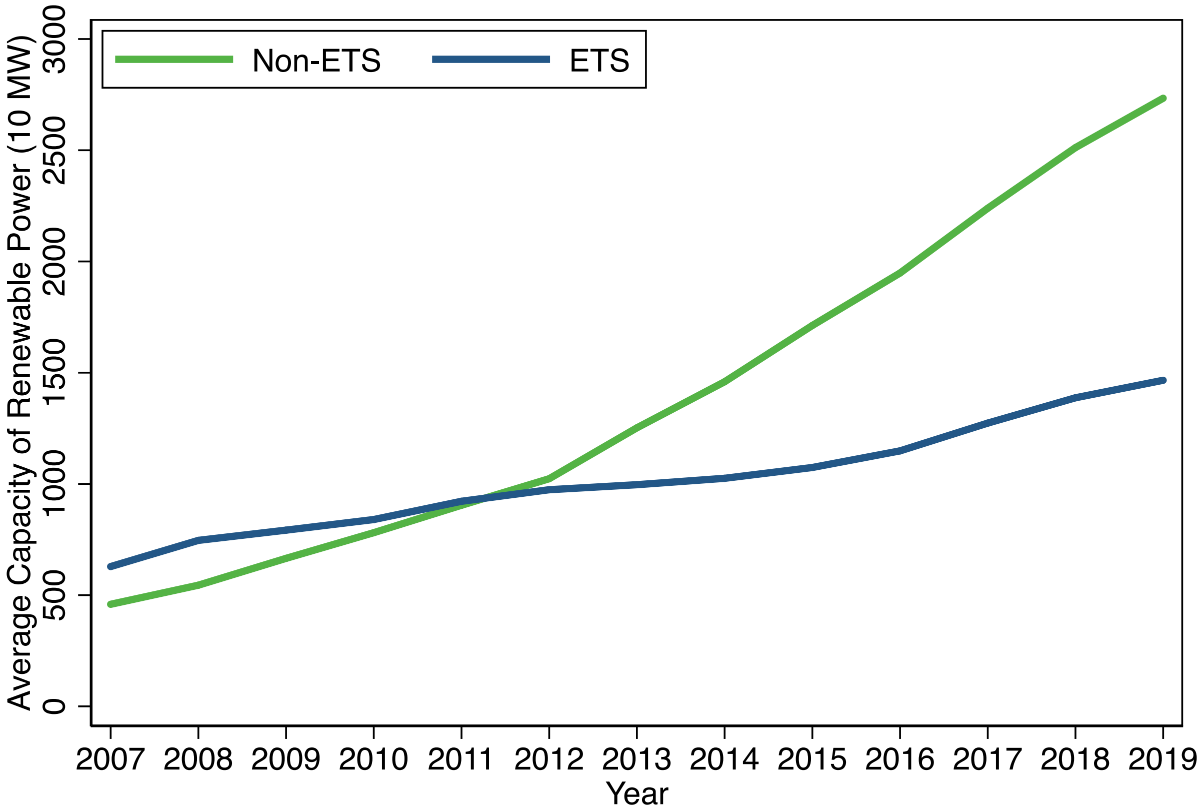


Figure A.3: Evolutions of the Renewable Power Capacity in China: ETS vs. Non-ETS

Table A.1: Threshold in Composite Energy Consumption Across ETS Regions

ETS regions	Year of establishment	Threshold in composite energy consumption (tons of standard coal)
Beijing	2013	2013-2014: >5,000 tons Since 2015: >2,500 tons
Tianjin	2013	>10,000 tons
Shanghai	2013	>10,000 tons
Guangdong	2013	>10,000 tons
Hubei	2014	>60,000 tons
Chongqing	2014	>5,000 tons

Table A.2: The Average CO_2 Emission Factor of China's Regional Power Grids in 2012

Regional Power Grid	Emission Factor (kg CO_2/kWh)
Northern Power Grid	0.8843
Northeastern Power Grid	0.7769
Eastern Power Grid	0.7035
Central Power Grid	0.5257
Northwestern Power Grid	0.6671
Southern Power Grid	0.5271

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 Xu, "Regulating Conglomerates in China: Evidence from an Energy Conservation Program," *American Economic Review*, 2025.

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.

_ , _ , Zhenxuan Wang, Junjie Zhang, and Yang Zheng, "Carbon Leakage within Firm Ownership Networks: Evidence from China's Regional Carbon Market Pilots," 2022.

Fabra, Natalia and Mar Reguant, "Pass-through of emissions costs in electricity markets," *American Economic Review*, 2014, *104* (9), 2872–99.

Fowlie, Meredith, "Incomplete environmental regulation, imperfect competition, and emissions leakage," *American Economic Journal: Economic Policy*, 2009, *1* (2), 72–112.

_ , "Emissions trading, electricity restructuring, and investment in pollution abatement," *American Economic Review*, 2010, *100* (3), 837–69.

_ and Mar Reguant, "Mitigating emissions leakage in incomplete carbon markets," *Journal of the Association of Environmental and Resource Economists*, 2022, *9* (2), 307–343.

_ and Nicholas Muller, "Market-based emissions regulation when damages vary across sources: What are the gains from differentiation?," *Journal of the Association of Environmental and Resource Economists*, 2019, *6* (3), 593–632.

_ , 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," *The Journal of Industrial Economics*, 2014, *62* (1), 41–76.

Goulder, Lawrence H and Richard D Morgenstern, "China's Rate-Based Approach to Reducing CO2 Emissions: Attractions, Limitations, and Alternatives," in "AEA Papers and Proceedings," Vol. 108 2018, pp. 458–62.

_ , Xianling Long, Chenfei Qu, and Da Zhang, "China's nationwide Co2 emissions trading system: A general equilibrium assessment," Technical Report, National Bureau of Economic Research 2023.

_ , _ , 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," *The Quarterly Journal of Economics*, 2020, *135* (4), 2135–2185.

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

Holland, Stephen P, "Emissions taxes versus intensity standards: Second-best environmental policies with incomplete regulation," *Journal of Environmental Economics and management*, 2012, *63* (3), 375–387.

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

Lam, Pun-Lee, "Pricing of electricity in China," *Energy*, 2004, *29* (2), 287–300.

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.

Li, Hongbin and Li-An Zhou, "Political turnover and economic performance: the incentive role of personnel control in China," *Journal of public economics*, 2005, *89* (9-10), 1743–1762.

Liu, Junxia, "China's renewable energy law and policy: a critical review," *Renewable and Sustainable Energy Reviews*, 2019, *99*, 212–219.

Meunier, Guy, Jean-Pierre Ponssard, and Philippe Quirion, "Carbon leakage and capacity-based allocations: Is the EU right?," *Journal of Environmental Economics and Management*, 2014, *68* (2), 262–279.

Ren, Mengjia, Lee G Branstetter, Brian K Kovak, Daniel Erian Armanios, and Jiahai Yuan, "Why has China overinvested in coal power?," *The Energy Journal*, 2021, *42* (2).

Rubin, Donald B, "Estimating causal effects of treatments in randomized and nonrandomized studies.," *Journal of educational Psychology*, 1974, *66* (5), 688.

_ , "Bayesian inference for causal effects: The role of randomization," *The Annals of statistics*, 1978, pp. 34–58.

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), 3814–54.

Walker, W Reed, "The transitional costs of sectoral reallocation: Evidence from the clean air act and the workforce," *The Quarterly journal of economics*, 2013, *128* (4), 1787–1835.

Wang, Chen, Kaile Zhou, and Shanlin Yang, "A review of residential tiered electricity pricing in China," *Renewable and Sustainable Energy Reviews*, 2017, *79*, 533–543.

Wang, Shaoda and David Y Yang, "Policy Experimentation in China: The Political Economy of Policy Learning," Technical Report, National Bureau of Economic Research 2021.

Yang, Lisha and Boqiang Lin, "Carbon dioxide-emission in China's power industry: evidence and policy implications," *Renewable and Sustainable Energy Reviews*, 2016, *60*, 258–267.

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.

Zhang, Peidong, Yanli Yang, Yonghong Zheng, Lisheng Wang, and Xinrong Li, "Opportunities and challenges for renewable energy policy in China," *Renewable and Sustainable Energy Reviews*, 2009, *13* (2), 439–449.

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.