Heliyon 10 (2024) e24326

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

The impact of China's carbon trading policy on enterprises' energy-saving behavior

Qianling Zhou [a,*], Xiaoyong Cui [b], Hongfu Ni [c,**], Liutang Gong [d,e], Shengzhi Mao [f]

[a] School of Economics, Beijing Technology and Business University, Beijing, 100048, China
[b] School of Economics, Peking University, Beijing, 100871, China
[c] Institute of Economics, Chinese Academy of Social Sciences, Beijing, 100871, China
[d] Guanghua School of Management, Peking University, Beijing, 100871, China
[e] Beijing Technology and Business University, Beijing, 100048, China
[f] School of Economics, Southwestern University of Finance and Economics, Chengdu, 610074, China

ARTICLE INFO

Keywords:
Carbon emissions trading policy
Firm-level energy intensity
Difference-in-differences method

ABSTRACT

This paper mainly investigates whether emissions trading for pollutant permits more effective. By employing difference-in-differences method and a compressive firm-level dataset, we evaluate the impact of carbon trading system pilot cities policy on enterprises' energy-saving behavior. The findings indicate that after carbon trading system pilot cities policy, enterprises' coal consumption and coal intensity decreased by almost 34 % and 33 % respectively. The policy effect is more pronounced for larger companies and for firms in energy-intensive sectors. Moreover, the policy effect becomes stronger over time. Our results satisfy the common trend assumption. Meanwhile, the investment in equipment and output are increased, which prove emissions marketization could bring about substantial improvements in productivity.

1. Introduction

The growing international energy crisis has led to a series of conflicts that seriously threaten global peace. Meanwhile, carbon emissions from energy consumption are causing global warming and other environmental problems. Because of various technical and cost constraints, new energy sources such as wind and solar energy currently cannot displace fossil fuels [1]. Therefore, reducing carbon emissions and improving energy efficiency is vital.

Similar to other countries, China is facing these serious challenges and has issued a series of policies to deal with them. As [2,3], these policies can be classified as command-and-control policies and market-based instruments. Compared with command-and-control regulations, which are mainly administrative measures [4], encompass establishing emissions reduction goals, mandating the closure of small energy- and emission-intensive businesses, and halting company operations. Market-based policies mainly rely on market regulations, such as emissions fees and tradable permits. This study focuses on a typical market-based instrument: the emissions trading system (ETS).

The first ETS was set up in the European Union (EU) in 2005. The underlying principle of an ETS is "cap and trade," in which a (shrinking) cap is set on the total amount of greenhouse gas (GHG) emissions and individual firms receive relatively small free

* Corresponding author.
** Corresponding author.
E-mail addresses: zhouqianling@btbu.edu.cn (Q. Zhou), nihf@cass.org.cn (H. Ni).

https://doi.org/10.1016/j.heliyon.2024.e24326
Received 3 August 2023; Received in revised form 20 December 2023; Accepted 7 January 2024
Available online 11 January 2024

allowances and trade on the carbon market to buy (sell) allowances if their emissions are larger (smaller) than their initial allowances (Aleksandar et al., 2021; Joachim et al., 2009; Michael, 2012; [5]. Theoretically, the ETS cap and an efficient pricing function limit total emissions and, more importantly, alleviate the misallocation of energy consumption and promote the utilization and invention of clean or low-carbon technologies (Teixidó et al., 2019).

China initiated a carbon-emission trading system pilot (CTP) program in 2011. The National Development and Reform Commission (NDRC) approved the launch of pilot carbon trading schemes in seven areas, including Beijing, Tianjin, Shanghai, Chongqing, Guangdong, Hubei, and Shenzhen, to gradually establish a domestic carbon market.[1] In 2013 after two years of preparation, these cities implemented an ETS similar to that in the EU, while other cities did not implement yet. Thus, it provides us a good quasi-natural experiment.

Employing difference-in-differences (DID) methodology, and a comprehensive firm-level pool dataset for the 2009–2015 period. We find the implementation of the CTP leads to a significant reduction in both coal consumption and coal intensity. This impact is particularly prominent in larger companies and energy-intensive sectors. Furthermore, the effectiveness of the policy strengthens over time, supporting the assumption of a common trend. Additionally, our analysis reveals that the CTP achieves its objective of energy conservation by incentivizing firms to improve fixed asset investments and management practices, rather than through production cuts. Overall, the intended outcome of the policy is successfully attained.

This study contributes to three gaps in the literatures.[2] First, the ETS aims to marketize emission charges, previous literature shows that China's CTP reform has improved environmental investment, and decreased China's carbon emissions [6,7]; Yang et al., 2020), improved air quality [8], promoted China's low-carbon economic transformation [9], and stimulated China's green total factor energy efficiency (Qi and Zhou, 2020), thereby promoting carbon equality among those regions [10]. The CTP has also increased overall employment (Yang et al., 2020) and rural residential income and employment [11]. However, research also shows that the EU ETS has not affected the performance of the cement, iron, and steel industries [12]. However, there is no evidence that the ETS improves energy efficiency.

Second, most of the relevant studies focus on region-level factors, but their findings may be partly driven by the pollution haven effect. Most of the literature involves regional-level analysis, such as at the city level [6,8] and province level [7,10,13]. Although the CTP has decreased carbon emissions and improved air quality in the affected cities, these changes may have been caused by structural industry changes, such as a decline in secondary industries [7–9], rather than substantial technical improvements. However, from a national perspective, those highly polluting industries have not disappeared but moved from developed regions to less developed regions (the pollution haven effect). Therefore, region-level studies are likely to overestimate the policy's effects. Firms' data hold certain advantages over regional data, which can identify the varied impacts of policies within different sectors (Zhou et al., 2022).

Third, a few studies are at the firm level, for instance Ref. [14], find that China's ETS significantly elevates firm-level TFP (total factor productivity). The policy also increases ETS firms' low-carbon innovation by 5–10 % [15]. The policy has accelerated outward direct investment from China intensively and extensively [16]. Luo et al. (2021) surveyed power firms in Guangdong and found that the ETS has led firms to standardize their low-carbon management systems and conduct transactions of carbon assets. Moreover, the ETS has possibly motivated advancements in energy-saving technologies and emission-reduction technologies. However, these studies did not study the impact of the ETS on enterprises' energy efficiency, and the underlying mechanisms.

The remaining part of this paper is organized as follows: Section 2 describes China's ETS and some related studies. Section 3 outlines our empirical strategy and describes the firm-level data. Section 4 reports empirical benchmark results, heterogeneous effects, and robustness analysis and investigates underlying mechanisms. Section 5 concludes the paper.

2. Policy background

This section presents a brief history and discusses the potential impact of China's ETS. After four decades of rapid industrialization as well as urbanization, China's ecological environment and natural resources are under enormous pressure and have become fragile, given China's large population and low per capita resources. Although China's energy intensity has decreased significantly in recent years (Zhou et al., 2022), its energy efficiency remains low compared with other countries [17]. In 2010, to promote resource conservation and achieve sustainable development, the State Council made decisions to promote the development and advancement of strategic emerging industries.[3] Among those decisions was the establishment and improvement of a trading system for major pollution and carbon emission enterprises.

In 2011, to implement the 12th Five-Year Plan and to control GHG emissions at a lower cost in 2020, the NDRC established pilot carbon-emission trading programs in five cities (Beijing, Tianjin, Shanghai, Chongqing, and Shenzhen) and two provinces (Hubei and Guangdong). Moreover, because of the complexity involved and the country's inexperience with such programs, these seven areas established and implemented their ETSs at various times, and the details of their programs vary. By 2013, all of the pilot cities had implemented carbon emission trading [18]. The NDRC also issued a methodology for measuring GHG emissions and reporting instructions for 10 energy-intensive industries, such as the iron and steel, cement, and chemical industries.

The policy's implementation makes it a good quasi-natural experiment to study the effects of the ETS. Although the policy does not cover many areas, the cities are scattered in the middle, east, and west of China and have radically different economic structures and

[1] See http://www.gov.cn/jrzg/2012-01/13/content_2043687.htm.
[2] The summary is shown in Appendix A1.
[3] The official statement can be found at http://www.gov.cn/zwgk/2010-10/18/content_1724848.htm.

resource endowments. Regions typically set an overall emission reduction goal, and then under that quota, companies trade emission allowances. The specific rules vary from region to region, but the essence of the programs is the same.[4] The proportion of GHG emissions covered by each region is between 40 % and 70 %.

3. Empirical method and data

3.1. Empirical method

We analysis the impact of the CTP on firm's energy-saving behavior with a DID model, which are frequently employed in research to identify the impacts of policies [19,20]. By comparing longitudinal data from treatment and control groups, before and after the reform, DID models could analysis whether an event has a causal effect. Specifically, we compare the consumption of coal as well as coal intensity of firms in cities with and without ETS programs before and after 2013. The estimation model is as follows:

$$energy_{it} = \alpha_0 + \beta_1 time_t + \beta_2 treat_i + \beta_3 time_t \times treat_i + X_{it}\gamma + firm_i + year_t + \mu_{it} \tag{1}$$

In the model, i represents the firm, t represents the year, and $energy_{it}$ denotes the consumption of energy of firm i in year t. We also analysis energy intensity, represented by $energyint_{it}$. The calculation for energy intensity is performed using the subsequent formula:

$$energy\ intensity = \frac{energy\ consumption}{output}. \tag{2}$$

$time_{it}$ is a dummy variable for the year of the reform that is set to 1 for observations after 2013 (Zhou and Qi, 2013), and otherwise 0. $treat_{it}$ is a dummy variable that indicates the firms affected by the reform; it equals 1 if firm i is in the treated group, and 0 otherwise. X_{it} is a vector of control variables used to control various firm characteristics. $firm_i$ represents firm fixed effects and controls all time-invariant differences between firms. $year_t$ represents year fixed effects and controls all of the yearly shocks common to firms, such as business cycles. α_0 is the constant term, and μ_{it} is the error term, clustered at the city level to deal with potential heteroskedasticity and serial autocorrelation.

After including firm and year fixed effects, the policy and time dummies are absorbed. Consequently, only the CTP interaction term remains. Thus, the estimation model becomes the following:

$$energy_{it} = \alpha_0 + \beta_3 time_t \times treat_i + X_{it}\gamma + firm_i + year_t + \mu_{it}. \tag{3}$$

In model (3), the coefficient β_3 of the interaction term ($time_t \times treat_i$) is the key result, denoted by *ctp*. It captures the gap between the treatment firms' and control firms' coal consumption and coal intensity after the CTP program implementation (the first difference), relative to before the implementation (the second difference). We expect β_3 to be negative and significant.

3.2. Data

Our firm-level data is from China's National Tax Survey Data (NTSD), which include firms' energy consumption, output, profit, labor and other firms' accounting data. This dataset includes firms of varying ownership types, sizes, and across different industries. Compared with other studies, which have utilized data on energy consumption costs from sources such as World Bank (Liao and Xu, 2019) or World Management Survey (see Boyd and Curtis (2014) for instance). However, given the variation in energy prices, the results of those studies may not accurately reflect the true effects of reducing carbon emissions. In addition, NTSD included all manufacturing industries across China, which avoid any potential sample selection bias and enhance the generalizability of our findings.[5]

To process the data, we have taken several steps. Firstly, we have eliminated duplicate observations by comparing taxpayer identification numbers and firms' names. Secondly, we have removed any unreasonable observations by applying the following criteria: (1) firms lose essential information for calculating variables or have output values not in the range of (0.1, 99.9); (2) firms with negative fixed assets or year-end assets; and (3) S or T categorized organizational units in the service sector, and enterprises with sector code number less than five digits. Thirdly, we employed region-industry calculated energy intensities of enterprises to identify abnormal fluctuations, and subsequently excluded any outliers. We then winsorized the observations by the top 1 % and bottom 99 %. Finally, we have grouped related industries by standardizing the industry classification codes given the GB/T 4754-2011 classification. After implementing these procedures, the resulting sample size is 174,244 observations.

The enterprise-level control variables include: (1) firm size, which is represented by the logarithmic value of the firms' total assets. Because of the scale effect, large firms usually have higher productivity [21]. Especially for high pollutant businesses (see Refs. [22, 23]; (2) firms' capital-to-labor ratio, which is calculated by dividing a firm's fixed assets by its labor costs, and Lan et al. (2012) shows that capital-intensive enterprises are also intensive in energy consumption. (3) Firm's ROA (return on asset), which is measured by firms' profit divided by firms' owners' equity.

4 http://www.cnemission.com/article/gywm/201907/20190700001681.shtmlhttp://www.cbeex.com.cn/article/gywm/jysjj/.

5 In contrast to some studies that concentrate on enterprises' energy efficiency by including specific industry section or provinces (Li, 2011) or solely targeting larger firms (Zhu et al., 2018).

The city-level control variables include: (1) GDP per person, which measures economic development of the cities where the firms are located. Firms located in developed regions can benefit from more favorable external environments that facilitate efficient production, compared to those in less developed regions [24]. (2) Population, which is measured urban population density [7]. The city-level data are collected from the *China City Statistical Yearbook*. We adjust GDP per capita and output for inflation using the province level price indices provided by the China's National Bureau of Statistics (NBS).

Table 1 shows the summary statistics, including (1) the quantities in logarithm form,[6] such as coal consumption (denoted as *Ln_coal*), coal intensity (*Ln_coal_int*), GDP per capita (*Ln_gdpper*), firm assets (*Ln_asset*), city population (*Ln_pop*); and (2) ratios, such as return on assets (*roa*) and capital-labor ratio (*kl_ratio*).

4. Empirical findings

4.1. Baseline results

Table 2 presents the fundamental findings. Columns (1) and (2) display the results for coal consumption, as calculated by equation (1). Columns (3) and (4) exhibit the results for coal intensity, as determined by equation (2). All columns incorporate year and firm fixed effects. Columns (1) and (3) display the reform variable without considering control variables. Columns (2) and (4) involve other control variables and present the estimations based on our primary specification.

Our focus is on the coefficients of *ctp*. The results indicate that the CTP decreases firms' coal consumption and coal intensity significantly. Specifically, the results in Column (2) show that after the CTP, enterprises' coal usage drops by around 34 % on average. Moreover, Column (4) results indicate a reduction of nearly 33 % in firms' average coal consumption, which translates to an enhancement in energy efficiency by approximately 33 %.

In addition, similar to Ref. [25]; Dai et al. (2018), and [26]; our results demonstrate that larger firms display superior energy efficiency without altering the intended meaning. Comparing with small firms, large firms are better at funding the green R&D in energy-saving and emission-reduction technologies. Moreover, the firms in more developed regions have greater energy efficiency relative to the firms in less developed regions.

4.2. Heterogeneous effects

Now we investigate the CTP's heterogeneous effects. We use interaction terms to examine the impact on enterprises of different size and industries. In our first heterogeneity analysis, we study whether the CTP has different effects on firms of varying sizes. For conducting this analysis, we execute the subsequent model:

$$energy_{it} = \alpha_0 + \beta_1 reform_{it} + \beta_2 lnscale_{it} + \beta_3\ reform_{it} \times lnscale_{it} + X_{it}\gamma + firm_i + year_t + \mu_{it}. \tag{4}$$

In model (4), $lnscale_{it}$ denotes firm *i*'s total assets in year *t*, and other variables remain the same as the benchmark specification. Given the differences in variable scales, we normalize the interaction variable intensity by demeaning and scaling it with its standard deviation for easier interpretation of the coefficients. The other variables are as defined in our basis Model.

Our focus is the coefficient of the interaction ($reform_{it} \times lnscale_{it}$), β_3, which we anticipate being significant and negative, which means after the reform, larger firms decrease coal consumption and coal intensity more. Table 3 gives the results. Columns (1) and (2) display the regression outcomes for coal consumption; Column (2) includes all control variables. Columns (3) and (4) feature the regression outcomes for coal intensity; Column (4) includes the control variables.

As Table 3, the influence of the CTP reform on energy efficiency is stronger for larger companies. The coefficient of $ctp \times lnscale$ in Column (2) is −0.0875, which suggests that for increase in firm size by one standard deviation, the CTP reform decreases firms' coal consumption by 8.75 %, on average. In Column (4), the coefficient of $ctp \times lnscale$ is −0.104, which suggests that for each one standard deviation increase in firm size, the CTP reform increases firms' energy efficiency by 10.4 %, on average. The results prove the policy effect is stronger on larger scale firms. Large firms typically have greater capacity to acquire equipment [27] and environmental investment compared to smaller firms, which allows them to enhance their energy efficiency more effectively.

We also investigate the varying effects on firms across different industries. To conduct this analysis, we employ the following model:

$$energy_{it} = \alpha_0 + \beta_1 ctp_{it} + \beta_2 intensity_{it} + \beta_3 ctp_{it} \times intensity_{it} + X_{it}\gamma + firm_i + year_t + \mu_{it}. \tag{5}$$

In model (5), $intensity_{it}$ is energy intensity at the two-digit industry code level (see the *China Energy Statistical Yearbook*), the same as firms' energy intensity, the unit is tons/1000 yuan.

Table 4 presents the impact of CTP on firms across industries of different energy intensity. The negative coefficient of $ctp \times intensity$, which is −0.152 in Column (2), aligns with the baseline findings. That is, the CTP reform reduces firms' coal consumption by 15.2 % once industries' energy intensity increases by one standard deviation. Column (4) results reveal that, on average, the CTP reform enhances firms' energy efficiency by 14.8 % more for each one standard deviation decrease in an industry's energy intensity. These findings confirm CTP reform affects more on energy-intensive industries and firms. The CTP reform is more effective in reducing

[6] To adjust for skewness, we take the logarithm of these variables.

Table 1
Summary statistics.

variables			mean	s.d.	min	p25	p75	p50	max
coal consumption	Ln_coal	firm-level,	5.363	3.132	0	2.996	7.409	5.338	13.40
coal intensity	Ln_coal_int	from NTSD	−5.111	2.600	−11.69	−6.769	−3.395	−4.994	0.750
GDP per person	Ln_gdpper	city-level,	10.690	0.707	8.391	10.13	11.27	10.65	12.94
city population	Ln_pop	from NBS	6.251	0.612	2.970	5.862	6.637	6.363	8.124
firms scale	Ln_asset	firm-level,	10.570	1.903	6.046	9.239	11.81	10.46	15.38
capital-labor ratio	kl_ratio	from NTSD	7.676	14.96	0.0208	1.262	7.167	3.058	109.8
return on assets	roa		0.0518	0.0745	0.0002	0.008	0.063	0.0246	0.462

Note: s.d. denotes standard deviation.

Table 2
The effects of the CTP reform: Baseline results.

VARIABLES	(1)	(2)	(3)	(4)
	Ln_coal	Ln_coal	Ln_coal_int	Ln_coal_int
ctp	−0.3667***	−0.3399**	−0.3460***	−0.3317**
	(0.119)	(0.137)	(0.126)	(0.137)
Ln_gdpper		−1.2511***		−1.2951**
		(0.422)		(0.549)
Ln_pop		−0.8796		−1.3806*
		(0.746)		(0.740)
Ln_asset		0.3615***		−0.1849***
		(0.021)		(0.026)
kl_ratio		−0.0024***		0.0032***
		(0.001)		(0.001)
roa		0.3924***		−1.5003***
		(0.134)		(0.130)
Constant	5.3748***	20.4232***	−5.1005***	19.3822**
	(0.004)	(6.936)	(0.004)	(9.146)
Observations	174,244	174,244	174,244	174,244
Firm FE	Controlled	Controlled	Controlled	Controlled
Year FE	Controlled	Controlled	Controlled	Controlled
R-squared	0.859	0.860	0.771	0.772

Notes：Robust standard errors in parentheses, ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$ and standard errors are clustered at city level for all regressions. The above notes also apply for following tables.

Table 3
Heterogeneity analysis for firms by scale.

VARIABLES	(coal consumption)	(coal consumption)	(coal intensity)	(coal intensity)
	Ln_coal	Ln_coal	Ln_coal_int	Ln_coal_int
ctp × *lnscale*	−0.1181***	−0.1166**	−0.1519***	−0.1448***
	(0.042)	(0.046)	(0.044)	(0.049)
ctp	−0.3243**	−0.3144**	−0.2915**	−0.2798*
	(0.129)	(0.143)	(0.139)	(0.150)
Control variables	No	Yes	No	Yes
Observations	174,244	174,244	174,244	174,244
Firm FE	Controlled	Controlled	Controlled	Controlled
Year FE	Controlled	Controlled	Controlled	Controlled
R-squared	0.859	0.860	0.771	0.772

coal consumption and coal intensity in energy-intensive industries.

4.3. Robustness analysis

4.3.1. Examining the parallel trend assumption

The credibility of baseline results hinges on the fact that no significant differences exist in the pretreatment trends between reformed and other firms (Beck et al., 2010; Nunn and Qian, 2011). Therefore, the differences between the above two groups shall be 0 before the reform. If their trends significantly diverge prior to the CTP reform policy implementation, our findings may stem from sample selection bias or time trends rather than the CTP reform itself. To deal with this issue, we propose the following parallel trend test model:

Table 4
Heterogeneous effect by different energy intensity industry.

VARIABLES	(coal consumption)	(coal consumption)	(coal intensity)	(coal intensity)
	Ln_coal	Ln_coal	Ln_coal_int	Ln_coal_int
ctp × *intensity*	−0.1609***	−0.1519***	−0.1565**	−0.1484**
	(0.056)	(0.055)	(0.061)	(0.061)
ctp	−0.3614***	−0.3344**	−0.3404***	−0.3260**
	(0.124)	(0.142)	(0.131)	(0.141)
Control variables	No	Yes	No	Yes
Observations	174,244	174,244	174,244	174,244
Firm FE	Controlled	Controlled	Controlled	Controlled
Year FE	Controlled	Controlled	Controlled	Controlled
R-squared	0.859	0.861	0.771	0.772

$$energy_{it} = \alpha_i + \sum\nolimits_{t=2009}^{2011} \beta_t D_t \times treat_i + \sum\nolimits_{t=2013}^{2015} \beta_t D_t \times treat_i + firm_i + X_{it} \times \gamma + year_t + \mu_{it}. \quad (6)$$

In model (6), D_t is a year dummy variable ($t = 2009, 2010, \ldots, 2015$), for example, for 2020, D_{2010} is 1, and otherwise 0. It should be noted that D_{2012} is dropped to avoid multicollinearity, so it is treated as a control year. Our model meets the parallel trend assumption if the coefficients of $D_t \times treat_i$ are nonsignificant.

Figs. 1 and 2 show the coefficients of β_t from model (6) and the 95 % confidence intervals and illustrate the dynamic effects of the policy. As shown, before the policy implementation year, the coefficients are nonsignificant and near 0, suggesting no significant difference between the reformed and the other firms before the reform, i.e., the parallel trend assumption is satisfied. After the CTP reform, a notable reduction in enterprises' coal consumption and coal intensity is observed. This finding indicates that the CTP reform substantially lowers the coal usage and coal intensity of impacted firms, with the policy effects intensifying over time.

4.3.2. Sensitivity tests

Here we do the robustness test for our baseline results further. Although the policy affected all enterprises, in the early stages, most of the transactions involved large and energy-intensive enterprises. Therefore, in the sensitivity tests, we limit the sample to large firms and firms in energy-intensive industries.

Table 5 presents the results for different subsamples. Columns (1) and (2) display the findings for large firms, specifically those in the top 70 % by size. Columns (3) and (4) present the outcomes for firms in energy-intensive industries. Based on their two-digit codes, we identify the following sectors as energy-intensive according to the NDRC: petroleum, coal, and other fuel processing industry with industry code 25; Chemical raw materials and chemical products manufacturing industry (26); nonmetallic mineral products manufacturing industry (30); ferrous metal smelting and rolling processing industry (31); nonferrous metal smelting and rolling processing industry (32); and electric power, heat production and supply industry (44). Results shown in Table 5 validate the solidity of our baseline findings.

4.3.3. Contemporaneous shocks

Other policies implemented during the sample period could also influence our results, implying that our results may be driven by those policies rather than the CTP reform. To check this issue, we conduct robustness tests to rule out their influence.

Initially, we evaluate the influence of the low-carbon pilot city (LCP) program. On July 19, 2010, the NDRC released the pilot work in terms of low-carbon provinces and cities (No. 1587), which implemented in 5 provinces and 8 cities. Subsequently, in 2012, a second

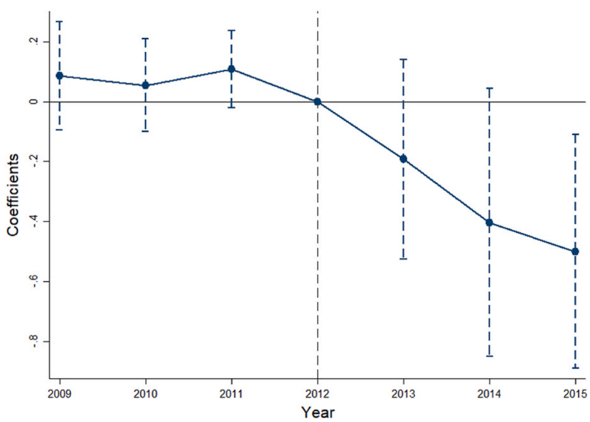

Fig. 1. The dynamic impact of the CTP on firms' coal consumption.

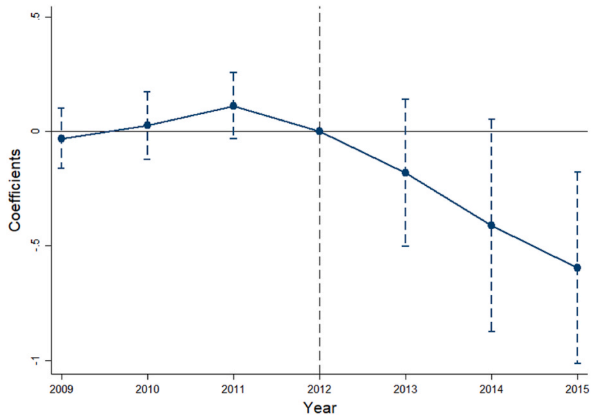

Fig. 2. The dynamic impact of the CTP on firms' coal intensity.

Table 5
Robustness analysis: Sensitivity tests with subsamples.

VARIABLES	(1)	(2)	(3)	(4)
	Ln_coal	Ln_coal_int	Ln_coal	Ln_coal_int
ctp	−0.4233*	−0.4041*	−0.3308*	−0.3329*
	(0.244)	(0.231)	(0.187)	(0.175)
Control variables	Yes	Yes	Yes	Yes
Observations	53,346	53,346	48,988	48,988
Firm FE	Controlled	Controlled	Controlled	Controlled
Year FE	Controlled	Controlled	Controlled	Controlled
R-squared	0.817	0.774	0.881	0.785

set of pilot areas was covered (No. 3760). The LCP program, mainly managed by local governments, involves multiple agencies and policies (Liu and Qin, 2016). These policies target the industrial structure to optimize energy distribution, enhance the efficiency of energy consumption, and decrease carbon emissions (see Khanna et al., 2014). The regulations vary across regions and cities since they set up their own low-carbon plans and industrial systems, carbon emission measurement and management systems, create different programs to achieve emission targets, and implement various other policies to encourage low-carbon lifestyles (Tie et al., 2020).

We add a control variable for the effects of the LCP reform. We define *LCP* as a dummy variable that equals 1 if a firm is covered by the LCP reform, and 0 otherwise. Table 6 reports the results, indicating that the impact of the CTP reform on enterprises' energy-saving behavior remains strong and significant after controlling for the influence of the LCP policy. The coefficients of both CTP and LCP are significant and negative, which suggests that both reforms reduce enterprises' coal consumption and coal intensity. After controlling for the LCP reform, the coefficients of CTP decrease slightly compared with the baseline regression, but they remain significant both economically and statistically.

We next examine an additional significant policy targeting pollution reduction that might influence the basic results. In 2003, the State Council promulgated the Regulations on the Administration of the Collection and Use of Pollution Discharge Fees, which stipulate the management of the collection and use of pollution discharge fees. In May 2007, the State Council gradually raising fees for SO2 emissions. Throughout this time, the SO2 emission fee doubled, from 0.63 yuan per kg to 1.26 yuan per kg, in the majority of provinces (refer to Appendix Table A2).

In order to understanding the impacts charges reform of SO_2 emission, we incorporate the control variable SO_2, which is a binary variable assigned the value of 1 if a firm is located in a region where the SO_2 emission charge was increased, and 0 otherwise. The results are shown in Table 7, and they are similar to the baseline regression results. The coefficients of *ctp* are significant and negative after controlling for the effects of the increased SO_2 emission charges. The coefficients of so_2 are nonsignificant, which suggests that the pollution charges do not improve firms' energy-saving behavior. Enterprises may choose to install filtration equipment rather than improve the energy efficiency of their production process. In a further robustness test, we control for both of these policy shocks, and the results are similar to the baseline results, as reported in Appendix Table A3.

4.4. *Underlying mechanisms*

This section investigates the mechanisms underlying the effects of the CTP on firms' energy-saving performances. We explore three potential mechanisms. First, we examine whether enterprises decrease energy consumption by reducing production by regressing *ctp* on the logarithm of firm output. Second, we examine whether companies enhance their energy efficiency through investments in fixed assets for upgrading their production equipment with higher production ability. We test this by regressing *ctp* on fixed assets. Third, we

Table 6
Low-carbon pilot cities policy shock.

VARIABLES	(1)	(2)
	Ln_coal	Ln_coal_int
ctp	−0.2832**	−0.2812***
	(0.110)	(0.107)
lcc	−0.1916*	−0.1707**
	(0.108)	(0.071)
Control variables	Yes	Yes
Observations	174,244	174,244
Firm FE	Yes	Yes
Year FE	Yes	Yes
R-squared	0.860	0.772

Table 7
Reform of SO_2 emission charges shock.

VARIABLES	(1)	(2)
	Ln_coal	Ln_coal_int
ctp	−0.3205**	−0.3293**
	(0.147)	(0.140)
so_2	−0.1297	−0.0159
	(0.124)	(0.108)
Control variables	Controlled	Controlled
Individual	Controlled	Controlled
Year	Controlled	Controlled
Observations	174,244	174,244
R-squared	0.860	0.772

examine whether firms improve their management and optimize production processes to eliminate energy waste and improve energy efficiency. We test this by regressing *ctp* on the logarithm of management fees.

The results are shown in Table 8, suggesting that the CTP reform stimulates firms' energy-saving behavior by increasing their investment in equipment and optimizing their management, rather than by decreasing their output. In Column (1), the coefficient of *ctp* is negative but nonsignificant and near 0, indicating that some firms reduce emissions by cutting production, but this mechanism is not significant. In Columns (2) and (3), the coefficients of *ctp* on fixed assets and management, respectively, are significant and positive, proving that when faced with increased emission costs, enterprises increase their investment in fixed assets to update equipment and increase their management costs to optimize management of the production process.

5. Conclusions

This study investigates the energy-saving impacts of China's CTP reform. By using a comprehensive firm-level dataset and a two-way fixed-effects DID model, we prove that the CTP reform significantly decreases enterprises' coal consumption and coal intensity. In other words, marketizing emissions leads to energy savings and greater energy efficiency. Further, the effect is stronger for sizable companies and those operating in energy-intensive sectors.

Our results are robust to the parallel trend test. We also consider contemporaneous policy shocks by controlling for the LCC program and increased SO_2 charges, and our results are robust. Furthermore, we analyze the underlying mechanisms of the effect, and the results suggest that it is driven by firms investing in equipment and improving management, not by reducing production. We also find that the effect becomes stronger over time.

This study has several limitations that provide directions for future research. We use a comprehensive dataset that includes all

Table 8
Mechanism analysis.

VARIABLES	(1)	(2)	(3)
	lnoutput	lninvest	lnmanage
ctp	−0.0550	0.0660***	0.0254*
	(0.045)	(0.024)	(0.015)
Control variables	Controlled	Controlled	Controlled
Observations	174,244	174,244	174,244
Firm FE	Controlled	Controlled	Controlled
Year FE	Controlled	Controlled	Controlled
R-squared	0.886	0.832	0.973

industries and specific energy consumption data, which is more accurate than regional analyses. However, because of limitations of the dataset, some mechanisms could not be analyzed. For example, the possible impacts of the CTP reform on enterprises' eco-friendly innovation, R&D, and pollution could be further investigated. In addition, as our sample comprises survey data are from all industries, we cannot capture the policy impacts on the entry and exit of firms. These issues warrant further study.

Data availability statement

The data are not publicly available due to legal restrictions.

Additional information

No additional information is available for this paper.

CRediT authorship contribution statement

Qianling Zhou: Conceptualization, Formal analysis, Writing - review & editing. **Xiaoyong Cui:** Conceptualization. **Hongfu Ni:** Conceptualization. **Liutang Gong:** Conceptualization. **Shengzhi Mao:** Writing - original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by grants from the National Natural Science Foundation of China (72204012) to Qianling Zhou; the National Natural Science Foundation of China (Grant No. 21&ZD097) to Xiaoyong Cui; the National Social Science Foundation of China (Grant No. 19ZDA069) to Liutang Gong; the General Program of National Natural Science Foundation of China (Grant No. 72073142) and Special Funds of the National Natural Science Foundation of China (Grant No. 72141309) to Hongfu Ni; Innovation Centre for Digital Business and Capital Development of Beijing Technology and Business University (SZSK202225) to Hongfu Ni and Qianling Zhou. This work was also supported by the National Social Science Fund of China (No. 21BJY192); Key Laboratory of Mathematical Economics and Quantitative Finance, Ministry of Education, Guanghua School of Management, Peking University.

Appendix

Appendix A1
Summary of literatures

Review of literature	Literature sources	Main contents of literature	Summaries
About the effect of China's CTP reform	Yang, 2023	CTP reform improved environmental investment	Different literatures analyze the different aspects of the reform, however, there is no evidence prove carbon trading system pilot cities policy improves energy efficiency.
	[6,7]; Yang et al., 2020	CTP reform decreased China's carbon emissions	
	[8]	improved air quality	
	[13]	promoted China's low-carbon economic transformation	
	Qi and Zhou, 2020	stimulated China's green total factor energy efficiency	
	[10]	promoted carbon equality among reform regions	
	Yang et al., 2020	increased overall employment	
	[11]	rural residential income and employment	
	[12]	EU ETS has had no effect on the performance of the cement, iron, and steel industries	
Regional-level analysis	[6,8]	at the city level	The decline of regional energy consumption maybe caused by structural industry changes (the pollution haven effect)
	[7,9,10]	province level	
Firm-level analysis	[14]	firm-level TFP (total factor productivity)	Sample size is too small may lead to section bias, and Previous studies did not study the impact on enterprises' energy efficiency and the underlying mechanisms.
	[15]	increases emission trade system (ETS) firms' low-carbon innovation by 5–10 %	

(*continued on next page*)

Appendix A1 (*continued*)

Review of literature	Literature sources	Main contents of literature	Summaries
	[16]	ETS accelerated outward direct investment	
	Luo et al., 2021	ETS has led power firms in Guangdong standardize their low-carbon management systems	

Table A2
Details of the charge reform on SO_2 sewage

Province	The beginning time of reform	The price before the reform	The price after the reform
Jiangsu	2007.7.1	0.63 yuan/kg	1.26 yuan/kg
Anhui	2008.1.1		1.26 yuan/kg
Hebei	2008.7.1		1.26 yuan/kg
Shandong	2008.7.1		1.26 yuan/kg
Inner Mongolia	2008.7.10		1.26 yuan/kg
Guangxi	2009.1.1		1.26 yuan/kg
Shanghai	2009.1.1		1.26 yuan/kg
Yunnan	2009.1.1		1.26 yuan/kg
Guangdong	2010.4.1		1.26 yuan/kg
Liaoning	2010.8.1		1.26 yuan/kg
Tianjin	2010.12.20		1.26 yuan/kg
Xinjiang	2012.8.1		1.26 yuan/kg
Beijing	2014.1.1		10 yuan/kg
Ningxia	2014.3.1		1.26 yuan/kg
Zhejiang	2014.4.1		1.26 yuan/kg

Table A3
Reform of SO2 emission charges shock

VARIABLES	(1)	(2)
	Ln_coal	Ln_coal_int
ctp	−0.2740**	−0.2835***
	(0.117)	(0.108)
so_2	−0.0904	0.0229
	(0.128)	(0.110)
lcc	−0.1768	−0.1745**
	(0.113)	(0.077)
Control variables	Controlled	Controlled
Observations	174,244	174,244
R-squared	0.860	0.772
Individual	Controlled	Controlled
Year	Controlled	Controlled

Notes : Robust standard errors in parentheses, ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$ and standard errors are clustered at city level for all regressions.

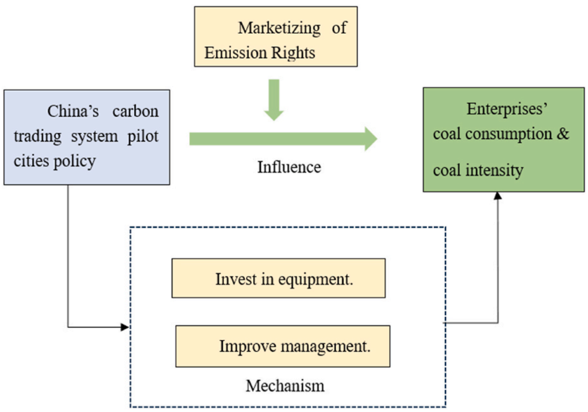

Fig. A1. Impact mechanism framework

References

[1] Q. Zhou, X. Cui, H. Ni, et al., The impact of environmental regulation policy on firms' energy-saving behavior: a quasi-natural experiment based on China's low-carbon pilot city policy, Resour. Pol. 76 (2022) 102538.
[2] A. Blackman, Z. Li, A.A. Liu, Efficacy of command-and-control and market-based environmental regulation in developing countries, Annual Review of Resource Economics 10 (2018) 381–404.
[3] Q. Zhou, T. Li, L. Gong, The effect of tax incentives on energy intensity: evidence from China's VAT reform, Energy Econ. 108 (2022) 105887.
[4] R-h Xie, Y-j Yuan, J-j Huang, Different types of environmental regulations and heterogeneous influence on "green" productivity: evidence from China, Ecol. Econ. 132 (2017) 104–112.
[5] J. Schleich, K. Rogge, R. Betz, Incentives for energy efficiency in the EU emissions trading scheme, Energy Efficiency 2 (1) (2009) 37–67.
[6] B. Shi, N. Li, Q. Gao, et al., Market incentives, carbon quota allocation and carbon emission reduction: evidence from China's carbon trading pilot policy, J. Environ. Manag. 319 (2022) 115650.
[7] X. Wang, J. Huang, H. Liu, Can China's carbon trading policy help achieve Carbon Neutrality?—a study of policy effects from the Five-sphere Integrated Plan perspective, J. Environ. Manag. 305 (2022) 114357.
[8] Z. Weng, T. Liu, Y. Wu, et al., Air quality improvement effect and future contributions of carbon trading pilot programs in China, Energy Pol. 170 (2022) 113264.
[9] H. Wang, Z. Chen, X. Wu, et al., Can a carbon trading system promote the transformation of a low-carbon economy under the framework of the porter hypothesis?—empirical analysis based on the PSM-DID method, Energy Pol. 129 (2019) 930–938.
[10] S. Zhang, Y. Wang, Y. Hao, et al., Shooting two hawks with one arrow: could China's emission trading scheme promote green development efficiency and regional carbon equality? [J]. Energy Economics 101 (2021) 105412.
[11] G. Zhang, N. Zhang, The effect of China's pilot carbon emissions trading schemes on poverty alleviation: a quasi-natural experiment approach, J. Environ. Manag. 271 (2020) 110973.
[12] H.S.R. Chan, S. Li, F. Zhang, Firm competitiveness and the European Union emissions trading scheme, Energy Pol. 63 (2013) 1056–1064.
[13] H. Wang, Z. Chen, X. Wu, X. Nie, Can a carbon trading system promote the transformation of a low-carbon economy under the framework of the porter hypothesis?—empirical analysis based on the PSM-DID method, Energy Pol. 129 (2019) 930–938.
[14] J. Xiao, G. Li, B. Zhu, et al., Evaluating the impact of carbon emissions trading scheme on Chinese firms' total factor productivity, J. Clean. Prod. 306 (2021) 127104.
[15] J. Zhu, Y. Fan, X. Deng, et al., Low-carbon innovation induced by emissions trading in China, Nat. Commun. 10 (1) (2019) 1–8.
[16] P. Yu, Z. Cai, Y. Sun, Does the emissions trading system in developing countries accelerate carbon leakage through OFDI? Evidence from China, Energy Econ. 101 (2021) 105397.
[17] Q. Zhou, C. Fu, H. Ni, et al., What are the main factors that influence China's energy intensity?—based on aggregate and firm-level data, Energy Rep. 7 (2021) 2737–2750.
[18] C. Zhou, S. Qi, Has the pilot carbon trading policy improved China's green total factor energy efficiency?[J]. Energy Economics 114 (2022) 106268.
[19] M. Bertrand, E. Duflo, S. Mullainathan, How much should we trust differences-in-differences estimates? Q. J. Econ. 119 (2004) 249–275.
[20] M. Lechner, The estimation of causal effects by difference-in-difference methods, Foundations and Trends® in Econometrics 4 (3) (2011) 165–224.
[21] L.R. Christensen, WHJJopE. Greene, Economies of scale in US electric power generation, J. Polit. Econ. 84 (1976) 655–676.
[22] M.A. Cole, R.J. Elliott, K. Shimamoto, Globalization, firm-level characteristics and environmental management: a study of Japan, Ecol. Econ. 59 (2006) 312–323.
[23] L. Du, Y. He, J. Yan, The effects of electricity reforms on productivity and efficiency of China's fossil-fired power plants: an empirical analysis, Energy Econ. 40 (2013) 804–812.
[24] H. Yu, The influential factors of China's regional energy intensity and its spatial linkages: 1988–2007, Energy Pol. 45 (2012) 583–593.
[25] V.J. Karplus, S. Zhang, D. Almond, Quantifying coal power plant responses to tighter SO2 emissions standards in China, Proc. Natl. Acad. Sci. USA 115 (2018) 7004–7009.
[26] M. Kafouros, C. Wang, P. Piperopoulos, M.J.R.P. Zhang, Academic collaborations and firm innovation performance in China: the role of region-specific institutions, Res. Pol. 44 (2015) 803–817.
[27] Y. Liu, J. Mao, How do tax incentives affect investment and productivity? Firm-level evidence from China, Am. Econ. J. Econ. Pol. 11 (2019) 261–291.