Energy Economics 112 (2022) 106157

Contents lists available at ScienceDirect

Energy Economics

journal homepage: www.elsevier.com/locate/eneeco

Emission trading, induced innovation and firm performance

Shenggang Ren [a], Xuanyu Yang [a,b], Yucai Hu [c,*], Julien Chevallier [d]

[a] School of Business, Central South University, Changsha 410083, PR China
[b] Audit Office, Normal University, Changsha 410083, PR China
[c] School of Economics and Management, Yanshan University, Qinhuangdao 066004, PR China
[d] IPAG Business School (IPAG Lab), 184 boulevard Saint-Germain, 75006 Paris and Université Paris 8 (LED), 2 avenue de la Liberté, 93526, Saint-Denis Cedex, France

ARTICLE INFO

Keywords:
Emissions trading
Induced innovation
Firm performance
Porter hypothesis

ABSTRACT

Whether or not carbon emission policies can achieve the "double dividend" of carbon reduction and economic growth is vital for realizing sustainable development. This paper investigates whether a market-based carbon emissions trading scheme (ETS) can stimulate firm innovation and further achieve a win-win situation for environmental and economic performance. Based on panel data for listed firms from 2006 to 2017, we use a difference-in-differences model to investigate the effects of China's ETS pilot policy. The results show that first, the pilot ETS is related positively to firm environmental and economic performance and performs better in areas with more stringent emissions caps, and second, that the pilot ETS is positively correlated with firm innovation. Moreover, further analysis shows that innovation induced by the ETS significantly improves firm environmental and economic performance. These findings suggest that imposition of an ETS which induces innovation could achieve a win-win situation for environmental and economic performance and provides direct empirical evidence supporting the Porter hypothesis.

1. Introduction

In recent decades, the level of global warming caused by greenhouse gas emissions has become very serious, and is resulting in more frequent, intense, and extreme weather and natural disasters (Yang et al., 2017; Lee et al., 2021; Touma et al., 2021). The environment and climate change have become major sustainable development issues in today's human society (Chen et al., 2021; Liu and Zhang, 2021), and addressing these problems requires a radical change of direction and acceleration of technological change towards low-carbon developments. In turn, this will require specific policies (Rogge, 2016; Calel and Dechezleprêtre, 2016) especially environmental policies aimed at transformation to a low-carbon economy. Carbon emissions trading schemes (ETSs) introduced by the Kyoto Protocol are considered critical drivers of a low-carbon economy and are being promoted worldwide. So far, the United States, the European Union countries, Japan, Australia, New Zealand, Canada, and China have introduced ETS which currently are considered the environmental policies with the greatest promise (Calel and Dechezleprêtre, 2016; Libo et al., 2022; Yu et al., 2021; Taylor, 2012).

The most basic ETS sets caps on permissible emissions and distribute corresponding emission allowances to firms. Firms can trade their allowances in the market but at each year end must surrender the number of allowances equivalent to the amount of their emissions (Liu et al., 2022; Rogge et al., 2011; Tan and Lin, 2022; Taylor, 2012). The primary goal of these ETSs is to achieve a given environmental target at minimal cost; however, they should also incentivize technological innovation. Technological innovation is essential for addressing long-term environmental problems, achieving a sustainable environment (Hu et al., 2020; Inoue et al., 2013), and achieving productivity growth and sustained competitiveness (Aghion et al., 2016; Wu and Wang, 2022; Zhang et al., 2021). In this context, the present study tries to investigate the effectiveness of cap-and-trade tools to achieve a radical transformation to a low-carbon economy.

The traditional view is that environmental regulation by imposing an additional burden on the firm has a negative effect on competitiveness. In other words, there is considered to be a conflict between competitiveness and environmental performance. However, Porter and Linde (1995) claim that strict but well-designed environmental regulation can lead to innovation which improves environmental performance and

* Corresponding author.
E-mail addresses: renshenggang1975@csu.edu.cn (S. Ren), hu-yucai@ysu.edu.cn (Y. Hu).

https://doi.org/10.1016/j.eneco.2022.106157
Received 19 November 2020; Received in revised form 15 June 2022; Accepted 25 June 2022
Available online 1 July 2022

partially or fully offsets the effects and costs of the regulation.[1] This result in a win-win situation that benefits both the firm's environmental and economic performance (Ambec et al., 2013; Zhang et al., 2021).

However, more in-depth analysis of the impact of an ETS provides different results. On the one hand, an ETS provides incentives for firms to invest in technological change and innovation to achieve emissions reductions by either decreasing firms' compliance costs from the reduced number of required allowances, or increasing revenue from the sale of superfluous emission allowances (Ambec et al., 2013; Gagelmann and Frondel, 2005). On the other hand, firms could accomplish reduced emissions by optimizing the allocation of factors of production (Cao et al., 2021; Hu et al., 2020; Yang et al., 2017), such as allowance trading, energy conversion and market exit etc. However, these measures might delay firm technological innovation or reduce the incentive to innovate due to the uncertainty inherent in innovation activities (Rogge et al., 2011). Although different mechanisms are not mutually exclusive, the mechanism by which ETS works is still unclear.

Several empirical studies have examined the ETSs implemented in Europe and the United States, including their impact on technological innovation (e.g. Chen et al., 2021; Martin et al., 2011; Rogge et al., 2011; Taylor, 2012), emission reductions (e.g. Anderson and Di Maria, 2011; Bel and Joseph, 2015; Clò et al., 2017; Tan and Lin, 2022), and economic performance (e.g. Anger and Oberndorfer, 2008; Costantini and Mazzanti, 2012; Wu and Wang, 2022). However, it should be noted that most studies examine a particular aspect and do not reach a consensus on the effectiveness of ETSs (Borghesi et al., 2015). More importantly, few studies investigate the impact of technological innovation induced by an ETS on the firm's environmental and economic performance, which is at the heart of the Porter hypothesis.

To fill this gap, the present paper uses China's carbon ETS pilot policy to investigate whether an ETS can stimulate innovation and further contribute to optimum environmental and economic performance. We chose China's pilot ETS to test our hypothesis for two reasons. First, China's rapid development has been accompanied by consumption of large amounts of resources and energy, resulting in considerable carbon dioxide (CO_2) emissions – since 2006, China has been the world's largest emitter of CO_2. In 2011, to control its CO_2 emissions China launched its carbon ETS, it is expected that the Chinese national carbon market will overtake the European Union carbon market and become the world's largest carbon market. Therefore, a comprehensive understanding of China's pilot ETS is significant in the context of reducing global carbon emissions. Second, the pilot areas were designated by the central government and are distributed in the east, central, and western regions of China. This top-down pilot area selection allows us to consider the policy as a quasi-natural experiment and an excellent context to examine the effect of a pilot ETS in a developing country (Hu et al., 2020; Zhang and Wang, 2021a, Zhang and Wang, 2021b).

This study contributes to the literature in several ways. First, we investigate the impact of an ETS on both the environmental and economic performance of firms. This provides comprehensive empirical evidence for ETS to achieve a win-win situation for firms' environmental and economic performance, and the role of ETS to promote an economic transition to low-carbon development. In contrast to studies which investigate only certain aspects of an ETS (e.g. environmental performance or economic performance, etc.), we conduct a comprehensive investigation of the impact of an ETS on corporate environmental and economic performance. The results show that while ETS promotes improvements to corporate environmental performance, it also promotes improvements to corporate economic performance. These results provide new empirical evidences of the ETSs to achieve coordinated development of environmental and economic performance.

Second, we provide direct empirical evidence supporting the Porter hypothesis from the perspective of induced innovation. Porter and Linde (1995) claim that environmental regulation can enhance firm competitiveness through induced innovation. However, few studies investigate the impact of the technological innovation induced by environmental regulation on firm competitiveness which is at the heart of the Porter hypothesis. The present paper investigates the impact of innovation induced by an ETS on firm environmental and economic performance and show that it can further enhance the firm's environmental and economic performance.

Third, we add to work on the impact of the ETS in the context of developing countries. We argue that developing countries with serious environmental pollution problems are the most in need of effective regulation (Hu et al., 2020). Investigating whether a market-based policy can cope effectively with environmental problems is important in a developing country context. Our findings suggest that the ETS can stimulate innovation in developing country firms, and achieve a positive environmental and economic performance outcome. The experience of China's pilot policy could act as a reference, and could spur other developing countries to use market-oriented ETS to address environmental issues.

The paper is organized as follows. Section 2 reviews the literature and discusses the policy context. Section 3 describes the research design and Section 4 reports the empirical results. Section 5 is the mechanism analysis and Section 6 offers some concluding remarks and some implications for policy.

2. The literature and the policy context

2.1. Environmental regulation and competitiveness

Environmental regulation through its inevitable effect on the firm's production costs, processes, resource allocation, investment, and innovation activity affects both environmental outcomes and economic performance (Albrizio et al., 2017; Zhu et al., 2021; Zhao et al., 2022). It is generally argued that environmental regulation imposes an additional burden on firms, and induces a reallocation of resources from traditional "productive" uses to means to reduce pollution (Albrizio et al., 2017; Ambec et al., 2013; Zhu et al., 2021; Zhao et al., 2022). However, the Porter hypothesis proposed in Porter and Linde (1995) challenges this conventional view and argues instead that well-designed regulation can lead to a Pareto improvement (i.e. improvement to environmental quality without any negative effect on economic performance) or a "win-win" situation. In the latter case, there are positive effects on both the environment and firm performance based on the innovation incentive provided by the regulation which offsets the regulation compliance costs (Ambec et al., 2013; Xie et al., 2017).

For more than 20 years, the Porter hypothesis has been the subject of extensive academic research and policy debate, and different versions of the Porter hypothesis have been proposed and tested (Jaffe and Palmer, 1997; Zhu et al., 2021). However, the findings related to how environmental regulation affects innovation and competitiveness remain mixed (Ambec et al., 2013; Chakraborty and Chatterjee, 2017). Some studies suggest that environmental regulation causes productivity losses (Barbera and McConnell, 1990; Gray and Shadbegian, 2003). For example, Gray and Shadbegian (2003) find a regulation-induced productivity decline of 9.3% in a typical integrated United States mill operation. Similarly, Greenstone et al. (2012) using manufacturing sector data for 1972–1993 find that stricter air quality regulation was associated with around a 2.6% decline in total factor productivity (TFP).

Other studies are more optimistic. For instance, Berman and Bui (2001) show that despite the more stringent air pollution regulation in Los Angeles, refineries located in the Los Angeles area achieved significantly higher productivity levels than refineries in other areas of the United States. Also, Alpay et al. (2002) find that the productivity of the

[1] Porter and Linde (1995) claim that if regulations are properly crafted and companies are attuned to the possibilities, then innovation to minimize and even offset the cost of compliance is likely in many circumstances.

Mexican food-processing industry increased with environmental regulation, leading them to conclude that more stringent regulation is not always detrimental to productivity. Hamamoto (2006) uses an indirect approach to examine the effect of environmental regulation on productivity growth in Japan and finds that environmental regulation has a positive influence on productivity improvements. The study by Yang et al. (2012) suggest that more stringent environmental regulation enhances rather than reduces industry competitiveness, and Rassier and Earnhart (2015) find a positive relationship between clean water regulation and the profitability of chemical manufacturing industries in the United States.

When considering these inconsistent findings, it should be remembered that Porter and Linde (1995) emphasize the importance of well-designed regulatory instruments for achieving "innovation offsets." Also, Ambec et al. (2013) suggest that the main reason for these conflicting findings is that the Porter hypothesis does not predict that all regulation leads to innovation. Therefore, in this paper we focus on the impact of market-based environmental regulation on competitiveness.

2.2. Emissions trading and competitiveness

Existing work examines many aspects of ETSs including the effects on emission abatement, economic performance, competitiveness, and technological innovation (e.g. Bel and Joseph, 2015; Calel and Dechezleprêtre, 2016; Cao et al., 2021; Clò et al., 2017; Costantini and Mazzanti, 2012; Martin et al., 2011; Rogge et al., 2011; Taylor, 2012; Zhang et al., 2021). We review two literature streams: the first discusses the impact of ETSs on firms' environmental and economic performance, the second examines the effect of ETSs on technological innovation.

2.2.1. Emission trading and firm performance

This first strand of work includes a large set of studies investigating the emission abatement effects of an ETS. For example, Ellerman et al. (2010) and Anderson and Di Maria (2011) focus on aggregate emissions and estimate emission reductions across all sectors during phase I to be close to 3%. Zhang and Cheng (2021) suggest that China's ETS could be an effective tool to control CO_2 emissions from the service sector. Zhang et al. (2021) find ETS could bring the double dividends of green development efficiency and regional carbon equality. However, Delarue et al. (2008) study the power sector and show that fuel conversion reduced emissions by between 26 million and 88 million tons representing the largest contribution to European Union emission reductions. Bel and Joseph (2015) use historical emission data to assess the impact of the European Union ETS on greenhouse gas emissions and find that the largest emissions reductions were due to the economic crisis. Clò et al. (2017) show that an ETS has a limited impact on emissions reductions due to loose allowances. Cao et al. (2021) find a significant reduction in coal consumption associated with participation in an ETS but that this reduction was achieved by reducing electricity production.

In terms of the impact of ETSs on firms' economic performance, the empirical literature is inconclusive (Joltreau and Sommerfeld, 2019). Anger and Oberndorfer (2008) analyze regulated companies in Germany and show that the ETS had no statistically significant effects on firm revenue or employment. Similarly, Jaraitė et al. (2010) find no significant economic impact on regulated firms. They stress that this result implies also that these firms did not experience windfall profits. Chan et al. (2013) study a panel of 5873 firms in 10 European countries during 2001–2009 and find no effect on competitiveness during the period. Cao et al. (2021) find China's ETS has no effect on changing coal efficiency of regulated coal-fired power plants. However, Zhang et al. (2020) predict that based on total industry transactions China's ETS could result in potential gains of 268.02 trillion yuan in the period 2006–2015. Wu and Wang (2022) also find that the carbon price promotes regulated firms' TFP through innovation. Kumar et al. (2020) predict that India could save about US$ 5 to 8 billion by an emission trading system.

2.2.2. Emissions trading and firm innovation

The second stream of work examines the effect on innovation of implementation of an ETS (Calel and Dechezleprêtre, 2016; Hoffmann, 2007; Rogge et al., 2011). For example, based on survey data, Hoffmann (2007) and Rogge et al. (2011) find a positive impact of the European Union ETS on investments and technological change. These results are confirmed by Calel and Dechezleprêtre (2016) who investigate the effect of the European Union ETS on technological change and find that it increased low-carbon innovations among regulated firms by as much as 10%. Du et al. (2021) find that China's ETS has had a significant effect on promoting green innovation in the pilot areas. Liu et al. (2022) also find China's SO_2 ETS triggers firms to engage in more innovation activities.

While there might appear to be a link between an ETS and technological innovation, this is dependent on institutional factors such as cap stringency, allowance prices, and predictability (Taylor, 2012; Xu et al., 2019). Some studies argue that overly generous emission permit allocations reduce the incentive to innovate (Gagelmann and Frondel, 2005; Grubb et al., 2005), while Borghesi et al. (2015) suggest that compared to non-participating sectors those sectors included in the program are more likely to innovate. However, policy stringency is associated negatively with environmental innovation. Also, in the context of lower-than-expected allowance prices, Taylor (2012) shows that the scheme does not provide a sustained incentive for private-sector investment in R&D in clean technologies. Finally, Yao et al. (2021) who examine the seven ETS pilot areas in China find that Hubei is the only one where innovation into low-carbon developments has increased.

There is a substantial body of work on the innovation effects of ETSs. However, we need more investigation into the impact of these schemes on economic performance. In particular, we need to know whether innovation induced by an ETS improves both environmental and economic performance. Also, most existing studies focus on developed countries such as those in Europe and the United States, and we need empirical evidence for developing countries.

2.3. China's CO_2 emissions trading program

China is the world's largest emitter of CO_2, and the Chinese government has responded to international efforts to reduce carbon emissions. For instance, at the 2009 United Nations Climate Change Conference held in Copenhagen, the Chinese government promised to reduce its carbon emissions by 2020 by between 40% and 45% compared to 2005. Since then, it has implemented a series of environmental regulations to reduce CO_2 emissions. In 2011 it introduced a market mechanism in the form of a pilot ETS applied to Beijing, Tianjin, Shanghai, Chongqing, Hubei, Guangdong, and Shenzhen. This pilot scheme was designed to test the efficacy of a national carbon trading market which in the future could be extended across the whole territory.

The pilot ETS covers mainly the petrochemical, chemical, construction materials, iron and steel, non-ferrous metal, paper, electricity, and aviation sectors[2] which use fossil fuels and also produce emissions related to their use of electricity (Zhang et al., 2014). All of the pilot areas introduced corresponding management measures to provide a common institutional basis for implementation of the ETS. Like the European Union ETS, China's pilot scheme includes coverage, cap setting, permit allocation, allowance trading, monitoring, reporting, verification, compliance, and emission trading centers and markets in each of the pilot areas.

Based on aggregate data, the cumulative trading volume allowance for the seven pilot markets whose combined turnover was 10.49 billion

[2] National Development and Reform Commission – NDRC, 2016. https://www.ndrc.gov.cn/xxgk/zcfb/tz/201601/t20160122_963576.html?code=&state=123

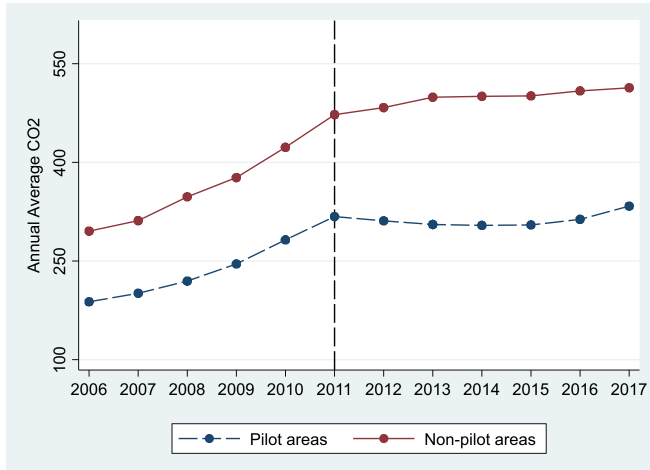


Fig. 1. Annual average CO_2 emissions.

yuan at December 31, 2017 was 470 million tons of CO_2.[3] It has been reported that by 2015 Shenzhen had reduced its CO_2 emissions by 11% compared to 2010.[4] Similarly, the Beijing Environment Exchange claims that total CO_2 emissions from the three main emitters in Beijing decreased by approximately 4.5%, 5.96%, and 6.17% between 2013 and 2015 (Hu et al., 2020).[5]

We are interested also in the CO_2 emissions from pilot and non-pilot areas. Fig. 1 shows annual CO_2 emission mean values for the pilot and non-pilot regions between 2006 and 2017. It shows that before 2011, CO_2 emissions grew at a similar rate in both the pilot and non-pilot areas, and that after 2011 CO_2 emissions in the pilot areas began to decline. We can say that the pilot ETS was implemented effectively and has provided some preliminary results.

3. Research design

3.1. Sample and data

China's ETS pilot started in 2011 and was extended from the power industry to the whole country in December 2017 under the "National Carbon Emission Trading Market Construction Plan (Power Generation Industry)." Therefore, we focus on publicly traded firms listed on the Shanghai or Shenzhen stock exchanges in mainland China between 2006 and 2017. The sample and data were constructed as follows.

First, the pilot ETS covers the petrochemical, chemical, building materials, iron and steel, non-ferrous metal, papermaking, power, and aviation industries (NDRC, 2016). Our initial sample was limited to the two-digit sectors subject to the policy intervention which resulted in ten two-digit industries. Second, data availability restricted out initial sample from the above industries to companies listed on the Shanghai and Shenzhen stock exchanges. We identified a sample of 577 unique firms and 5379 firm-year observations. Third, following the literature, we excluded firms with missing financial information and firms with ST and PT status (Xu et al., 2013) which resulted in a final sample of 4818 firm-year observations. We applied a difference in differences (DID) framework to our unbalanced panel dataset in which the pilot area firms are the treatment group, and the non-pilot area firms are the control group.

The data were collected from three different sources. Firm-level data on environmental performance, economic performance, R&D, patenting, financial information, and other firm-specific characteristics were obtained from the China Stock Market and Accounting Research (CSMAR) database. The environmental enforcement data are from the *China Environmental Statistics Yearbook*, and provincial per capita GDP is from the *Chinese Statistical Yearbook*.

3.2. Variables

3.2.1. Outcome variables

3.2.1.1. Environmental performance. Due to the limited data on firm-level CO_2 emissions, there are no standard environmental performance measures. Following the method in Ding et al. (2016), we measure environmental performance by the sewage charges paid by the firms – a measure used in some studies to measure environmental regulation (Huang and Chen, 2015). We chose this measurement because there are two factors which affect the sewage charge – the pollution released and the local government's levying stringency (Ding et al., 2016). The more pollutant emitted, the higher will be the sewage charge levied by regions with similar levying stringency,[6] and the better proxy the sewage charge for pollution attitude. Since we control for enforcement stringency of environmental regulation at the provincial level, we consider the annual sewage charge to be a good proxy for firm environmental performance (*Charge*).

To reduce concern over measurement bias, in a robustness analysis we use environmental capital expenditure to proxy for environmental performance. Li and Lu (2016) suggest that firms' environmental practices can be assessed based on inputs or outputs. While environmental performance refers to the outcome of the firm's environmental practices including recycling of hazardous waste, toxic releases, discharge of polluted water, non-compliance with environmental statutes, and the firm's environmental rating, the firm's environmental capital expenditure refers to inputs. Since direct assessment of firms' environmental outcomes is difficult, in a robustness check we use environmental capital investment related to carbon emissions to measure environmental performance which is an indirect measure of the firm's environmental actions (Li and Lu, 2016).

[3] http://www.tanpaifang.com/tanjiaoyi/2018/0129/61449.html

[4] http://jjckb.xinhuanet.com/2015-01/26/content_535981.htm

[5] China Beijing Environment Exchange, 2017. Annual Report of Beijing carbon market 2016. http://files.cbex.com.cn/cbeex/201701/20170123173810410.pdf (accessed January 23, 2017).

[6] We controll for enforcement stringency of the environmental regulation at the provincial level (i.e. the intensity of the command-and-control environmental regulation measured by the annual number of provincial environmental administrative penalty cases).

3.2.1.2. Economic performance. The natural logarithm of firm TFP (*LnTFP*) is used in several studies to measure the firm's economic performance (Faccio, 2010; Giannetti et al., 2015). Most works measure firm TFP using the semi-parametric method proposed by Olley and Pakes (1992) and Levinsohn and Petrin (2003). For the main analysis, we use Levinsohn and Petrin's (2003) method to measure firm TFP, and use the Olley and Pakes (1992) method in the robustness tests. Specifically, we compute firm TFP as the residual ε_{ijt} of the firm-level regression.

$$y_{ijt} = \alpha_{jt} + \beta_{jt} l_{ijt} + \gamma_{jt} k_{ijt} + \delta_{jt} m_{ijt} + \varepsilon_{ijt} \tag{1}$$

where y_{ijt} is the logarithm of the sales of firm i in industry j during year t, l_{ijt} is the logarithm of the number of firm i's employees in year t, k_{ijt} is the logarithm of firm i's total assets in year t, and m_{ijt} is the logarithm of firm i's expenditure on materials and other inputs in year t.

3.2.1.3. Technological innovation. Innovation inputs are often measured as R&D expenditure, and technological value and innovation outputs are usually based on number of patent applications. We constructed two proxies – for *R&D* measured as the firm's annual R&D expenditure, and for *Patent* measured as the annual number of the firm's patent applications.

3.2.2. Carbon emissions trading

*3.2.2.1. ETS*Post.* It is the interacting term between ETS and Post. ETS is a dummy variable which equals 1 for a firm located in one of the ETS pilot areas and is 0 otherwise. The pilot areas include Beijing, Tianjin, Shanghai, Chongqing, Hubei, Guangdong, and Shenzhen.[7] The remaining 24 provinces are considered non-pilot areas. Post is a dummy variable which equals 1 for the post-policy period and 0 otherwise.

3.2.3. Control variables

In our analysis, we consider three groups of control variables. The first group controls for general firm characteristics. Firm size (*Size*) is the natural logarithm of the firm's total assets at the end of the fiscal year (Zhang and Wang, 2021a, Zhang and Wang, 2021b). Firm age (*Age*) is the number of years since the firm's foundation. State ownership (*State*) is the number of state-owned shares in the total number of shares in year t (Chen et al., 2017). We use shares held by institutional investors scaled by the total shares outstanding as a measure of institutional ownership (*Institution*).

The second group of control variables includes financial indicators and firm governance factors affecting corporate investment. The rate of growth of sales revenue (*Growth*) is based on current compared to previous year sales (Chen et al., 2017). We also control for asset liability ratio (*Lev*). Government subsidy (*Subsidy*) is a dummy variable that is equal to 1 if the firm received any subsidies in a given year and 0 otherwise. Independence (*Independence*) measures the percentage of independent directors in total board members (Li et al., 2016). *Ten_holder* is the ratio of the ten largest shareholdings to total number of shares.

Finally, we add the influence of external factors on firm performance. Better environmental protection laws and regulations can reduce the firm's negative externalities. We follow Huang and Chen (2015) and use the annual number of provincial environmental administrative penalty cases to measure the intensity of command-and-control environmental regulation (*CER*). The environmental Kuznets curve predicts that areas with higher levels of economic development tend to have superior environmental quality (Grossman and Krueger, 1995). The level of economic development (*Per GDP*) is the ratio of per capita GDP to mean per capita GDP in each province (Huang and Chen, 2015).

3.2.4. Descriptive statistics

Table 1 reports the descriptive statistics of the variables in our analysis. The mean value of sewage charge is 2.919 in non-pilot firms and 2.738 in the pilot firms, and the logarithm of TFP is 4.495 in the non-pilot firms and 4.480 in the pilot firms. It can be seen that the pilot firms pay less sewage charges and have lower LnTFP (Table 1 column 7). Also, the pilot firms have invested more in R&D and have a higher number of patent applications (higher innovation performance). The pilot firms are larger than the non-pilot firms, receive more subsidies, have higher board independence, and have a higher concentration of equity. There are no significant statistical differences between the treatment and control groups in relation to age, growth and leverage. This provides some preliminary evidences but we need a more rigorous multiple regression analysis.

3.3. Empirical model

3.3.1. Impacts of ETS on firm performance

We use the DID model to investigate the influence of the ETS on the firms' environmental and economic performance. The regression model is written as follows:

$$Perf_{ijt} = \beta_0 + \beta_1 ETS_{ij} \times Post_t + \beta_2 X_{ijt} + Pro_i + Ind_j + Year_t + \varepsilon_{ijt}, \tag{2}$$

where *i* is province, j is industry, and *t* is year. $Perf_{ijt}$ is the dependent variable which includes the firm's environmental and economic performance measured respectively by *Charge* and *LnTFP*. ETS_{ij} equals 1 if the firm is located in one of the seven provinces included in the scheme and is 0 otherwise; $Post_t$ equals 1 after 2011 and is 0 otherwise. The coefficient β_1 captures the average change in the environmental and economic performance of the firms in the pilot areas relative to the non-pilot areas during the policy period. X_{ijt} includes a set of the firm-level and province-level control variables described above. We control also for the possible influence of general province-, industry-, and time-specific factors on province, industry, and year fixed effects (Elrod and Malik, 2017).

3.3.2. Impacts of innovation induced by ETS on firm performance

To analyze the effect of innovation induced by ETS on firm performance, we use Hamamoto's (2006) two-step method which has been applied in other studies including Lanoie et al. (2011) and Yang et al. (2012). In the first step, we use eq. (3) to estimate the impact of ETS on firm innovation:

$$Inno_{ijt} = \beta_0 + \beta_1 ETS_{ij} \times Post_t + \beta_2 X_{ijt} + Pro_i + Ind_j + Year_t + \varepsilon_{ijt}, \tag{3}$$

where $Inno_{ijt}$ is the firm's R&D investment and patent applications. The other variables are defined as in eq. (2).

The first step estimates the innovation (if any) induced by the ETS. In the second step, we estimate the impacts of the innovation induced by the ETS on firm performance. The model is written as follows:

$$Perf_{ijt} = \beta_0 + \beta_1 Inno_{1ij} + \beta_2 Inno_{2ij} + \beta_2 X_{ijt} + Pro_i + Ind_j + Year_t + \varepsilon_{ijt}, \tag{4}$$

where $Inno_{1ij}$ is innovation induced by the ETS, and $Inno_{2ij}$ is the remaining innovation performance. Hamamoto (2006) and Yang et al. (2012) calculate induced $Inno_{1ij}$ and non-induced $Inno_{2ij}$ as follows:

$$Inno_{1ij} = \beta_{ETS} \times \left[\frac{\Delta ETS_{it,t-1}}{ETS_{it-1}}\right] \times Inno_{ij}, \text{and } Inno_{2ij} = Inno_{ij} - Inno_{1ij}$$

The other variables are defined as in eq. (2).

[7] In line with China's administrative divisions, Shenzhen city is included in Guangdong Province.

Table 1
Descriptive statistics.

Variable	All sample		Non-pilot firms		Pilot firms		t-test
	Mean	SD	Mean	SD	Mean	SD	Difference
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Charge	2.879	10.172	2.919	9.569	2.738	12.082	0.181
LnTFP	4.491	0.709	4.495	0.696	4.480	0.752	0.015
R&D	8.443	58.148	6.494	20.857	15.388	117.604	−8.894***
Patent	5.46	38.79	3.711	19.043	11.693	74.36	−7.982***
Size	22.18	1.406	22.157	1.308	22.259	1.708	−0.102**
Age	15.513	5.304	15.45	5.141	15.736	5.845	−0.286
State	12.019	20.469	12.433	20.702	10.543	19.555	1.89***
Institution	28.449	25.53	29.077	25.496	26.209	25.539	2.868***
Lev	0.674	12.578	0.738	14.233	0.445	0.217	0.293
Growth	1.608	49.623	1.875	55.623	0.656	14.541	1.219
Subsidy	0.894	0.307	0.89	0.313	0.911	0.285	−0.021**
Independence	0.366	0.052	0.365	0.05	0.369	0.058	−0.004**
Ten_holder	58.859	16.055	58.165	15.536	61.335	17.568	−3.17***
CER	0.511	0.533	0.456	0.478	0.708	0.658	−0.252***
Per GDP	4.787	2.612	4.206	2.203	6.859	2.89	−2.653***

Note: ***, **, and * significant at 1%, 5%, and 10%, respectively.

4. The ETS and firm performance

4.1. Parallel trend test

We first conduct a parallel trend hypothesis test which is one of the assumptions underlying the DID model to check whether pre-existing time trends are driving the variability between the pilot and non-pilot firms. In line with Wang et al. (2018), we compare the difference in the time trends for the two groups before implementation of the ETS by estimating the following regression:

$$Perf_{ijt} = \beta_0 + \beta_1 ETS_{ij} \times Trend_t + \beta_2 ETS_{ij} + \beta_3 Trend_t + \beta_2 X_{ijt} + Pro_i + Ind_j + Year_t + \varepsilon_{ijt} \quad (5)$$

where *Trend* captures the linear time trend between the pilot and non-pilot firms and $Trend_t$ 1, 2, 3…6 refer respectively to 2006, 2007, 2008…2011. If the pilot firms and non-pilot firms show a similar trend, the coefficient of $ETS_{ij} \times Trend_t$ will be statistically insignificant. The other variables are defined as in the baseline eq. (2).

Table 2 reports the estimation results related to the parallel trend hypothesis. The insignificant coefficients of the interaction term $ETS_{ij} \times Trend_t$ in columns 1 and 2 indicate that there is no significant statistical difference in the time trends for the pilot and non-pilot firms which is consistent with the parallel trend assumption. In other words, the DID model assumption is not violated.

4.2. Baseline results

The baseline model estimation results are presented in Table 3. The results for corporate environmental and economic performance measured by Charge and LnTFP are reported in Table 3, columns 1 and 2. Column 1 shows that the estimated coefficient of ETS × Post is negative and statistically significant at 1% which implies that the ETS is associated with reduced sewage charges. Thus, the sewage charges for the firms in the pilot areas are 1.90 lower on average. Column 2 shows that the coefficient of ETS × Post is positive and statistically significant at the 1% level which implies that the ETS results in better pilot firm economic performance (LnTFP) compared to non-pilot firms. Given that the average annual LnTFP is 4.49, this effect is economically significant.

Although we control for province and industry fixed effects, there may be other firm-level factors which do not change over time. We ran some additional tests, including firm fixed effects as the control variable. Table 3 column 3 shows a negative and statistically significant relationship between the ETS and environmental performance, and column 4 shows a positive effect of the ETS on firm economic performance. Taken together, these results are consistent with the proposition that a carbon ETS promotes both environmental and economic firm performance.

4.3. Dynamic treatment effects

We next examine the dynamics of the relation between ETS and firm performance. Specifically, following the method in Beck et al. (2010), we estimate year effects using the following equation:

$$Perf_{ijt} = \beta_0 + \sum_{k=-5}^{4} \beta_t ETS_{ij} \times Yeardum_{2011+k} + \beta_1 X_{ijt} + Pro_i + Ind_j + Year_t + \varepsilon_{ijt} \quad (6)$$

where β_t is the yearly policy effects from 2006 to 2017, and the default (omitted) year is 2011. The other variables are defined as in eq. (2). The respective estimated year effects for environmental and economic performance are plotted in Fig. 2a and b. The figures show that the coefficients of the firm performance dummy variables are insignificantly different from zero for all years before 2011 with no performance trends identified before the pilot policy. Note that immediately after 2011 the year effects of sewage charge fall, and TFP begins to rise.

Insert Fig. 2a and b.

4.4. Robustness tests

4.4.1. Triple differences test

There is a potential issue related to the fact that our results for the effect of the ETS may be driven by other national or local environmental policies such as the sulfur dioxide (SO_2) emissions trading program launched in 2007.[8] If the impact of this policy differs between the pilot and non-pilot firms, our DID model will not show the causal impact of the carbon ETS. There are also other time-varying unobservables which might be confounding our results. For example, firm performance might be affected by a change in regional agglomeration based on the movement of skilled workers among firms. If these changes differ across the treatment and control groups, this might produce inconsistent DID estimates. We exploit the fact that different industries are affected differently by the policy, and conduct a triple-differences estimation as an additional test. Specifically, we add industry variation (e.g. regulated relative to unregulated industries). The control group includes all listed firms in the unregulated mining, manufacturing, and electricity industries. The difference in difference in difference estimation is written as follows:

$$Perf_{ijt} = \beta_0 + \beta_1 ETS_i \times Post_t \times Ind_j + \beta_2 ETS_i \times Post_t + \beta_3 Post_t \times Ind_j + \beta_4 ETS_i \times Ind_j + \beta_5 X_{ijt} + Pro_i + Ind_j + Year_t + \varepsilon_{ijt} \tag{7}$$

where Ind_j equals 1 if the policy regulates an industry and 0 otherwise. β_1 measures the effect of the pilot ETS policy on firms in the regulated industries relative to firms in the unregulated industries. The estimator estimates the impact of the pilot ETS on firm performance if unobservables such as other regulations have the same effect on regulated and unregulated industries. The remaining variables are the same as in eq. (2).

Table 4 presents the results of triple difference estimates. The results show that the pilot ETS has a negative impact on the environmental performance of firms in the regulated compared to the unregulated sectors. Similarly, the pilot ETS has a positive impact on firms' economic performance. These results are similar to our benchmark results.

4.4.2. Controlling for province and industry effects

In the baseline model we control for province and industry fixed effects but it is possible that there are some unobserved regional and industry factors which might be influencing our estimations and leading to biased results. For example, a change of technology in a certain province-sector could be an essential factor influencing firm R&D investment. Some industry-level policies implemented in previous decades may also have changed the firms' environmental or economic performance. To control for these unobserved regional and industry factors, we first include province-sector fixed effects in our baseline model. We then added the industry*year interaction dummies to account for potential industry time-varying factors.

These results are reported in Table 5 which shows that the estimated impacts of the ETS on firm performance remain statistically significant, indicating that our results are unlikely to be driven by time-varying omitted variables.

4.4.3. Alternative variables

To check the validity of our findings, we also used alternative

[8] In 2007, China implemented a SO_2 pilot program covering 11 provinces. It was approved by the Finance and Environmental Protection Ministries and included Jiangsu, Tianjin, Zhejiang, Hubei, Chongqing, Hunan, Inner Mongolia, Hebei, Shaanxi, Henan, and Shanxi provinces.

Table 2
Parallel trend test.

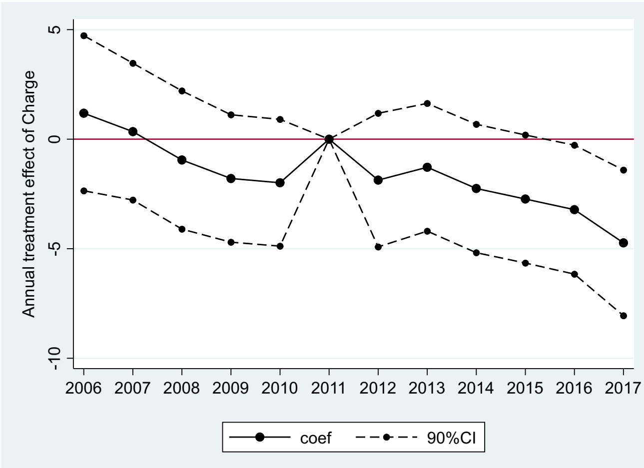
VARIABLES	Charge	LnTFP
	(1)	(2)
ETS × Trend	−0.243	0.006
	(0.288)	(0.021)
Trend	−0.337	0.016
	(0.249)	(0.021)
ETS	−0.080	−0.726***
	(1.396)	(0.175)
Controls	Y	Y
Year fixed effects	Y	Y
Ind fixed effects	Y	Y
Pro fixed effects	Y	Y
Constant	−40.586***	0.816**
	(5.314)	(0.382)
Observations	1966	1960
R-squared	0.144	0.389

Note: Standard errors in parentheses. ***, **, and * significant at 1%, 5%, and 10%, respectively.

Table 3
Baseline regression.

VARIABLES	Charge	LnTFP	Charge	LnTFP
	(1)	(2)	(3)	(4)
ETS × Post	−1.903***	0.129***	−2.307***	0.078***
	(0.531)	(0.038)	(0.752)	(0.030)
ETS	−0.264	−0.418***		
	(1.023)	(0.132)		
Post	−1.527	−0.210**		
	(2.088)	(0.085)		
Size	2.382***	0.160***	1.384***	0.007
	(0.224)	(0.008)	(0.246)	(0.029)
Age	0.032	−0.001	0.210	0.010
	(0.036)	(0.002)	(0.235)	(0.007)
State	−0.029***	0.001*	−0.024**	−0.000
	(0.009)	(0.000)	(0.011)	(0.000)
Institution	−0.005	0.001*	0.001	0.000
	(0.008)	(0.000)	(0.010)	(0.000)
Lev	0.022***	0.005***	0.018***	0.003***
	(0.003)	(0.000)	(0.003)	(0.000)
Growth	0.000	−0.001	−0.001	−0.000
	(0.001)	(0.001)	(0.001)	(0.001)
Subsidy	−1.137	0.155***	−1.897	0.020
	(1.347)	(0.053)	(1.461)	(0.031)
Independence	1.597	0.021	−4.519	0.209
	(2.329)	(0.159)	(3.015)	(0.196)
Ten_holder	0.020*	0.001	−0.022	0.001
	(0.011)	(0.001)	(0.014)	(0.001)
CER	−0.289	−0.023	−0.371	−0.010
	(0.273)	(0.015)	(0.292)	(0.012)
Per GDP	0.454**	0.022*	0.229	0.019*
	(0.202)	(0.013)	(0.274)	(0.011)
Constant	−50.625***	0.834***	−25.023***	4.021***
	(4.755)	(0.200)	(5.644)	(0.622)
Year fixed effects	Y	Y	Y	Y
Firm fixed effects			Y	Y
Ind fixed effects	Y	Y		
Pro fixed effects	Y	Y		
Observations	4818	4812	4818	4812
R-squared	0.127	0.362	0.445	0.797

Note: Standard errors are in parentheses. ***, **, and * significant at 1%, 5%, and 10%, respectively.



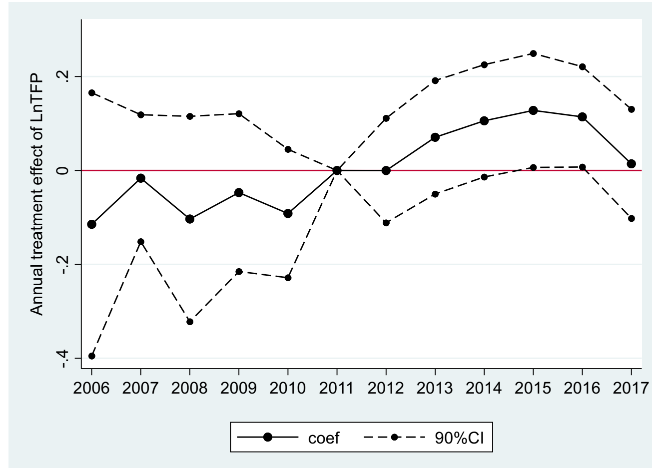


Fig. 2. (a) Annual treatment effect of charge.
(b) Annual treatment effect of LnTFP.

Table 4
Average treatment effects of DDD estimates.

VARIABLES	Charge	LnTFP	Charge	LnTFP
	(1)	(2)	(3)	(4)
ETS × Post×Ind	−1.762***	0.081	−1.922***	0.081**
	(0.608)	(0.054)	(0.721)	(0.039)
ETS × Post	−0.148	0.066***	−0.278**	0.029
	(0.118)	(0.024)	(0.139)	(0.021)
ETS × Ind	1.054**	−0.077	−0.626	0.021
	(0.474)	(0.049)	(0.812)	(0.058)
Post×Ind	1.007***	0.031	1.356***	−0.030*
	(0.279)	(0.024)	(0.284)	(0.017)
Constant	−15.079***	−0.139	−8.943***	3.271***
	(1.920)	(0.136)	(1.963)	(0.328)
Year fixed effects	Y	Y	Y	Y
Firm fixed effects			Y	Y
Ind fixed effects	Y	Y		
Pro fixed effects	Y	Y		
Observations	16,963	16,937	16,963	16,937
R-squared	0.096	0.332	0.444	0.785

Note: We add industry variation (e.g. regulated relative to unregulated industries) and conduct the triple-differences estimation as a robust test. Standard errors are in parentheses. ***, **, and * significant at 1%, 5%, and 10%, respectively.

Table 5
Control for time-varying province and industry effects.

VARIABLES	Controls for province-industry fixed effects		Controls for industry year trends	
	Charge	LnTFP	Charge	LnTFP
	(1)	(2)	(3)	(4)
ETS × Post	−1.260**	0.064*	−1.551***	0.127***
	(0.512)	(0.033)	(0.530)	(0.041)
Controls	Y	Y	Y	Y
Year fixed	Y	Y	Y	Y
Ind fixed	Y	Y	Y	Y
Pro fixed	Y	Y	Y	Y
Pro-Ind fixed	Y	Y	N	N
Ind*year fixed	N	N	Y	Y
Constant	−57.469***	0.475**	−51.982***	0.950***
	(6.709)	(0.234)	(4.894)	(0.222)
Observations	4818	4812	4818	4812
R-squared	0.219	0.564	0.153	0.379

Note: Columns 1 and 2 control for the province-ind fixed effects; And columns 3 and 4 control for the industry* year fixed effects. Standard errors in parentheses. ***, **, and * significant at 1%, 5%, and 10%, respectively.

Table 6
Alternative variable.

VARIABLES	Environmental performance		Economic performance	
	ECE	ISO	LnTFP_OP	LnRevenue
	(1)	(2)	(3)	(4)
ETS × Post	26.214**	0.059**	0.014**	0.145***
	(12.545)	(0.024)	(0.006)	(0.041)
ETS	−58.993***	−0.032	−0.057***	−0.480***
	(19.622)	(0.031)	(0.020)	(0.150)
Post	−103.171***	−0.002	−0.111***	−0.331***
	(35.208)	(0.059)	(0.014)	(0.088)
Controls	Y	Y	Y	Y
Year fixed	Y	Y	Y	Y
Ind fixed	Y	Y	Y	Y
Pro fixed	Y	Y	Y	Y
Constant	−1170.672***	−1.248***	−1.007***	−0.224
	(180.054)	(0.153)	(0.034)	(0.211)
Observations	4818	4818	4812	4818
R-squared	0.080	0.266	0.994	0.855

Note: Columns 1 and 2 report the impact of the ETS on firm environmental performance measured by environmental capital expenditure and ISO certification, respectively; Columns 3 and 4 report the impact of the ETS on firm economic performance measured by TFP and revenue, respectively. Standard errors in parentheses. ***, **, and * significant at 1%, 5%, and 10%, respectively.

measures for environmental and economic performance. First, the firm's environmental capital expenditure is a relatively accurate indicator of environmental performance. We use the current year's environmental capital expenditure as an alternative measure of environmental performance. Second, we measure firms' environmental performance based on ISO14001 certification which is the international standard for environmental management systems (Trumpp et al., 2015) and can be considered an adequate measure of emissions reductions in China (Wang, 2002). Firms with ISO14001 certification take the value 1 and otherwise are 0. To measure firm economic performance, we first use Olley and Pakes's (1992) method as a robustness test for firm TFP, and then use the logarithm of revenue to proxy for firm economic performance.

Table 6 reports the results for the basic model re-estimated including these alternative variables. Columns 1 and 2 present the results of the estimates, including the alternative measures for environmental performance. They show that ETS × Post promotes firm environmental capital expenditure (column 1) at the 5% statistical level. We see also that the ETS increases ISO14001 certification among the pilot firms (column 2). Columns 3 and 4 present the results for economic

Table 7
Other robustness tests.

VARIABLES	The impact on output	Taking 2013 as the baseline year	
	LnWorker	Charge	LnTFP
	(1)	(2)	(3)
ETS × Post	0.106**		
	(0.045)		
ETS × Post2013		−1.840***	0.134***
		(0.516)	(0.035)
Controls	Y		
Year fixed	Y		
Ind fixed	Y		
Pro fixed	Y		
Constant	−7.444***	−50.685***	0.839***
	(0.252)	(4.752)	(0.200)
Observations	4812	4818	4812
R-squared	0.746	0.127	0.362

Note: Column 1 reports the impact of the ETS on firm output; Columns 2 and 3 report the estimated results of taking 2013 as the baseline year. Standard errors in parentheses. ***, **, and * significant at 1%, 5%, and 10%, respectively.

Table 8
Heterogeneity analysis.

VARIABLES	Charge	LnTFP
	(1)	(2)
ETS_1 × Post	−3.310***	0.140***
	(0.854)	(0.053)
ETS_2 × Post	−0.335	0.110**
	(0.384)	(0.047)
ETS_1	0.626	−0.420***
	(1.089)	(0.136)
ETS_2	−5.023***	−0.571***
	(1.322)	(0.139)
Post	−1.376	−0.212**
	(2.083)	(0.086)
Controls	Y	Y
Year fixed effects	Y	Y
Ind fixed effects	Y	Y
Pro fixed effects	Y	Y
Constant	−51.301***	0.806***
	(4.780)	(0.202)
Observations	4818	4812
R-squared	0.130	0.363

Note: ETS_1 is equal to 1 if the cap is larger than the average cap in the pilot areas and is 0 otherwise. ETS_2 is equal to 1 if the cap in the pilot province is lower than the average in the pilot areas and is 0 otherwise. Standard errors in parentheses. ***, **, and * significant at 1%, 5%, and 10%, respectively.

performance using the alternative measures. The coefficients of ETS × Post are all positive and statistically significant which implies that implementation of the ETS is associated with an increase in firm economic performance. Overall, these findings support the idea of a win-win situation due to implementation of the ETS.

4.4.4. *Other robustness tests*

We conducted additional tests as a further check on the robustness of our results. First, if output and emissions are reduced for the firms in the treated provinces, then these firms will be liable for lower annual sewage charges. To test this, we investigated the impact of the ETS on firm output. Output is measured by number of employees. The results in Table 7 show that the ETS does not reduce firm output significantly.

Table 9
Impacts of ETS on firm innovation.

VARIABLES	R&D	Patent	R&D	Patent
	(1)	(2)	(3)	(4)
ETS × Post	7.196*	4.945**	9.915*	9.908**
	(3.830)	(2.365)	(5.743)	(4.358)
ETS	−5.729	−2.432		
	(4.055)	(2.332)		
Post	−21.065**	5.215		
	(10.287)	(3.430)		
Size	8.228***	2.358***	1.715*	4.101***
	(1.478)	(0.376)	(0.963)	(0.962)
Age	0.180	0.007	−1.181	0.124
	(0.149)	(0.112)	(0.897)	(0.413)
State	−0.228***	0.025	−0.292**	−0.004
	(0.061)	(0.025)	(0.125)	(0.034)
Institution	0.028	0.009	0.023	−0.029
	(0.057)	(0.016)	(0.079)	(0.025)
Lev	0.080***	0.020***	4.951***	−1.829
	(0.014)	(0.004)	(1.374)	(3.896)
Growth	−0.004***	−0.003	−0.001	−0.004*
	(0.001)	(0.002)	(0.002)	(0.002)
Subsidy	−5.772***	1.852**	−4.054**	−0.165
	(1.996)	(0.801)	(2.060)	(1.043)
Independence	−10.807	9.937	2.161	4.262
	(15.196)	(8.891)	(19.865)	(12.394)
Ten_holder	0.175***	−0.012	0.213**	0.078
	(0.057)	(0.024)	(0.100)	(0.071)
CER	−0.499	8.857**	−0.367	9.933**
	(2.734)	(3.992)	(3.072)	(5.043)
Per GDP	4.349**	−0.921	4.974**	−0.077
	(1.745)	(0.748)	(2.153)	(0.917)
Year fixed effects	Y	Y	Y	Y
Firm fixed effects			Y	Y
Ind fixed effects	Y	Y		
Pro fixed effects	Y	Y		
Constant	−181.020***	−60.605***	−1963.714***	616.514
	(33.572)	(10.545)	(538.644)	(1534.001)
Observations	4818	4818	4818	4818
R-squared	0.297	0.051	0.582	0.230

Note: Standard errors in parentheses. ***, **, and * significant at 1%, 5%, and 10%, respectively.

Second, China announced the ETS pilot program in October 2011, and launched it in 2013. Since choosing 2013 as the pre-treatment baseline year might give rise to an announcement effect, we consider 2011 as the baseline year. As a robustness test, we conducted the analysis using 2013 as the baseline year. The results presented in Table 7 show that overall, the estimated impacts of the ETS are similar to those in the baseline regressions.

4.5. *Heterogeneity analysis*

Some studies show that the effects of an ETS depends heavily on its design (Borghesi et al., 2015). Rogge (2016) suggests that it is policy design rather than policy type which has a significant impacts on the effect of the policy. It has been shown also that cap stringency has an influence on the effectiveness of an ETS (Frondel et al., 2008; Taylor, 2012). To analyze the heterogeneous effects of cap stringency on firm environmental and economic performance, we estimated the following model:

$$Perf_{ijt} = \beta_0 + \beta_1 ETS_{ij1} \times Post_t + \beta_2 ETS_{ij2} \times Post_t + \beta_3 X_{ijt} + Pro_i + Ind_j + Year_t + \varepsilon_{ijt} \quad (8)$$

Table 10
Impacts of ETS induced innovation on firm performance.

VARIABLES	Charge		LnTFP	
	(1)	(2)	(3)	(4)
R&D1	−0.264***		0.018***	
	(0.074)		(0.005)	
R&D2	0.001		0.001***	
	(0.004)		(0.000)	
Patent1		−0.385***		0.026***
		(0.107)		(0.008)
Patent2		0.005		0.000*
		(0.005)		(0.000)
Controls	Y	Y	Y	Y
Year fixed effects	Y	Y	Y	Y
Ind fixed effects	Y	Y	Y	Y
Pro fixed effects	Y	Y	Y	Y
Constant	−98.485***	−73.944***	4.086***	2.418***
	(14.096)	(7.981)	(0.923)	(0.460)
Observations	4818	4818	4812	4812
R-squared	0.127	0.127	0.366	0.363

Note: Standard errors in parentheses. ***, **, and * significant at 1%, 5%, and 10%, respectively.

Given that the emissions caps in pilot provinces differ across provinces, we use two dummy variables to proxy for cap stringency in different pilot areas. ETS_{ij1} is equal to 1 if the cap is larger than the average cap in the pilot areas and is 0 otherwise. ETS_{ij2} is equal to 1 if the cap in the pilot province is lower than the average in the pilot areas and is 0 otherwise. The remaining variables are defined as in eq.(2). By comparing the coefficients of the interaction terms $ETS_{ij1} \times Post_t$ and $ETS_{ij2} \times Post_t$ we can identify the heterogeneous effects of ETS on cap stringency.

Table 8 reports the results of the heterogeneity analysis (eq. (8)). Columns 1 and 2 show that a stricter emissions cap (ETS1 × Post) promotes better environmental and economic firm performance. However, in ETS areas with less strict caps (ETS2 × Post), firm environmental performance is insignificant but economic performance is significant. Overall, these results are in line with previous research (Hu et al., 2020).

5. Mechanism analysis

5.1. Impacts of ETS on firm innovation

To investigate the impact of ETS on firm innovation, we use eq. (3) to estimate the effects of emissions trading on corporate R&D investment and patent applications. The results are reported in Table 9. Columns 1 and 2 control for year, industry, and province fixed effects, and columns 3 and 4 present the results for the firm fixed effects.

In column 1, the estimated coefficient of ETS × Post is significantly positive at the 10% level, meaning that the ETS promotes firm R&D investment. Column 2 shows that ETS × Post has a significant effect on patent applications at the 5% level. Columns 3 and 4 show that the ETS promotes firm innovation. These results are consistent with Borghesi et al. (2015) and Calel and Dechezleprêtre (2016) who showed that the European Union ETS has a positive effect on innovation among regulated firms.

Based on the above analysis, these results suggest that the ETS increased technological innovation in the pilot enterprises. This might be because the ETS encouraged firms to make technological changes to achieve emissions reductions to reduce costs based on the number of allowances required (Ambec et al., 2013) or to earn additional revenue from the sale of unwanted emissions allowances (Gagelmann and Frondel, 2005).

5.2. Impacts of innovation induced by ETS on firm performance

The first stage estimation results show that the ETS promoted firm R&D investment and patent applications (Table 9). This section investigates the impacts of innovation induced by ETS on firm performance based on eq. (4).

The estimation results are presented in Table 10. Columns 1 and 2 report the impact of innovation induced by the ETS on firm environmental performance, and columns 3 and 4 report the results of innovation induced by the ETS on firm economic performance. In columns 1 and 2, induced R&D investment (R&D1) and patent applications (Patent1) are significantly and negatively correlated to sewage charges, indicating that innovation induced by ETS improves environmental performance among regulated firms. In contrast, non-induced R&D investment (R&D2) and non-induced patent applications (Patent2) have an insignificant effect on environmental performance. If we compare the coefficients of R&D1 and R&D2, and Patent1 and Patent2, we find that the effects of innovation induced by the ETS on environmental performance are higher than the effects of innovation not induced by the ETS which supports the idea that induced innovation is essential for improved environmental performance.

The results in columns 3 and 4 show that induced R&D (R&D1) and patent applications (Patent1) improve economic performance (LnTFP) significantly, indicating that the ETS indirectly improves the economic performance of regulated firms via technological innovation. At the same time, R&D investment by non-ETS (R&D2) and patent applications by non-ETS (Patent2) also enhance firm LnTFP significantly. If we compare the coefficients of R&D1 and R&D2, and Patent1 and Patent2 we find that innovation induced by ETS on economic performance is higher than the effects of innovation in non-ETS which shows that induced innovation is vital for improving firm economic performance.

These findings are partly in line with Yang et al. (2012) who find that R&D induced by environment regulation was significantly and positively related to productivity in Taiwanese industry. Similarly, Luo et al. (2021) find that emission reduction technology mediates the relationship between an ETS and competitiveness. Overall, our findings suggest that an ETS which promotes technological innovation can result in a win-win situation for environmental and economic performance. That is, strict but flexible environmental regulation indirectly increases productivity by encouraging innovation activity.

6. Conclusions and discussion

China is the world's largest emitter of CO_2 which resulted in a series of Chinese government environmental regulations to reduce carbon emissions. The impacts on firm behavior and the economy generally, of the carbon ETS implemented by the Chinese government in 2011 need to be understood to inform future policies.

We use the context of China's carbon ETS pilot policy to explore whether an ETS stimulates innovation and results in a win-win for environmental and economic performance. We employ a DID model and a quasi-experimental setting to test the positive impact of the ETS on firms' environmental and economic performance. We find that a stricter emissions cap enhances performance and that ETS induced technological innovation in the regulated firms has a significantly positive impact on firms' environmental and economic performance. These results indicate that an ETS results in both better environmental and economic performance due to increased innovation; this supports the Porter hypothesis.

There are some implications for policy which could be critical for the development of a long-term national ETS. First, our results show that the ETS has had a positive effect on firm environmental and economic performance. This is evidence that market-based environmental regulation can result in a win-win situation related to firm environmental and economic performance. The government could exploit this policy to achieve a better balance between environmental quality and economic growth. It should be extended to include more regions and more industries to achieve more impressive carbon emissions reductions.

Second, further analysis showed that the ETS resulted in better firm performance if accompanied by a stricter emissions cap which suggests that the effects of the ETS on the sample firms shows some heterogeneity. Previous work shows that aspects of policy design such as emission cap stringency have an essential impact on the effect of the policy (Borghesi et al., 2015; Taylor, 2012). Based on our evidence, future ETSs should set emission caps appropriate to the particular industries.

Third, we show that the ETS was correlated positively with firm innovation, and further analysis show that ETS-induced innovation has a significant positive impact on firm environmental and economic performance. This suggests that ETSs could result in innovation offsets and enhanced firm performance. Technological innovation is a complex, long-term and uncertain process and is required to address environmental problems and achieve a sustainable environment. The government could implement ETSs to encourage firms to innovate, and provide support to reduce the uncertainties involved in technological innovation. This would further enhance the innovation effect of the policy and contribute to improved environmental and economic performance.

Overall, our results show that the results of the ETS are satisfactory. The experience of the pilot firms provides a reliable reference for future market-based environmental regulation in China aimed at sustainable economic development. Our findings contribute to the carbon abatement literature in the context of developing countries by showing that ETSs can be a cost-effective policy tool.

Ethical approval

This article does not contain any studies with human participants or animals performed by any of the authors.

CRediT authorship contribution statement

Shenggang Ren: Conceptualization, Methodology, Supervision, Project administration, Investigation, Validation, Resources, Funding acquisition, Writing – review & editing. **Xuanyu Yang:** Data curation, Software, Formal analysis, Writing – original draft. **Yucai Hu:** Data curation, Software, Writing – original draft, Writing – review & editing, Funding acquisition. **Julien Chevallier:** Conceptualization, Methodology.

Declaration of Competing Interest

The authors declare that they have no conflict of interest.

Acknowledgements

This research is supported by Science and Technology Project of Hebei Education Department [grant number: QN2022066], and Fundamental Research Funds for the Central Universities of Central South University [grant number: 2016zzts006].

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eneco.2022.106157.

References

Aghion, P., Dechezleprêtre, A., Hémous, D., Martin, R., Reenen, J.V., 2016. Carbon taxes, path dependency, and directed technical change: evidence from the auto industry. J. Polit. Econ. 124 (1), 1–51.
Albrizio, S., Kozluk, T., Zipperer, V., 2017. Environmental policies and productivity growth: evidence across industries and firms. J. Environ. Econ. Manag. 81, 209–226.
Alpay, E., Kerkvliet, J., Buccola, S., 2002. Productivity growth and environmental regulation in Mexican and US food manufacturing. Am. J. Agric. Econ. 84 (4), 887–901.
Ambec, S., Cohen, M.A., Elgie, S., Lanoie, P., 2013. The Porter hypothesis at 20: can environmental regulation enhance innovation and competitiveness? Rev. Environ. Econ. Policy 7 (1), 2–22.
Anderson, B., Di Maria, C., 2011. Abatement and allocation in the pilot phase of the EU ETS. Environ. Resour. Econ. 48 (1), 83–103.
Anger, N., Oberndorfer, U., 2008. Firm performance and employment in the EU emissions trading scheme: an empirical assessment for Germany. Energy Policy 36 (1), 12–22.
Barbera, A.J., McConnell, V.D., 1990. The impact of environmental regulations on industry productivity: direct and indirect effects. J. Environ. Econ. Manag. 18 (1), 50–65.
Beck, T., Levine, R., Levkov, A., 2010. Big bad banks? The winners and losers from bank deregulation in the United States. J. Finance 65 (5), 1637–1667.
Bel, G., Joseph, S., 2015. Emission abatement: untangling the impacts of the EU ETS and the economic crisis. Energy Econ. 49, 531–539.
Berman, E., Bui, L.T., 2001. Environmental regulation and productivity: evidence from oil refineries. Rev. Econ. Stat. 83 (3), 498–510.
Borghesi, S., Cainelli, G., Mazzanti, M., 2015. Linking emission trading to environmental innovation: evidence from the Italian manufacturing industry. Res. Policy 44 (3), 669–683.
Calel, R., Dechezleprêtre, A., 2016. Environmental policy and directed technological change: evidence from the European carbon market. Rev. Econ. Stat. 98 (1), 173–191.
Cao, J., Ho, M.S., Ma, R., Teng, F., 2021. When carbon emission trading meets a regulated industry: evidence from the electricity sector of China. J. Public Econ. 200, 104470.
Chakraborty, P., Chatterjee, C., 2017. Does environmental regulation indirectly induce upstream innovation? New evidence from India. Res. Policy 46 (5), 939–955.
Chan, H.S., Li, S., Zhang, F., 2013. Firm Competitiveness and the European Union Emissions Trading Scheme. The World Bank.
Chen, Y.C., Hung, M., Wang, Y., 2017. The effect of mandatory CSR disclosure on firm profitability and social externalities: evidence from China. J. Account. Econ. 65 (1).
Chen, X., Fu, Q., Chang, C.P., 2021. What are the shocks of climate change on clean energy investment: a diversified exploration. Energy Econ. 95, 105136.
Clò, S., Ferraris, M., Florio, M., 2017. Ownership and environmental regulation: evidence from the European electricity industry. Energy Econ. 61, 298–312.
Costantini, V., Mazzanti, M., 2012. On the green and innovative side of trade competitiveness? The impact of environmental policies and innovation on EU exports. Res. Policy 41 (1), 132–153.
Delarue, E., Voorspools, K., D'haeseleer, W., 2008. Fuel switching in the electricity sector under the EU ETS: review and prospective. J. Energy Eng. 134 (2), 40–46.
Ding, S., Jia, C., Wu, Z., Yuan, W., 2016. Environmental management under subnational institutional constraints. J. Bus. Ethics 134 (4), 631–648.
Du, G., Yu, M., Sun, C., Han, Z., 2021. Green innovation effect of emission trading policy on pilot areas and neighboring areas: an analysis based on the spatial econometric model. Energy Policy 156, 112431.
Ellerman, A.D., Convery, F.J., De Perthuis, C., 2010. Pricing Carbon: The European Union Emissions Trading Scheme. Cambridge University Press.
Elrod, A.A., Malik, A.S., 2017. The effect of environmental regulation on plant-level product mix: a study of EPA's cluster rule. J. Environ. Econ. Manag. 83, 164–184.
Faccio, M., 2010. Differences between politically connected and nonconnected firms: a cross-country analysis. Financ. Manag. 39 (3), 905–928.
Frondel, M., Horbach, J., Rennings, K., 2008. What triggers environmental management and innovation? Empirical evidence for Germany. Ecol. Econ. 66 (1), 153–160.
Gagelmann, F., Frondel, M., 2005. The impact of emission trading on innovation–science fiction or reality? Eur. Environ. 15 (4), 203–211.
Giannetti, M., Liao, G., Yu, X., 2015. The brain gain of corporate boards: evidence from China. J. Financ. 70 (4), 1629–1682.
Gray, W.B., Shadbegian, R.J., 2003. Plant vintage, technology, and environmental regulation. J. Environ. Econ. Manag. 46 (3), 384–402.
Greenstone, M., List, J.A., Syverson, C., 2012. The Effects of Environmental Regulation on the Competitiveness of US Manufacturing (0898–2937). Retrieved from.
Grossman, G.M., Krueger, A.B., 1995. Economic growth and the environment. Q. J. Econ. 110 (2), 353–377.
Grubb, M., Azar, C., Persson, U.M., 2005. Allowance allocation in the European emissions trading system: a commentary. Clim. Pol. 5 (1), 127–136.
Hamamoto, M., 2006. Environmental regulation and the productivity of Japanese manufacturing industries. Resour. Energy Econ. 28 (4), 299–312.
Hoffmann, V.H., 2007. EU ETS and investment decisions: the case of the German electricity industry. Eur. Manag. J. 25 (6), 464–474.
Hu, Y., Ren, S., Wang, Y., Chen, X., 2020. Can carbon emission trading scheme achieve energy conservation and emission reduction? Evidence from the industrial sector in China. Energy Econ. 85, 104590.
Huang, R., Chen, D., 2015. Does environmental information disclosure benefit waste discharge reduction? Evidence from China. J. Bus. Ethics 129 (3), 535–552.
Inoue, E., Arimura, T.H., Nakano, M., 2013. A new insight into environmental innovation: does the maturity of environmental management systems matter? Ecol. Econ. 94, 156–163.
Jaffe, A.B., Palmer, K., 1997. Environmental regulation and innovation: a panel data study. Rev. Econ. Stat. 79 (4), 610–619.
Jaraitė, J., Convery, F., Di Maria, C., 2010. Transaction costs for firms in the EU ETS: lessons from Ireland. Clim. Pol. 10 (2), 190–215.

Joltreau, E., Sommerfeld, K., 2019. Why does emissions trading under the EU emissions trading system (ETS) not affect firms' competitiveness? Empirical findings from the literature. Clim. Pol. 19 (4), 453–471.
Kumar, S., Managi, S., Jain, R.K., 2020. CO2 mitigation policy for Indian thermal power sector: potential gains from emission trading. Energy Econ. 86, 104653.
Lanoie, P., Laurent-Lucchetti, J., Johnstone, N., Ambec, S., 2011. Environmental policy, innovation and performance: new insights on the Porter hypothesis. J. Econ. Manag. Strateg. 20 (3), 803–842.
Lee, C.C., Wang, C.W., Ho, S.J., Wu, T.P., 2021. The impact of natural disaster on energy consumption: international evidence. Energy Econ. 97, 105021.
Levinsohn, J., Petrin, A., 2003. Estimating production functions using inputs to control for unobservables. Rev. Econ. Stud. 70 (2), 317–341.
Li, W., Lu, X., 2016. Institutional interest, ownership type, and environmental capital expenditures: evidence from the most polluting Chinese listed firms. J. Bus. Ethics 138 (3), 459–476.
Li, D., Huang, M., Ren, S., Chen, X., Ning, L., 2016. Environmental legitimacy, green innovation, and corporate carbon disclosure: evidence from CDP China 100. J. Bus. Ethics (1), 1–16.
Libo, W.U., Zhou, Y., Qian, H., 2022. Global actions under the Paris agreement: tracing the carbon leakage flow and pursuing countermeasures. Energy Econ. 105804.
Liu, J.-Y., Zhang, Y.-J., 2021. Has carbon emissions trading system promoted non-fossil energy development in China? Appl. Energy 302, 117613.
Liu, D., Ren, S., Li, W., 2022. SO2 emissions trading and firm exports in China. Energy Econ. 109, 105978.
Luo, Y., Li, X., Qi, X., Zhao, D., 2021. The impact of emission trading schemes on firm competitiveness: evidence of the mediating effects of firm behaviors from the guangdong ETS. J. Environ. Manag. 290, 112633.
Martin, R., Muûls, M., Wagner, U., 2011. Climate change, investment and carbon markets and prices: evidence from manager interviews. In: Climate Strategies, Carbon Pricing for Low-Carbon Investment Project, 2011.
Olley, G.S., Pakes, A., 1992. The Dynamics of Productivity in the Telecommunications Equipment Industry. Retrieved from.
Porter, M.E., Linde, C.v. d., 1995. Toward a new conception of the environment-competitiveness relationship. J. Econ. Perspect. 9 (4), 97–118.
Rassier, D.G., Earnhart, D., 2015. Effects of environmental regulation on actual and expected profitability. Ecol. Econ. 112, 129–140.
Rogge, K., 2016. Reviewing the Evidence on the Innovation Impact of the EU Emission Trading System.
Rogge, K.S., Schneider, M., Hoffmann, V.H., 2011. The innovation impact of the EU emission trading system — findings of company case studies in the German power sector. Ecol. Econ. 70 (3), 513–523.
Tan, R., Lin, B., 2022. The long term effects of carbon trading markets in China: evidence from energy intensive industries. Sci. Total Environ. 806, 150311.
Taylor, M.R., 2012. Innovation under cap-and-trade programs. Proc. Natl. Acad. Sci. 109 (13), 4804–4809.
Touma, D., Stevenson, S., Lehner, F., Coats, S., 2021. Human-driven greenhouse gas and aerosol emissions cause distinct regional impacts on extreme fire weather. Nat. Commun. 12 (1), 1–8.
Trumpp, C., Endrikat, J., Zopf, C., Guenther, E., 2015. Definition, conceptualization, and measurement of corporate environmental performance: a critical examination of a multidimensional construct. J. Bus. Ethics 126 (2), 185–204.
Wang, H., 2002. Pollution regulation and abatement efforts: evidence from China. Ecol. Econ. 41 (1), 85–94.
Wang, X., Cao, F., Ye, K., 2018. Mandatory corporate social responsibility (CSR) reporting and financial reporting quality: evidence from a quasi-natural experiment. J. Bus. Ethics 152 (1), 253–274.
Wu, Q., Wang, Y., 2022. How does carbon emission price stimulate enterprises' total factor productivity? Insights from China's emission trading scheme pilots. Energy Econ. 109, 105990.
Xie, R.-H., Yuan, Y.-J., Huang, J.-J., 2017. Different types of environmental regulations and heterogeneous influence on "green" productivity: evidence from China. Ecol. Econ. 132, 104–112.
Xu, J., Tan, X., He, G., Liu, Y., 2019. Disentangling the drivers of carbon prices in China's ETS pilots—an EEMD approach. Technol. Forecast. Soc. Chang. 139, 1–9.
Yang, C.-H., Tseng, Y.-H., Chen, C.-P., 2012. Environmental regulations, induced R&D, and productivity: evidence from Taiwan's manufacturing industries. Resour. Energy Econ. 34 (4), 514–532.
Xu, N., Xu, X., Yuan, Q., 2013. Political connections, financing friction, and corporate investment: evidence from Chinese listed family firms. Eur. Financ. Manag. 19 (4), 675–702.
Yang, Z., Fan, M., Shao, S., Yang, L., 2017. Does carbon intensity constraint policy improve industrial green production performance in China? A quasi-DID analysis. Energy Econ. 68, 271–282.
Yao, S., Yu, X., Yan, S., Wen, S., 2021. Heterogeneous emission trading schemes and green innovation. Energy Policy 155, 112367.
Yu, P., Cai, Z., Sun, Y., 2021. Does the emissions trading system in developing countries accelerate carbon leakage through OFDI? Evidence from China. Energy Econ. 101, 105397.
Zhang, Y.-J., Cheng, H.-S., 2021. The impact mechanism of the ETS on CO2 emissions from the service sector: evidence from Beijing and Shanghai. Technol. Forecast. Soc. Chang. 173, 121114.
Zhang, Y.J., Wang, W., 2021a. How does China's carbon emissions trading (CET) policy affect the investment of CET-covered enterprises? Energy Econ. 98, 105224.
Zhang, Y.-J., Wang, W., 2021b. How does China's carbon emissions trading (CET) policy affect the investment of CET-covered enterprises? Energy Econ. 98, 105224.
Zhang, D., Karplus, V.J., Cassisa, C., Zhang, X., 2014. Emissions trading in China: Progress and prospects. Energy Policy 75, 9–16.
Zhang, Y.-J., Liang, T., Jin, Y.-L., Shen, B., 2020. The impact of carbon trading on economic output and carbon emissions reduction in China's industrial sectors. Appl. Energy 260, 114290.
Zhang, S., Wang, Y., Hao, Y., Liu, Z., 2021. Shooting two hawks with one arrow: could China's emission trading scheme promote green development efficiency and regional carbon equality? Energy Econ. 101, 105412.
Zhao, L., Zhang, L., Sun, J., He, P., 2022. Can public participation constraints promote green technological innovation of Chinese enterprises? The moderating role of government environmental regulatory enforcement. Technol. Forecast. Soc. Chang. 174, 121198.
Zhu, X., Zuo, X., Li, H., 2021. The dual effects of heterogeneous environmental regulation on the technological innovation of Chinese steel enterprises—based on a high-dimensional fixed effects model. Ecol. Econ. 188, 107113.