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Abstract

This study aims to explore if Japan's environmental regulation, such as its regional emissions trading scheme (ETS), can improve innovation without inducing carbon leakage. Using unique firm-level data for the period from 2003 to 2018, based on the difference-in-differences method, this study investigates how firms address issues such as innovation and outsourcing under Japan's regional ETS framework. The key findings are as follows. (1) Japan's regional ETS is effective in improving targeted firms' innovation during the early stage of the compliance period. (2) Targeted firms that pursued innovation before the ETS promoted subsequent innovations after the ETS. (3) Japan's regional ETS did not induce the risk of carbon leakage through outsourcing activities. (4) Firms that did not actively encourage innovation increased their outsourcing activities during the compliance period. Based on these findings, we discuss the study implications and directions for future policy design.

Keywords: Emissions trading scheme, Japan, innovation, carbon leakage, outsourcing activity, difference-in-differences

1. Introduction

Climate change caused by the increase in carbon dioxide (CO2) emissions is a challenging global issue. Emissions trading schemes (ETSs), which are market-based environmental instruments, have emerged as an effective tool to mitigate the impact of climate change. Ever since the European Union (EU) implemented the EU ETS in 2005, ETSs have been introduced worldwide for meeting mitigation objectives through the cap-and-trade scheme for emissions specifically in China, South Korea, and Austria. A number of studies support the evidence that ETSs have contributed toward reducing CO2 emissions from firms that are regulated by ETSs (Martin et al., 2016; Zhang et al., 2020).

Theoretically, a firm targeted by an ETS (hereafter referred to as a targeted firm) can pursue several strategies to respond to the ETS. First, the firm can reduce emissions through its own efforts, such as fuel switching and improving energy efficiency in the production process. This requires investment in R&D to improve energy management. Second, regulation increases the costs of targeted firms that may lose their competitiveness compared with their counterparts from unregulated countries. This asymmetry may force targeted firms to reduce CO2 emissions by shifting their production processes rather than using technological innovations. This can cause carbon leakage through three channels: (i) outsourcing (i.e., outsourcing the production process to other firms), (ii) intensive margin (i.e., shifting production activities from regulated facilities to unregulated facilities within the firm), and (iii) extensive margin (i.e., downsizing facilities below the targeting threshold and establishing new facilities in unregulated regions). Third, a firm can also purchase emissions credits from other firms to offset emissions it cannot eliminate. Under the flexible ETS mechanism, targeted firms are expected to reduce emissions in a cost-effective way to avoid carbon leakage through free allocation of allowances.

In practice, concerns about innovation and production outsourcing are ambiguous. Firms' decisions to respond to an ETS are determined by the degree of regulatory uncertainty and compliance costs. Firms may choose to invest in R&D to reduce their emissions in the long term if they are concerned about the uncertainty of the ETS in the future. Conversely, if they face high compliance costs, firms may choose to outsource their production process to other firms to reduce their emissions immediately. Based on these arguments, a growing body of literature has examined the impact of ETS on innovation and carbon leakage, with mixed findings. On the relationship between ETSs and technological innovation, several empirical studies infer that ETSs have encouraged innovation (Martin et al., 2013; Calel & Dechezleprêtre, 2016; Calel, 2020; Chen et al., 2021; Hamamoto, 2021; Ren et al., 2022), while some studies indicate a limited impact

(Rogge et al., 2011; Löfgren et al., 2014; Chen et al.,2020). Empirical findings regarding the impact of ETSs on carbon leakage range from positive leakage (Fell & Maniloff, 2018; Gao et al., 2020; Bartram et al., 2022) and limited impact (Sartor, 2013; Martin et al., 2014; Branger et al., 2016; Koch and Basse Mama, 2019) to negative leakage (Sadayuki & Arimura, 2021). Different types of literature examined the impact of ETS on carbon leakage at firm level through channels such as CO2 emissions (Dechezleprêtre et al., 2022), changes in trade flows (Naegele & Zaklan, 2019), downsizing of businesses (Martin et al., 2014), or foreign direct investment (FDI) (Koch & Mama, 2019). Notwithstanding the number of studies on the intensive margin (Fell & Maniloff, 2018; Bartram et al., 2022) and extensive margin (Martin et al., 2014; Sadayuki & Arimura, 2021), no study has yet investigated carbon leakage through ETS outsourcing.[1]

The diversity in empirical findings regarding the impact of ETSs on outcomes such as innovation and carbon leakage may be partly attributable to existing studies that examined the impact of ETSs on each outcome independently, without considering any alternative options that firms may choose. For instance, a firm that finds it expensive to invest in a new technology or R&D to reduce emissions could outsource a part of its production process to other firms to achieve the reduction target economically. Conversely, a firm could expand its R&D to establish an energy-efficient production process that is more cost efficient in the long term. Therefore, studies that consider the impact of the ETS on these outcomes are required to understand the mechanism of the ETS in the context of firms' decisions on each outcome, given the other options.

This study examines firms' decisions on innovation and outsourcing activities that are governed by the ETS regulation by leveraging Japan's regional ETS, namely the Saitama ETS. Among other ETSs worldwide, Saitama ETS provides an appropriate experiment for two reasons. First, in the Saitama ETS, most firms are manufacturing companies that are directly involved in production and are suitable for analyzing the impact on R&D. To reduce CO2 emissions during the production process, manufacturing firms must improve their technologies by investing in energy-efficient equipment or R&D investment to achieve reduction by saving on electricity or upgrading to energy-saving equipment instead of R&D investment. Second, manufacturing firms face the problem of relocating production across regions, which is easier under a geographically limited ETS, thus facilitating our effort to investigate firms' outsourcing activity. A regional ETS has a higher risk of carbon leakage compared to a national ETS because the targeted firms can

[1] List of existing empirical studies on the impact of ETS on innovation and carbon leakage is summarized in Table A1 in the Appendix.

reduce costs with domestic outsourcing activities compared to overseas outsourcing.

This study makes several contributions to the existing literature. (1) The impact of Japan's regional ETS on firms' innovation. To the best of our knowledge, no study has analyzed firms' innovation in Japan. We accessed confidential firm data to investigate innovation activities that are conducted at firm level (Calel &Dechezleprêtre, 2016). The results confirm that ETS improved innovation during the early stages of the compliance period. (2) Focusing on outsourcing-induced carbon leakage, empirical studies that examined carbon leakage are still limited, specifically outsourcing-induced carbon leakage under the ETS. The result does not provide any evidence to support ETS induced outsourcing carbon leakage. (3) This study also focuses on firms that invested in innovation. Regulations encourage firms to improve their environmental performance to reduce emissions. Firms that pursued innovation independently prior to the ETS may make considerable efforts to develop after implementing the ETS. Mansfield (1968) and Peters (2009) argued that the experience of successful innovation would encourage a firm to pursue subsequent innovations. This argument is also applicable to firms under the ETS. However, to the best of our knowledge, no existing study has examined if targeted firms that implemented innovation contributed to subsequent innovations after compliance with the ETS. Our result suggests that increases in R&D rely on firms that had experience in R&D activities before the Saitama ETS.

The remainder of the study is organized as follows. Section 2 introduces the study background and hypotheses. Section 3 describes the methodology and data. Section 4 presents the results and discussion. Section 5 concludes the study with policy implications.

2. Background and hypotheses development

2.1. Japan's regional ETSs

Japan's Tokyo and Saitama prefectures implemented regional ETS in 2010 and 2011, respectively. Tokyo prefecture is adjacent to Saitama prefecture, located in the central-eastern part of Japan. These two prefecture-based Japanese ETSs cover firms that operate at least one facility with an annual energy consumption of 1500 kl in crude oil equivalent or more.[2] Emissions caps were set for the targeted firms, and they complied with reduction targets that varied between those set for commercial and manufacturing industries. Emissions caps relate to reduction targets, and the emissions baseline was calculated based on average emissions during any three consecutive years from 2002 to

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[2] Approximately 2800 tons of CO2 threshold follows the benchmark of the Energy Conservation Act (Arimura & Iwata, 2015).

2007. Japan's ETSs featured free allocation of emissions allowances to targeted firms that were permitted to trade these allowances and use other credits. A firm can receive an allowance equal to the amount of excess reduction if it curbs emissions that surpass the reduction target. Targeted firms can also purchase allowances from other firms that own such allowances. There are several differences between the Saitama and Tokyo ETSs, even though both are implemented in Japan. For instance, compliance is voluntary under Saitama ETS, as it does not financially penalize targeted firms even if they fail to comply with reduction targets, which is a unique feature compared to other global ETSs. The Tokyo ETS, however, imposes a penalty if an entity fails to comply with the defined reduction targets and its name is published. In addition, as the Tokyo ETS is a mandatory regulation, reduction targets are more stringent under the Saitama ETS than those under the Tokyo ETS. For instance, the targets of the second compliance period of both Saitama and Tokyo ETSs were 13% and 15%, respectively. Moreover, only the first compliance period of the two ETSs varies due to different implementation years, which is 2010 to 2014 for the Tokyo ETS and 2011 to 2014 for the Saitama ETS. The second and third compliance periods for both ETSs ranged from 2015 to 2019, and the third compliance period is from 2020 to 2024. Another major difference between these two ETSs is the industrial structure. The structure of Tokyo's manufacturing industry accounts for 7%, which is lower than the national average of 8.6% (Japan's Ministry of Internal Affairs and Communications [MIC] & Ministry of Economy, Trade and Industry [METI], 2017). However, the Saitama ETS covers manufacturing firms that account for 80% of the total number of targeted firms. This study focuses on innovation and outsourcing activities that are more sensitive to manufacturing firms and investigates the impact of Saitama ETS on the innovation and outsourcing activities of these entities.

Focusing on the Saitama ETS, this study leverages two advantages compared to the literature on other ETSs worldwide, which have lower threshold and regional characteristics. Compared to other ETSs, for instance, the California cap-and-trade program that regulated around 450 entities, Saitama's ETS with a low inclusion threshold offers more than 700 samples within a small region. In addition, it provides an empirical case for analyzing the emission reduction strategies of relatively small firms. Moreover, under the regional ETS, it is fairly easy to construct groups for analysis and observe the shift in domestic production. Therefore, analyzing firms under the geographically restricted Saitama ETS provides robust incentives and evidence to explore the impact on innovation and carbon leakage.

2.2. Hypotheses

This study examines four hypotheses on how firms' innovation and outsourcing activities are influenced under the Saitama ETS.

First, innovation can be defined as the development of valuable technological improvements (Popp, 2019). Innovation activities are mainly of two types: (i) process innovation or the development of new production processes, and (ii) production innovation or the manufacture of new products (Stock et al, 2002; OECD, 2018). In other words, process innovation can be regarded as the input of the innovative activity and production innovation can be regarded as the output of the innovative activity.

Environmental regulations aim to promote environmental innovation to achieve carbon mitigation (Pan et al., 2022). Specifically, ETS may incentivize firms to promote innovations to reduce emissions from carbon-intensive production processes by developing new technologies (Zhu et al., 2019). The existing literature examined the impact of ETS on both process (Hoffmann, 2007; Testa et al., 2011; Schmidt et al., 2012; Calel, 2020) and production innovation (Calel & Dechezleprêtre, 2016; Bel & Joseph, 2018; Calel, 2020; Ren et al., 2020; Tang et al., 2020).

By promoting innovation such as energy-efficient technologies, firms can meet emission reduction targets set in the ETS, reduce mitigation costs, and gain additional benefits by selling excess carbon credits to other firms (Oestreich &Tsiakas, 2015; Chen et al., 2020). However, if firms maintain their technology level under the ETS, their profit and market competitiveness could be hampered by other competitors adopting advanced technologies with higher social responsibility (Lanoie et al., 2008; Yu et al., 2022). In the case of Japan, while no other study investigated innovation at the firm and facility levels, Hamamoto (2021) found that the Saitama ETS improved low-carbon technologies. We also find information on firms that invested in R&D to improve energy efficiency in the production process under the Saitama ETS on their websites, such as papermaking process (NIPPON FELT CO., LTD.), carbon recycling in the cement production process (TAIHEIYO CEMENT CO.,), and decarbonization in the production process (Mitsubishi Electric Home Appliance Co.,).[3] Therefore, although the impact on firm-level innovation has not been empirically examined as yet, the Saitama ETS can promote targeted firms' R&D based on the available literature. Therefore, we propose Hypothesis 1.1.

Hypothesis 1.1. Firms targeted by the Saitama ETS increase process innovation.

Second, the experience of innovation success encourages firms to pursue

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[3] See https://www.felt.co.jp/csr/, https://www.taiheiyo-cement.co.jp/news/news/pdf/220204.pdf, https://www.mitsubishielectric.co.jp/works/mhk/company/index.html.

subsequent innovations (Mansfield, 1968; Peters, 2009). As an auxiliary to Hypothesis 1.1, firms that had implemented R&D prior to the ETS may have gained an advantage in accelerating R&D after the ETS was implemented. Castillejo et al. (2004) indicated that innovation experience has a crucial effect on promoting subsequent innovation. The persistence of innovation has important implications for policy makers who support promotion of innovation by firms because well-designed policies can improve both current and long-term innovation activities. The firm's experience of innovation or knowledge accumulation relates to innovation persistence (Peters, 2009; Holl et al., 2022), which offers firms a priori advantage to continue to innovate in the future. This also applies to firms that are targeted by the ETS. For instance, ETS firms that conducted R&D and knowledge accumulation in the past may have an advantage in evolving the firm's R&D model for an energy-efficient manufacturing process when complying with the ETS. Through continuous innovation activities, firms can achieve the goal of sustainability through their efforts without carbon leakage. Therefore, we propose Hypothesis 1.2:

Hypothesis 1.2: Firms that pursued R&D before ETS tend to promote subsequent R&D after ETS.

Third, to avoid the high costs of mitigation, manufacturing firms may choose to outsource their production process to achieve emissions reduction targets. Antonietti et al. (2017) investigated the effect of environmental regulation on outsourcing by using survey data of Italian manufacturing firms, which indicated that stringent environmental regulations increased outsourcing to the South. Carbon leakage is more important for the Saitama ETS than for other national ETSs because Japan has only implemented unilaterally regional ETSs. The geographically restricted regional ETS may not be adequate to limit targeted firms to comply with the ETS without pursuing outsourcing activities. Domestic outsourcing is a feasible and easier choice to avoid high environmental costs when targeted firms face regional ETS. For instance, when a relatively small-sized targeted firm uses energy-intensive production processes, it may not be able to comply with the targets set in the regional ETS due to limited financial resources. To meet the targets and avoid abatement costs, the firm can outsource the production process to other domestic untargeted firms. Therefore, we propose Hypothesis 2:

Hypothesis 2: Firms targeted by ETS increase their outsourcing activity after implementing ETS.

Fourth, we assume that targeted firms may try to reduce emissions by outsourcing activities based on the firm's activities on innovation investment. Outsourcing helps the firm to reduce emissions immediately by the aggregate manufactured in the production process that is to be outsourced. Conversely, R&D investments take time to achieve emissions reduction targets, while for some firms it may be more cost efficient than outsource their production processes in the long run. Therefore, to achieve the mitigation, increasing outsourcing activities, as an alternative option, can be expected from firms that did not actively invest in new technologies in the short term. That is, for each firm, the optimal choice between outsourcing and R&D in response to ETS tends to be a corner solution, that is, the firm may choose to outsource more than R&D or the other way around based on their R&D investment. Therefore, we propose Hypothesis 3:

Hypothesis 3: The increase in a firm's R&D spending and outsourcing in response to ETS are negatively correlated. Similarly, firms' strategies to increase outsourcing activity in response to ETS relate to R&D.

3. Methodology and data

3.1. Basic empirical model

Difference-in-differences (DiD) is a widely used method to evaluate policies (Imbens & Wooldridge,2009; Miyamoto & Takeuchi, 2019; Sun & Abraham, 2021; Xiao et al., 2021; Athey & Imbens, 2022). The DiD method identifies the impact of a policy by comparing differences in interest outcomes before and after the policy intervention and between the treatment and control groups. In this study, firms are categorized under the treatment group if they are targeted by the Saitama ETS after 2011. Firms are categorized into the control group if they are not targeted by the Saitama ETS during the study period. By comparing their changes in values representing innovation and outsourcing activities, this study examines how the Saitama ETS contributed to these activities. Since our data period ranges from 2006 to 2018, it covers the pre-period of the Saitama ETS, first compliance period (2011–2014), and a part of the second compliance period (2015 –2019). As the impact of the ETS can differ by phases, we divide the treatment period into two phases. The baseline DiD model is constructed as follows:

$$Y_{it} = \beta_1 ETS_i \times Post1114_t + \beta_2 ETS_i \times Post1518_t + \boldsymbol{X}_{it}B + \mu_t + \gamma_i + \varepsilon_{it} \quad (1).$$

The dependent variable is a logarithmic value of the outcome Y_{it} regarding firm i in year t. We examine two outcomes, that is, R&D and outsourcing. We transformed the outcome variables by adding 1 to each value and taking the logarithm of the transformed value.

On the right-hand side of the equation, ETS_i is a dummy variable taking value

1 if firm i falls in the treatment group (i.e., targeted by the Saitama ETS after 2011), and $Post1114_t$ and $Post1518_t$ are dummy variables taking value 1 if year t falls between 2011 and 2014 (i.e., first compliance period) and between 2015 and 2018 (i.e., second compliance period), respectively. The coefficients of the interaction terms of these variables, β_1 and β_2, measure the impact of the ETS on the outcome during the two compliance periods, which are expected to show positive signs under Hypothesis1.1 and Hypothesis 2.

To estimate the impact of the ETS on firms' R&D and outsourcing activities, we consider other factors that could influence these activities. For this purpose, the firm-level fixed effect, μ_t, is controlled for capturing time-invariant unobserved effects of firms' characteristics; the annual fixed effect, γ_i, is controlled to capture the year-specific shock that is common to all Japanese firms. B is a series of coefficients of $\boldsymbol{X}_{it}$, which is a set of time-variant firm-level characteristics that can affect the outcome Y_{it}, besides the introduction of ETS and unobservable time and individual fixed effects. All continuous variables are transformed into logarithm values. Lastly, ε_{it} is an error term, which is assumed to be clustered at the firm level.

To further validate the estimation result of equation (1), we conduct a series of robustness tests, such as parallel trend tests, propensity score matching (PSM), DiD (or doubly-robust estimation) model, a test of the assumption of stability of unit treatment values, and a placebo test for DiD estimators.

3.2. Data

This study uses annual firm-level panel data between 2003 and 2018 from the Basic Survey of Japanese Business Structure and Activities, conducted by the Japan Ministry of Economy, Trade and Industry (METI). This survey covers all firms in Japan with more than 50 employees or at least 30 million JPY of stated capital or contribution. This survey records more than 200 items of information on approximately 30,000 firms annually, including firms' identification (name, address), various characteristics and financial information (number of employees, sales, exports, R&D, outsourcing, assets, liabilities). The data accurately investigate firm-level innovation and outsourcing. We follow Cole et al. (2021), who used data similar to our study, to handle the missing values and outliers for obtaining the unbalanced panel of 1909 observations for targeted firms and 87142 observations for untargeted firms for the period from 2003 to 2018.[4] To

[4] We removed observations with negative values for R&D activity and export values that are larger than sales because sales include exports.

eliminate the impact Tokyo ETS may have on our study, we excluded firms targeted by the Tokyo ETS from our sample.

In this study, R&D activities of firms targeted by the Saitama ETS represent innovation activities, such as reducing plastic usage for product packaging, developing technologies to reduce fuel and electric power consumption, and developing environmentally friendly products. To avoid costs associated with environmental regulations, firms tend to outsource energy (pollution) intensive production processes to other firms (Cole et al., 2021). Based on our survey data and literature, carbon leakage is measured based on outsourcing, that is, the transfer of production processes or outsourcing of firms' activities. However, the survey data have changed the definition of outsourcing activities since the 2010 survey (converted to 2009 data).[5] CO (2013), an official report from the Cabinet Office of Japan, suggested that it is necessary to consider these changes carefully when analyzing data, including 2008 and 2009. The data show unusual changes in firms' outsourcing from 2008 to 2009. Therefore, we use data from 2009 to 2018 for examining the ETS on outsourcing and e prior data for testing the parallel trends assumption. Table 1 shows the descriptive statistics of the treatment and control groups.

Multiple firms' characteristics are controlled in this study. Firm scale is the natural logarithm of the firm's employment (Capasso et al., 2013). Firm age is the natural logarithm of the survey year that deducts the firm's foundation and adds 1 (Zhu et al., 2019). Firm structure is the ratio of capital to labor (Aghion et al., 2013). A firm's capital structure is denoted by the liabilities–to–assets ratio. The export dummy variable, which can be considered as the new technology and experience obtained by exports, is also controlled in this study (Ren et al., 2020; Yang et al., 2017). Moreover, the dummy variable for stock options is also considered. The values of continuous variables are converted to 2015 prices based on the GDP deflator.

	Treatment group					Control group				
	Obs	Mean	S.D	Min	Max	Obs	Mean	S.D	Min	Max
R&D (million JPY)	1909	4.97	23.73	0	309.69	87142	1.11	14.56	0	923.46
Outsourcing (million JPY)	1208	4.71	16.85	0	201.31	54363	2.45	725.99	0	6205.71

[5] Prior to 2009, outsourcing included production and other activities. After 2010, outsourcing includes only production (manufacturing) activities.

Capital to labor ratio	1909	58.23	55.47	2.87	528.42	87142	37.10	43.19	1.05	1586.74
Employment	1909	2002.3	4194.0	52	39761	87142	469.58	1964.40	50	82560
Liability to assets ratio	1909	0.59	0.26	0.03	2.46	87142	0.58	0.27	0.01	7.04
Age	1909	60.03	22.52	1	114	87142	51.25	17.60	1	174
Stock option	1909	0.24	0.42	0	1	87142	0.16	0.37	0	1
Export dummy	1909	0.48	0.49	0	1	87142	0.38	0.49	0	1

Table1. Descriptive statistics

Notes: Outsourcing activities are investigated for the period from 2009 to 2018.

4 Empirical Results

4.1 Basic result

Table 2 shows the estimation results of equation (1). Columns (1) and (2) present the results for R&D and outsourcing, respectively. In column (1), the coefficient of the interaction term $ETS_i \times Post1114_t$ is 0.214 and statistically significant at the 5% level, which indicates that targeted firms increased R&D investment by 21% compared with untargeted firms during the first compliance period of the Saitama ETS. The result supports Hypothesis 1.1 that the ETS promotes innovation. However, the coefficient of the interaction term $ETS_i \times Post1518_t$ is not significant, implying that targeted firms did not engage in R&D during the second compliance period as in the first compliance period, which is consistent with Xie et al. (2017) that firms may be reluctant to further increase their compliance costs to invest in new technologies once excess mitigation is achieved. In fact, an official report by Saitama prefecture[6] provides evidence to confirm our results that the reduction in total emissions from the first to the second compliance periods increased by only 7%. It means that the Saitama ETS did not motivate firms to further reduce CO2 emissions, which is consistent with our result indicating an insignificant impact on innovation during the second compliance period. Another possible explanation is that the Saitama ETS offered a reserve policy that allows firms to reserve allowances from the first to second compliance period. Even though only 4% of targeted firms used the reserving allowances to meet their targets, this mechanism will probably crowd out any improvement in innovation during the upcoming compliance periods.

In column (2), the coefficients of interaction terms $ETS_i \times Post1114_t$ and $ETS_i \times Post1518_t$ show positive signs while they are not statistically significant.

[6] See https://www.pref.saitama.lg.jp/a0502/sakugen.html

Therefore, the result does not statistically support Hypothesis 2 indicating that targeted firms increased their outsourcing after ETS implementation. The insignificant impact of the Saitama ETS on outsourcing can be explained by targeted firms that are willing to achieve emissions mitigation from a long-term perspective. Even though outsourcing can be a short-term solution to achieve the reduction targets, it is not cost efficient in the long-term. At the same time, in the context of stringent reduction targets in the upcoming compliance period, improving R&D in the early stage of the ETS is a reasonable strategy to comply with future targets instead of increasing outsourcing activities. Therefore, targeted firms may not have adequate reason to outsource their production process as a temporary measure to meet the reduction targets.[7]

	DiD	
	(1)	(2)
Outcome variables	Ln(R&D)	Ln(Outsourcing)
Period	2003-2018	2009-2018
ETS × $Post_{1114}$	0.214**	0.275
	(0.0972)	(0.180)
ETS × $Psot_{1518}$	0.168	0.189
	(0.144)	(0.290)
Employment	0.685***	0.518***
	(0.0612)	(0.135)
Capital labor ratio	0.310***	0.347***
	(0.0429)	(0.0969)
Age	0.0207	0.129
	(0.0654)	(0.131)
Liability to asset ratio	-0.0944**	0.0199
	(0.0371)	(0.0702)
Stock option dummy	0.0288	-0.0616
	(0.0492)	(0.0960)

[7] We also provide our analysis based on a firm's sales instead of employment as the proxy for scale of firm in Appendix B Table B2. It shows results similar to the baseline results.

Export dummy	0.155***	0.282***
	(0.0322)	(0.0740)
Year-fixed effect	Yes	Yes
Firm-fixed effect	Yes	Yes
Observations	89,051	55,571
R-squared	0.017	0.020

Table 2. DiD results

Notes: Robust standard errors are reported in parentheses. *p < 0.1; **p < 0.05; ***p < 0.01. All continuous variables are transformed into logarithm functions, except for dummy variables. Value 1 is added to the value of outcome variables before the log transformation.

4.2 Robustness tests

To ensure the implication of our result, we conducted several robustness checks. We adopted (1) a matched DiD model based on the propensity score, (2) parallel trend tests, (3) stability of unit treatment values assumption (SUTVA), and (4) placebo tests to examine the robustness of the basic results.

4.2.1 Parallel trend test

An important precondition of the DiD method to estimate an unbiased treatment effect is that in the absence of a policy intervention, outcomes in the treatment group would have the same trend as outcomes in the control group. However, as outcomes in the treatment group are not observable without intervention, researchers tested the assumption by examining trends in the pre-treatment period (Sant'Anna & Zhao, 2020; Cabrera et al., 2021; Ma et al., 2021; Deng et al., 2022; Zhou & Qi, 2022). We tested the parallel trends assumption by estimating the following model:

$$Y_{it} = \sum_{t \in pre-period} \beta_t ETS_i \times D_t + X_{it}B + \mu_t + \gamma_i + \varepsilon_{it} \quad (2),$$

D_t represents the dummy variable indicating year t. We considered 2010 as the base year, which is one year prior to the implementation of the ETS for R&D. The definition of outsourcing activities changed since 2009 in the survey data so that parallel trends during all study periods cannot be investigated. However, the assumption of parallel trend can be checked based on whether pre-compliance periods induce variability between the treatment and control groups (Ren et al., 2022). Therefore, this study plots the parallel trend from 2003 to 2009 for outsourcing. Figures 1 and 2 show the estimates of β_t with 95% confidence intervals for R&D and outsourcing, respectively. The figures suggest parallel trends of the outcomes between both treatment and control groups during the pre-implementation period.

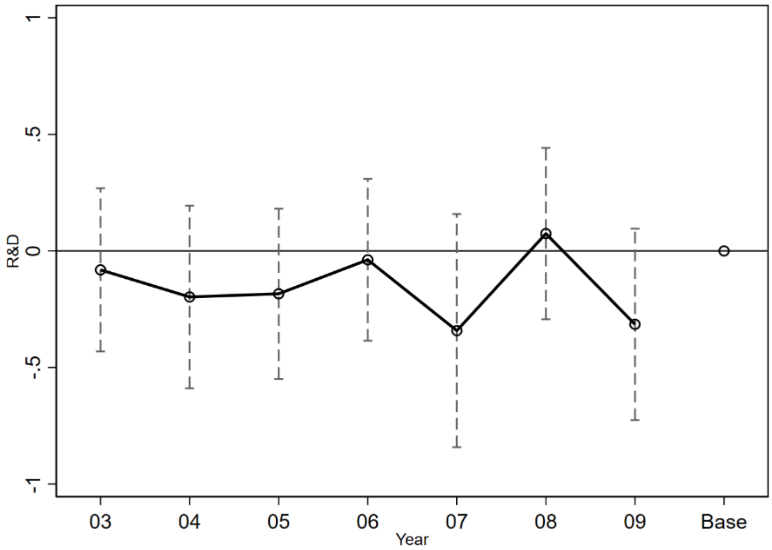

Fig.1 Parallel trend of impact on R&D

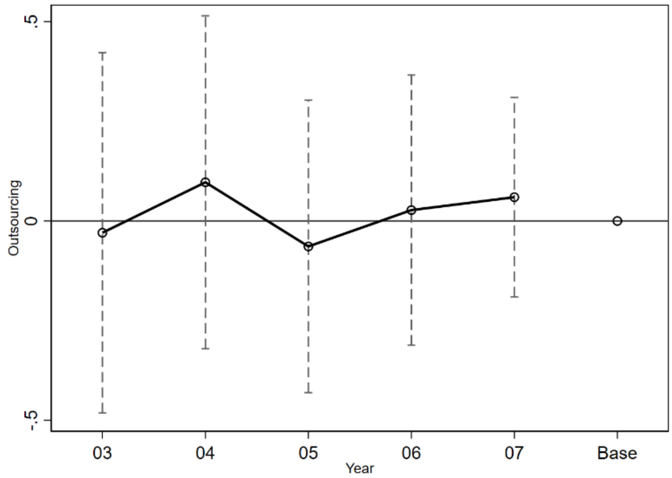

Fig.2 Parallel trend of impact on outsourcing

4.2.2 Matched DiD model

To validate the robustness of the baseline results, we adopted the matched DiD model based on the propensity score (PSM-DiD). Propensity matching is an optimal strategy to ensure that the regulatory status of the ETS is a randomly assigned conditional on firm characteristics (Zhu et al., 2019; Lu et al., 2023). It leverages our large sample size with significant differences in characteristics across firms. We first matched targeted firms with non-targeted firms one-to-one by the nearest neighbor matching estimator (Abadie et al., 2004). Based on the existing literature, Pairs of firms were matched by firm observable characteristics such as scale, capital–labor ratio, age, financing constraints, and trade (Aghion et al., 2013; Bernard & Okubo, 2016; Calel & Dechezleprêtre, 2016; Löschel et al., 2019). All matching variables were matched one year prior to the implementation of Saitama's ETS. Our sample size is reduced based on the strict conditions to restrict the matching process to match close firms. However, the accuracy and robustness of our results satisfy the loss in sample size (Dehejia & Wahba, 1999). Second, we used matched firm pairs to estimate the casual effect by the DiD method. The results of the PSM-DiD suggest the same implication as the main results despite larger standard errors with a smaller sample size (Table 3).

	PSM-DiD	
	(1)	(2)
Outcome variables	ln(R&D)	ln(Outsourcing)
Period	2003-2018	2009-2018
ETS × $Post_{1114}$	0.272*	0.400
	(0.158)	(0.289)
ETS × $Psot_{1518}$	0.108	0.485
	(0.180)	(0.412)
Controls	Yes	Yes
Year-fixed effect	Yes	Yes
Firm-fixed effect	Yes	Yes
Observations	3,657	2,297
R-squared	0.025	0.023

Table 3. PSM–DiD results

Notes: Robust standard errors are reported in parentheses. *p < 0.1; **p < 0.05; ***p < 0.01.

4.2.3 Stability of unit treatment values assumption (SUTVA)

The DiD method relies on the stability of unit treatment values assumption (SUTVA), assuming that non-targeted firms are not affected by targeted firms (Fowlie et al., 2012; Löschel et al., 2019; Themann & Koch, 2021). In our study, a probable situation where

SUTVA violations can occur is that R&D progress among targeted firms in Saitama prefecture generates spillover effects on surrounding firms, thus increasing R&D among untargeted firms in the same prefecture. For instance, it happens when they compete with targeted firms, thereby leading to untargeted firms increasing their R&D. In this case, the DiD approach underestimates the impact of ETS on R&D. In practice, however, the SUTVA cannot be proven empirically. Our strategy is to test if the SUTVA is violated in a specific case. We excluded targeted firms from the samples and ran a regression model in which untargeted firms in Saitama prefecture are now considered as a treatment group, and firms outside Saitama prefecture constitute the control group. Violations appear when DiD terms are statistically significant, indicating that the ETS affects untargeted firms in Saitama prefecture. Table 4, column (1) shows the results, indicating that the DiD terms are not significant. We concluded, therefore, that non-targeted firms in Saitama are not influenced by the regional ETS to adjust their innovation strategy.

	(1)
Outcome variables	ln(R&D)
ETS' × $Post_{1114}$	-0.0734
	(0.0789)
ETS' × $Psot_{1518}$	-0.127
	(0.104)
Control variables	Yes
Year-fixed effect	Yes
Firm-fixed effect	Yes
Observations	86,600
R-squared	0.017

Table 4. SUTVA results

Notes: Robust standard errors are reported in parentheses. *p < 0.1; **p < 0.05; ***p < 0.01.

4.2.4 Placebo test

A placebo test is conducted to further check the validity of the robustness test. Basically, the placebo test follows Ferrara et al. (2012) and Cai et al. (2016) by randomly choosing firms from our sample as the counterfactual treatment group.[8] The omitted variable or

[8] This study did not find evidence on the spillover effect of the Saitama ETS (Table 4). Therefore,

other unobserved factors that may influence the treatment effect of the treated can be validated by the placebo test. As counterfactual treatment firms are randomly selected, the counterfactual treatment effect should be statistically insignificant on R&D if the impact of the omitted variable or other unobserved factors is not present. In other words, if the counterfactual firm group significantly affects R&D, the placebo effect exists, and the result is deemed unreliable. In this study, we randomly selected 143 firms, which is equal to the number of firms that targeted by Saitama ETS in reality in the sample, as the counterfactual firm group to estimate the treatment effect (Qi et al., 2021; Liu et al., 2022; Wu & Wang, 2022; Yu & Zhang, 2022). Following Lu et al. (2017), we generated counterfactual data 500 times to obtain the distribution of the counterfactual DiD estimators. Figure 3 plots the density distribution of 500 coefficients highlighting the real DiD estimator (dash line) and counterfactual DiD estimator (solid line). We find that the density distribution concentrates to 0 with a mean value of -0.003 and standard deviation of 0.0846, and the real DiD estimator is larger than the counterfactual DiD estimator. We concluded that the real DiD estimator is significantly different from the counterfactual estimator, indicating that the placebo effect does not exist.

untargeted firms from Saitama prefecture can also be chosen as the counterfactual treatment firms.

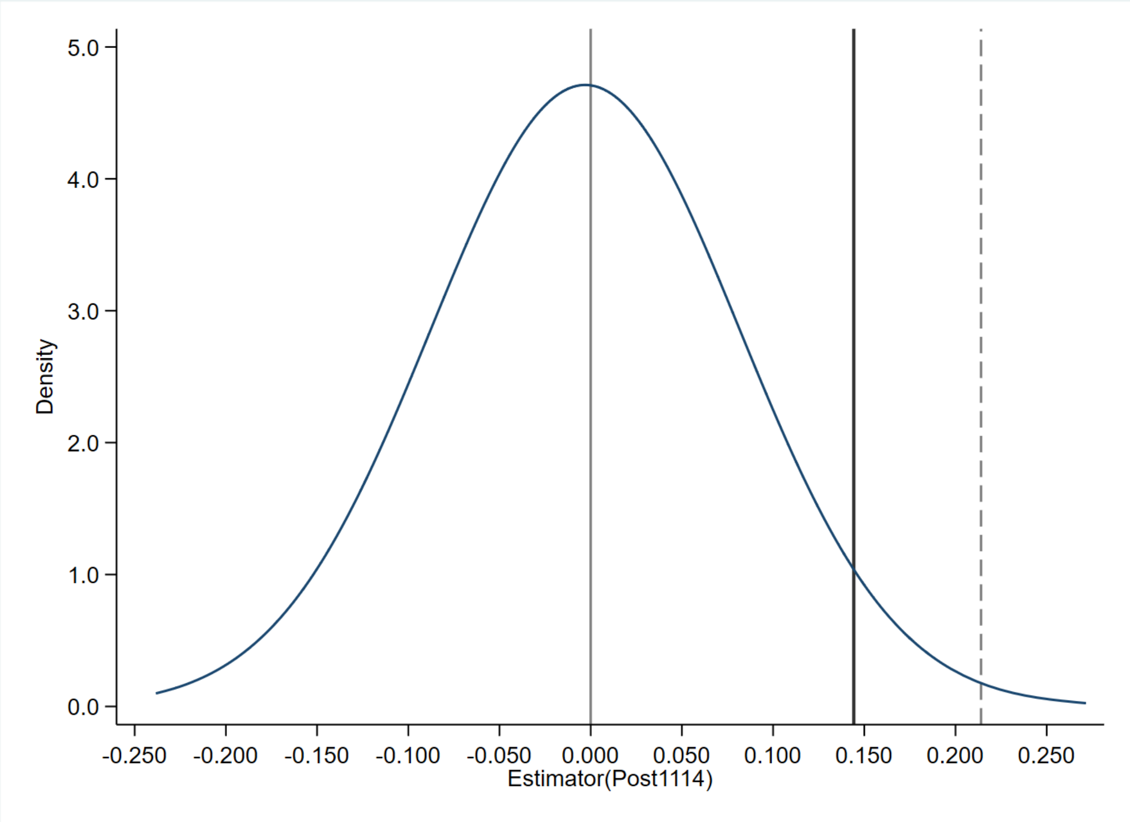

Fig.3 Placebo test

4.3 Heterogeneity analysis

4.3.1 Heterogeneous effects on innovation (Hypothesis 1.2)

Innovation experience is a key element of subsequent innovation (Mansfield, 1968; Kelly & Amburgey, 1991; Peters, 2009). We hypothesize that firms that had conducted R&D before complying with the ETS had the advantage of accelerating R&D after the ETS was implemented compared to firms that had never conducted R&D (Hypothesis 1.2). To test this hypothesis, we ran two regressions. First, we restricted samples to firms that had never conducted R&D during the pre-implementation period, that is, firms with zero R&D experience from 2003 to 2009 (hereafter firms without R&D experience) and estimated the pooled ordinary least squares (OLS) model without the intercept and control variables during the period from 2011 to 2018 as follows:

$$Y'_{it} = \beta_1^1 ETS_i \times Post1114_t + \beta_2^1 ETS_i \times Post1518_t + \beta_3 Post1114_t + \beta_4 Post1518_t + \varepsilon_{it} \quad (3),$$

In equation (3), the outcome variable (Y') is a dummy taking the value 1 if firm i has innovation activities. ETS_i is a dummy variable taking value 1 if firm i is targeted by ETS, and $Post1114_t$ and $Post1518_t$ are dummy variables for both compliance periods. Through equation (3), if coefficients β_1^1 and β_2^1 are statistically insignificant, we can confirm that firms without R&D did not have innovation experience during both compliance periods.

Second, another heterogeneity analysis is adopted to investigate how the Saitama ETS affected firms with innovation experience during subsequent innovation. We restricted samples to firms that had conducted R&D during the pre-implementation period, that is, firms whose R&D is positive at least one year between 2003 and 2009 (hereafter firms with R&D experience), and estimated the equation based on equation (1) as follows:

$$Y_{it} = \beta_1^2 ETS_i \times Post1114_t + \beta_2^2 ETS_i \times Post1518_t + \boldsymbol{X}_{it} B^2 + \mu_t + \gamma_i + \varepsilon_{it} \qquad (4).$$

In equation (4), the outcome variable is R&D, and ETS, $Post1114_t$, $Post1518$, and $\boldsymbol{X}_{it}$ follow equation (1). If R&D had improved during the compliance period, we can confirm Hypothesis 1.2. In Table 5, columns (1) and (2) show the results of equations (3) and (4), respectively. We find that the coefficients ETS × Year_{1114} and ETS × Year_{1518} are insignificant, indicating that firms without R&D activities before the ETS was implemented did not increase their innovation activities during the compliance periods in column (1). Column (2) shows that the interaction term $ETS_i \times Post1114_t$ on R&D is statistically significant. It highlights that targeted firms with innovation experience promote subsequent innovations during the compliance period of the Saitama ETS because they have gained more experience to accelerate development and maintain the innovation status after the implementation of the Saitama ETS, which is consistent with Hypothesis 1.2. Combined with column (1) in Table 5, it can be concluded that increases in R&D are contributed by firms with experience in R&D activities during the pre-implementation period.

	(1)	(2)	(3)	(4)
	Firms without R&D	Firms with R&D	Heterogeneity in outsourcing	
Outcome variable	R&D Dummy	ln(R&D)	ln(Outsourcing)	
Period	2011~2018	2003~2018	2009-2018	

			~50%	50%~
ETS × $Post_{1114}$	-0.0245	0.288**	0.515*	-0.009
	(0.0166)	(0.117)	(0.290)	(0.268)
ETS × $Psot_{1518}$	0.0118	0.251	0.528	-0.095
	(0.0308)	(0.174)	(0.495)	(0.425)
Control variables	No	Yes	Yes	Yes
Year-fixed effect	No	Yes	Yes	Yes
Firm-fixed effect	No	Yes	Yes	Yes
Observations	15,497	58,123	18,102	18,222
R-squared	0.099	0.023	0.020	0.028

Table 5. Results of heterogeneity analysis

Notes: Robust standard errors are reported in parentheses. *p < 0.1; **p < 0.05; ***p < 0.01.

4.3.2 Heterogeneity in outsourcing (Hypothesis 3)

Although our results did not show the significant impact of the Saitama ETS on outsourcing activities, firms that did not innovate actively may tend to increase their outsourcing activities to meet the reduction targets owing to the incentive on increased outsourcing by these firms (Hypothesis 3). To test this hypothesis, we offer two types of heterogeneity analysis based on the median value of the R&D growth rate. Specifically, we focused on the impact of the ETS on outsourcing in two different samples that distinguish firms with lower and higher median values of R&D growth rate. We calculated the R&D growth rate for the treatment and control groups while considering other effects based on equation (1). If the outcomes are significant in the two types of heterogeneity analysis, we can confirm that Hypothesis 3 is correct. Table 4 shows the results of the heterogeneity analysis in columns (3) and (4). Column (3) indicates that firms with a lower R&D growth rate increased their outsourcing activities during the Saitama ETS compliance period compared with non-targeted firms. However, column (4) indicates that firms with higher R&D growth rates did not increase their outsourcing after the Saitama ETS was implemented. Combined with these results, we can conclude that targeted firms with a lower R&D growth rate tend to increase their outsourcing activities, consistent with Hypothesis 3.

5. Conclusions and policy implications

This study examines if firms targeted by the Saitama ETS improved their R&D and outsourcing activities. Unique firm-level data were used based on DiD methods from 2003 to 2018. Robustness tests are conducted to confirm the robustness of our results such as parallel trend tests, PSM, SUTVA, and placebo tests. Moreover, heterogeneity analysis examines the relationship between innovation and outsourcing under the Saitama ETS. This study highlights two key findings.

First, our analysis suggests that the Saitama ETS encourages targeted firms to improve their R&D efforts during the early phase of ETS. Specifically, to meet the reduction targets, after implementing the ETS, targeted firms made significant efforts to increase their R&D investment during the first compliance period to improve their energy efficiency performance in production processes. In particular, firms with prior innovation experience contributed toward improvement in R&D activities during the first compliance period than firms that did not have experience with R&D activities. This implies that firms with R&D activities accelerated development and maintained their innovation status following the introduction of the Saitama ETS. However, although reduction targets during the second compliance period became more stringent, targeted firms were reluctant to continuously improve innovation from the first to the second compliance periods. We conclude that firms tend to concentrate their R&D investments in the initial phase to achieve long-term carbon mitigation by enhancing energy efficiency. These results remain valid after several robustness tests.

Second, we find that targeted firms do not outsource their production process while complying with the Saitama ETS. Apparently, the ETS did not stimulate outsourcing-induced carbon leakage. However, our heterogeneity analysis shows that targeted firms with lower R&D growth rates increased their outsourcing activities during the compliance period. To comply with the ETS, targeted firms can employ multiple strategies, including reducing CO2 emissions through their own efforts, improve their energy efficiency performance through R&D and by outsourcing production processes. Based on our results, we conclude that firms that cannot actively improve their energy efficiency through R&D or allocate sufficient funds for R&D reduce CO2 emissions by outsourcing their production processes.

Based on these conclusions, we propose several policy recommendations. First, the increase in outsourcing activities of firms that not actively invest in R&D, induced by the Saitama ETS, must remain vigilant. Compared to firms that actively invest in R&D, these firms may have limited financial resources or are the small and medium enterprises. How to prevent such firms from outsourcing their production process to other untargeted firms is an important issue. Japan launched its Domestic Clean Development Mechanism to reduce CO2 emissions of both small and medium manufacturing enterprises. Under this program, large firms can provide financial support to these firms and receive credits. Local governments can also adopt similar schemes to reduce the risk of firms shifting their production activities due to insufficient R&D funds. Moreover, the local government can encourage firms to improve their innovation capacities by establishing inter-firm innovative centers or networks, and this will benefit firms that are unable or reluctant to innovate or invest in technological innovations. In the absence of penalties, the Saitama ETS improves firm-level innovation activities. If the government provides more support and strengthens regulations, the targeted firms will be able to improve their performance. However, with reduction targets becoming gradually stringent, some firms are likely to outsource their production process to eliminate environmental costs. This is especially true in the absence of additional subsidies for firms with carbon leakage risks and relatively small firms. Therefore, policies that can benefit firms with a significant risk of carbon leakage must be implemented, such as those under the EU ETS.

Even though this study explores the impact of the Saitama ETS, the findings should be interpreted with caution for the following reasons. First, the Saitama ETS targets at the facility level and not firm level. As this study does not evaluate facility activities, we could not fully capture the impact of the ETS, especially in outsourcing activities. Second, the survey only provides total R&D information for each firm. Thus, our results may overestimate or underestimate the influence of the ETS on efforts to improve technological innovations.

Appendix A. Summary of the literature

Table A1. Summary of the literature on ETS

Publication	Countries or regions (industry/sector)	ETS	Finding
Impact on innovation			
Rogge et al. (2011)	Germany (Power)	EU ETS	Limited impact of the EU ETS on power plants
Martin et al. (2013)	European countries (manufacturing)	EU ETS	Firms' innovation activities on process innovation than product innovation
Löfgren et al. (2014)	Sweden (manufacturing)	EU ETS	No impact on firms' investment decisions on mitigation technologies
Borghesi et al. (2015)	Italy (manufacturing)	EU ETS	EU ETS improved firms' innovation.
Calel and Dechezleprêtre (2016)	28 countries (sectors in three-digit level)	EU ETS	EU ETS increased low-carbon innovation at firm level.
Calel (2020)	UK (sectors in three-digit level)	EU ETS	EU ETS encouraged patents and R&D at firm level
Chen et al. (2020)	China (three industries)	China's pilot ETS	Limited effect of pilot ETS on innovation
Cui et al. (2021)	China (manufacturing and utility sector)	China's pilot ETS	Increases on low-carbon patenting of targeted firms by China's pilot ETS
Ren et al. (2020)	China (mining and manufacturing)	China's SO2 ETS	China's SO2 ETS increased firm-level patenting.
Hamamoto (2021)	Japan's Saitama prefecture (manufacturing)	Saitama ETS	Increases on low-carbon technologies at ETS facilities
Ren et al. (2022)	China (sectors in two-digit level)	China's ETS pilot	China's CO2 ETS increased firm-level technological innovation.
Impact on carbon leakage			
Sartor (2013)	EU-27 and non-EU countries (aluminum industry)	EU ETS	EU ETS had a limited impact on carbon leakage.
Martin et al. (2014)	EU firms (manufacturing)	EU ETS	Targeted firms considered downsizing businesses that may induce leakage.
Branger et al. (2016)	European countries	EU ETS	No evidence of carbon leakage induced by

	Cement and Steel)		EU ETS
Jaraite-Kažukauske and Di Maria (2016)	Lithuania (including 40 industries)	EU ETS	EU ETS caused potential carbon leakage from other countries to firms.
Fell and Maniloff (2018)	U.S. (electricity industry)	Regional Greenhouse Gas Initiative	While coal-fired generation was reduced in targeted regions, generation was increased in adjacent targeted regions.
Wang et al. (2018)	China's provinces (six and eight four-digit level)	China's pilot ETS	Carbon leakage is induced by pilot ETS.
Koch and Mama (2019)	Germany (industries with 4-digit code)	EU ETS	Limited potential for carbon leakage is induced by EU targeted firms.
Naegele and Zaklan (2019)	EU firms (manufacturing)	EU ETS	EU ETS did not cause carbon leakage in the EU manufacturing sector.
Sadayuki and Arimura (2021)	Japan Tokyo and Saitama prefecture (19 industrial classification)	Tokyo and Saitama ETS	Tokyo and Saitama ETSs induced carbon leakage at facility level.
Bartram et al. (2022)	California (NAICS industry code)	California's carbon cap-and-trade program	California's carbon cap-and-trade program induced carbon leakage at plant level.
Dechezleprêtre et al. (2022)	European countries (nine industries)	EU ETS	No evidence of carbon leakage is induced by the EU ETS to other countries.

Appendix B. DiD results

Table B1 Results with firms' sales

	DiD		PSM	
	(1)	(2)	(3)	(4)
Outcome variables	Ln(R&D)	Ln(Outsourcing)	Ln(R&D)	Ln(Outsourcing)
Period	2003-2018	2009-2018	2003-2018	2009-2018
ETS × $Post_{1114}$	0.217**	0.281	0.269*	0.403
	(0.0973)	(0.180)	(0.159)	(0.289)
ETS × $Psot_{1518}$	0.177	0.202	0.114	0.491
	(0.144)	(0.291)	(0.180)	(0.410)

Control variables	Yes	Yes	Yes	Yes
Sales	Yes	Yes	Yes	Yes
Employment	No	No	No	No
Year-fixed effect	Yes	Yes	Yes	Yes
Firm-fixed effect	Yes	Yes	Yes	Yes
Observations	89,051	55,571	3,657	2,297
R-squared	0.013	0.022	0.025	0.023

Notes: Robust standard errors are reported in parentheses. *p < 0.1; **p < 0.05; ***p < 0.01.

Table B2 Results with one period lead of ETS

	DiD		PSM	
	(1)	(2)	(3)	(4)
Outcome variables	Ln(R&D)	Ln(Outsourcing)	Ln(R&D)	Ln(Outsourcing)
Period	2003-2017	2009-2017	2003-2017	2009-2017
F.ETS × $Post_{1114}$	0.220**	0.282	0.282*	0.402
	(0.0979)	(0.181)	(0.159)	(0.290)
F.ETS × $Psot_{1518}$	0.185	0.181	0.149	0.562
	(0.144)	(0.286)	(0.181)	(0.412)
Control variables	Yes	Yes	Yes	Yes
Year-fixed effect	Yes	Yes	Yes	Yes
Firm-fixed effect	Yes	Yes	Yes	Yes
Observations	81,967	49,296	3,410	2,063
R-squared	0.016	0.019	0.023	0.023

Notes: Robust standard errors are reported in parentheses. *p < 0.1; **p < 0.05; ***p < 0.01.

References

Abadie, A., Drukker, D., Herr, J. L., Imbens, G. W., 2004. Implementing matching estimators for average treatment effects in Stata. Stata J. 4(3), 290–311. doi/pdf/10.1177/1536867X0400400307

Aghion, P., Van Reenen, J., Zingales, L., 2013. Innovation and institutional ownership. Am. Econ. Rev. 103(1), 277–304. DOI: 10.1257/aer.103.1.277

Antonietti, R., De Marchi, V., Di Maria, E., 2017. Governing offshoring in a stringent environmental policy setting: Evidence from Italian manufacturing firms. J. Clean. Prod. 155, 103–113. https://doi.org/10.1016/j.jclepro.2016.11.106

Athey, S., Imbens, G. W., 2022. Design-based analysis in difference-in-differences settings with staggered adoption. J. Econom. 226(1), 62–79. https://doi.org/10.1016/j.jeconom.2020.10.012

Bartram, S. M., Hou, K., Kim, S., 2022. Real effects of climate policy: Financial constraints and spillovers. J. Financ. Econ. 143(2), 668–696. https://doi.org/10.1016/j.jfineco.2021.06.015

Bel, G., Joseph, S., 2018. Policy stringency under the European Union Emission trading system and its impact on technological change in the energy sector. Energy Policy, 117, 434–444. https://doi.org/10.1016/j.enpol.2018.03.041

Bernard, A. B., Okubo, T., 2016. Product switching and the business cycle. **DOI** 10.3386/w22649

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. https://doi.org/10.1016/j.respol.2014.10.014

Branger, F., Quirion, P., Chevallier, J., 2016. Carbon leakage and competitiveness of cement and steel industries under the EU ETS: Much ado about nothing. Energy J. 37(3). DOI**:** 10.5547/01956574.37.3.fbra

Cabrera, J. M., Caffera, M., Cid, A., 2021. Modest and incomplete incentives may work: Pricing plastic bags in Uruguay. J. Environ. Econ. Manage. 110, 102525. https://doi.org/10.1016/j.jeem.2021.102525

Cai, X., Lu, Y., Wu, M., Yu, L., 2016. Does environmental regulation drive away inbound foreign direct investment? Evidence from a quasi-natural experiment in China. J. Dev. Econ. 123, 73–85. https://doi.org/10.1016/j.jdeveco.2016.08.003

Calel, R., 2020. Adopt or innovate: Understanding technological responses to cap-and-trade. Am. Econ. J.: Econ. Policy, 12(3), 170–201. DOI: 10.1257/pol.20180135

Capasso, M., Cusmano, L., Morrison, A., 2013. The determinants of outsourcing and offshoring strategies in industrial districts: Evidence from Italy. Reg. Stud. 47(4),

465–479. https://doi.org/10.1080/00343404.2011.571668
Castillejo, J. A. M., Barrachina, M. E. R., Llopis, A. S., Llopis, J. A. S., 2004. A Dynamic Approach to the Decision to Invest in R&D: The role of sunk costs. Universidad Valencia.
Chen, S., Shi, A., Wang, X., 2020. Carbon emission curbing effects and influencing mechanisms of China's Emission Trading Scheme: The mediating roles of technique effect, composition effect and allocation effect. J. Clean. Prod. 264, 121700. https://doi.org/10.1016/j.jclepro.2020.121700
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. https://doi.org/10.1016/j.eneco.2021.105136
CO., 2013. Annual Economic and Financial Report of 2013 (Cabinet Office).
Cui, J., Zhang, J., Zheng, Y., 2021. The Impacts of Carbon Pricing on Firm Competitiveness: Evidence from the Regional Carbon Market Pilots in China. Available at SSRN 3801316.
Dechezleprêtre, A., Gennaioli, C., Martin, R., Muûls, M., Stoerk, T., 2022. Searching for carbon leaks in multinational companies. J. Environ. Econ. Manag. 112, 102601. https://doi.org/10.1016/j.jeem.2021.102601
Dehejia, R. H., Wahba, S., 1999. Causal effects in nonexperimental studies: Reevaluating the evaluation of training programs. J. Am. Stat. Assoc. 94(448), 1053–1062. DOI: 10.1080/01621459.1999.10473858
Deng, N., Wang, B., Qiu, Y., Liu, J., Shi, H., Zhang, B., Wang, Z., 2022. The discrepancies in the impacts of COVID-19 lockdowns on electricity consumption in China: Is the short-term pain worth it? Energy Econ. 106318. https://doi.org/10.1016/j.eneco.2022.106318
Fell, H., Maniloff, P., 2018. Leakage in regional environmental policy: The case of the regional greenhouse gas initiative. J. Environ. Econ. Manage. 87, 1–23. https://doi.org/10.1016/j.jeem.2017.10.007
Ferrara, E. L., Chong, A., Duryea, S., 2012. Soap operas and fertility: Evidence from Brazil. Am. Econ. J.: Appl. Econ. 4(4), 1–31.
Fowlie, M., Holland, S. P., Mansur, E. T., 2012. What do emissions markets deliver and to whom? Evidence from Southern California's NOx trading program. Am. Econ. Rev. 102(2), 965–993. DOI: 10.1257/aer.102.2.965
Gao, Y., Li, M., Xue, J., Liu, Y., 2020. Evaluation of effectiveness of China's carbon emissions trading scheme in carbon mitigation. Energy Econ. 90, 104872. https://doi.org/10.1016/j.eneco.2020.104872

Hamamoto, M., 2021. Impact of the Saitama Prefecture target-setting emissions trading program on the adoption of low-carbon technology. Environ. Econ. Policy Stud. 23(3), 501–515. https://doi.org/10.1007/s10018-020-00270-x

Hoffmann, V. H., 2007. Eu ets and investment decisions:: The case of the German electricity industry. Eur. Manag. J. 25(6), 464–474. https://doi.org/10.1016/j.emj.2007.07.008

Holl, A., Peters, B., Rammer, C., 2022. Local knowledge spillovers and innovation persistence of firms. Econ. Innov. New Technol. 1–25. https://doi.org/10.1080/10438599.2022.2036609

Imbens, G. W., Wooldridge, J. M., 2009. Recent developments in the econometrics of program evaluation. J. Econ. Lit. 47(1), 5–86. DOI: 10.1257/jel.47.1.5

Jaraite-Kažukauske, J., Di Maria, C., 2016. Did the EU ETS make a difference? An empirical assessment using Lithuanian firm-level data. Energy J. 37(1). DOI: 10.5547/01956574.37.2.jjar

Kelly, D., Amburgey, T. L., 1991. Organizational inertia and momentum: A dynamic model of strategic change. Acad. Manage. J. 34(3), 591–612. https://doi.org/10.5465/256407

Koch, N., Mama, H. B., 2019. Does the EU Emissions Trading System induce investment leakage? Evidence from German multinational firms. Energy Econ. 81, 479–492. https://doi.org/10.1016/j.eneco.2019.04.018

Lanoie, P., Patry, M., Lajeunesse, R., 2008. Environmental regulation and productivity: testing the porter hypothesis. J. Product. Anal. 30(2), 121–128. https://doi.org/10.1007/s11123-008-0108-4

Liu, D., Ren, S., Li, W., 2022. SO2 emissions trading and firm exports in China. Energy Econ. 109, 105978. https://doi.org/10.1016/j.eneco.2022.105978

Löfgren, Å., Wråke, M., Hagberg, T., Roth, S., 2014. Why the EU ETS needs reforming: an empirical analysis of the impact on company investments. Clim. Policy, 14(5), 537–558. DOI: 10.1080/14693062.2014.864800

Löschel, A., Lutz, B. J., Managi, S., 2019. The impact of the EU ETS on efficiency and economic performance–an empirical analyses for German manufacturing firms. Resour. Energy Econ. 56, 71–95. https://doi.org/10.1016/j.reseneeco.2018.03.001

Lu, G., Tanaka, K., Toshi, H. A., 2023. The Impacts of the Tokyo and Saitama ETSs on the Energy Efficiency Performance of Manufacturing Facilities, Research Institute of Economy, Trade and Industry (RIETI).

Lu, Y., Tao, Z., Zhu, L., 2017. Identifying FDI spillovers. J. Int. Econ. 107, 75–90. https://doi.org/10.1016/j.jinteco.2017.01.006

Ma, H., Ning, J., Xu, M. J., 2021. An eye for an eye? The trade and price effects of China's retaliatory tariffs on US exports. China Econ. Rev. 69, 101685. https://doi.org/10.1016/j.chieco.2021.101685

Mansfield, E. (1968). Industrial research and technological innovation; an econometric analysis.

Martin, R., Muûls, M., De Preux, L. B., Wagner, U. J., 2014. On the empirical content of carbon leakage criteria in the EU Emissions Trading Scheme. Ecol. Econ. 105, 78–88. https://doi.org/10.1016/j.ecolecon.2014.05.010

Martin, R., Muûls, M., Wagner, U., 2013. Carbon markets, carbon prices and innovation: Evidence from interviews with managers. In: Annual Meetings of the American Economic Association, San Diego.

Martin, R., Muûls, M., Wagner, U. J., 2016. The impact of the European Union Emissions Trading Scheme on regulated firms: what is the evidence after ten years? Rev. Environ. Econ. Policy.

Miyamoto, M., Takeuchi, K., 2019. Climate agreement and technology diffusion: Impact of the Kyoto Protocol on international patent applications for renewable energy technologies. Energy Policy, 129, 1331–1338. https://doi.org/10.1016/j.enpol.2019.02.053

Naegele, H., Zaklan, A., 2019. Does the EU ETS cause carbon leakage in European manufacturing? J. Environ. Econ. Manage. 93, 125–147. https://doi.org/10.1016/j.jeem.2018.11.004

The Organisation for Economic Co-operation and Development (OECD), 2018. Guidelines for collecting, reporting and using data on innovation. The measurement of Scientific, Technological and Innovation Activities. 4th Edition. 255p.[Consultado 29 agosto 2020] Disponible en: https://doi.org/10.1787/9789264304604-en.

Oestreich, A. M., Tsiakas, I., 2015. Carbon emissions and stock returns: Evidence from the EU Emissions Trading Scheme. J. Bank. Financ. 58, 294–308.

Peters, B., 2009. Persistence of innovation: stylised facts and panel data evidence. J. Technol. Transf. 34(2), 226–243. https://doi.org/10.1007/s10961-007-9072-9

Qi, S., Cheng, S., Cui, J., 2021. Environmental and economic effects of China's carbon market pilots: Empirical evidence based on a DID model. J. Clean. Prod. 279, 123720. https://doi.org/10.1016/j.jclepro.2020.123720

Ren, S., Hu, Y., Zheng, J., Wang, Y., 2020. Emissions trading and firm innovation: Evidence from a natural experiment in China. Technol. Forecast. Soc. Change, 155, 119989. https://doi.org/10.1016/j.techfore.2020.119989

Ren, S., Yang, X., Hu, Y., Chevallier, J., 2022. Emission trading, induced innovation and firm performance. Energy Econ. 106157. https://doi.org/10.1016/j.eneco.2022.106157

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. https://doi.org/10.1016/j.ecolecon.2010.09.032

Sadayuki, T., Arimura, T. H., 2021. Do regional emission trading schemes lead to carbon leakage within firms? Evidence from Japan. Energy Econ. 104, 105664. https://doi.org/10.1016/j.eneco.2021.105664

Sant'Anna, P. H., Zhao, J., 2020. Doubly robust difference-in-differences estimators. J. Econom. 219(1), 101–122. https://doi.org/10.1016/j.jeconom.2020.06.003

Sartor, O., 2013. Carbon leakage in the primary aluminium sector: What evidence after 6.5 years of the EU ETS? Available at SSRN: https://ssrn.com/abstract=2205516 or http://dx.doi.org/10.2139/ssrn.2205516

Schmidt, T. S., Schneider, M., Rogge, K. S., Schuetz, M. J., Hoffmann, V. H., 2012. The effects of climate policy on the rate and direction of innovation: A survey of the EU ETS and the electricity sector. Environ. Innov. Soc. Transit. 2, 23–48. https://doi.org/10.1016/j.eist.2011.12.002

Stock, G. N., Greis, N. P., Fischer, W. A., 2002. Firm size and dynamic technological innovation. Technovation, 22(9), 537–549. https://doi.org/10.1016/S0166-4972(01)00061-X

Sun, L., Abraham, S., 2021. Estimating dynamic treatment effects in event studies with heterogeneous treatment effects. J. Econom. 225(2), 175–199. https://doi.org/10.1016/j.jeconom.2020.09.006

Tang, H.-l., Liu, J.-m., Mao, J., Wu, J.-g., 2020. The effects of emission trading system on corporate innovation and productivity-empirical evidence from China's SO2 emission trading system. Environ. Sci. Pollut. Res. 27(17), 21604–21620. https://doi.org/10.1007/s11356-020-08566-x

Testa, F., Iraldo, F., Frey, M., 2011. The effect of environmental regulation on firms' competitive performance: The case of the building & construction sector in some EU regions. J. Environ. Manage. 92(9), 2136–2144. https://doi.org/10.1016/j.jenvman.2011.03.039

Themann, M., Koch, N., 2021. Catching up and falling behind: Cross-country evidence

on the impact of the EU ETS on firm productivity. USAEE Research Paper Series (21–492).
Wang, X., Teng, F., Wang, G., Zhou, S., Cai, B., 2018. Carbon leakage scrutiny in ETS and non-ETS industrial sectors in China. Resour. Conserv. Recycl. 129, 424–431. https://doi.org/10.1016/j.resconrec.2016.09.017
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. https://doi.org/10.1016/j.eneco.2022.105990
Xiao, J., Li, G., Zhu, B., Xie, L., Hu, Y., Huang, J., 2021. Evaluating the impact of carbon emissions trading scheme on Chinese firms' total factor productivity. J. Clean. Prod. 306, 127104. https://doi.org/10.1016/j.jclepro.2021.127104

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. https://doi.org/10.1016/j.ecolecon.2016.10.019
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. https://doi.org/10.1016/j.eneco.2017.10.009
Yu, P., Hao, R., Cai, Z., Sun, Y., Zhang, X., 2022. Does emission trading system achieve the win-win of carbon emission reduction and financial performance improvement?—Evidence from Chinese A-share listed firms in industrial sector. J. Clean. Prod. 333, 130121. https://doi.org/10.1016/j.jclepro.2021.130121
Yu, Y., Zhang, N., 2022. Does industrial transfer policy mitigate carbon emissions? Evidence from a quasi-natural experiment in China. J. Environ. Manage. 307, 114526. https://doi.org/10.1016/j.jenvman.2022.114526
Zhang, W., Li, J., Li, G., Guo, S., 2020. Emission reduction effect and carbon market efficiency of carbon emissions trading policy in China. Energy, 196, 117117. https://doi.org/10.1016/j.energy.2020.117117
Zhou, C., Qi, S., 2022. Has the pilot carbon trading policy improved China's green total factor energy efficiency? Energy Econ. 114, 106268. https://doi.org/10.1016/j.eneco.2022.106268
Zhu, J., Fan, Y., Deng, X., Xue, L., 2019. Low-carbon innovation induced by emissions trading in China. Nat. Commun. 10(1), 1–8. https://doi.org/10.1038/s41467-019-12213-6