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Abstract

This study aims to examine the effect of the EU emissions trading system (EU-ETS) on corporations' research and development (R&D) expenditure. The effect of the EU-ETS is estimated by combining the propensity score matching method with the difference-in-differences approach. We found that the EU-ETS had a strong positive effect on corporations' R&D expenditure in the second and third phases, but only a limited effect during the first phase. Our estimation results are consistent with the Porter hypothesis that stricter environmental regulation promotes innovation.

Keywords: EU-ETS, R&D, Innovation, Porter hypothesis, Propensity Score Matching, Difference in Differences

1. Introduction

Climate change caused by greenhouse gas emissions is one of the most serious problems in the world. Recent anthropogenic emissions of greenhouse gases (GHG) are the highest in history (IPCC Fifth Assessment Report, 2014). Although corporations have been trying to reduce emissions in various ways, they face certain challenges because of concerns about economic profits.

Technological innovation is expected to be an important contributor to the reduction of greenhouse gas emissions. In particular, internal technological innovation allows corporations to reduce emissions while ensuring a certain amount of expected profits. Therefore, corporations are trying to tackle this problem by encouraging internal innovation and enhancing innovative capability. At the same time, corporations' decisions are related to the governmental policies in place. A question then arises: How do environmental policies affect a corporation's internal decisions to innovate and which policies can lead to innovation?

According to the Porter hypothesis, strict environmental regulations can induce efficiency and encourage innovation that helps enhance commercial competitiveness (Porter and van der Linde, 1995). A large body of literature has examined the relationship between environmental regulations and innovation. However, few studies have empirically examined the effect of the EU emissions trading system (EU-ETS) on innovation. This study examines the effect of the EU-ETS, a policy that uses market mechanisms for mitigating climate change, on the research and development (R&D) expenditure of EU corporations.

In this study, we use propensity score matching and a difference-in-differences (PSM-DID) model to examine the effect of the EU-ETS on EU corporations' R&D expenditure. The propensity score matching method is used to control for the size of corporations, and the difference-in-differences model is used to estimate the effect of a policy that was implemented in 2005. Variables representing corporation characteristics and potential factors that affect R&D expenditure are also included in the model.

2. Literature review

The relation between environmental policy and technological change has received increasing attention in recent years (Jaffe et al., 2003). Scholars have expressed two views on environmental regulation and corporate management. One view is that environmental regulation can lead to an increase in corporate costs, which in turn reduces its competitiveness.

Rothwell (1992) pointed out that government regulations frequently had, quite unnecessarily, a large negative impact on regulated firms during the earlier period of intense regulatory activity. An alternative view holds that environmental regulation can stimulate corporate innovation and enhance competitiveness. The Porter hypothesis is based on this view. Porter (1991) argued that strict environmental regulation will not affect the competitive advantage of firms over rivals, but it will stimulate innovation to produce less-polluting or more resource-efficient products that will be highly valued internationally. Thereafter, it has been repeatedly suggested that strict environmental regulations can actually enhance competitiveness by stimulating innovation.

Meanwhile, other studies have also confirmed the Porter hypothesis. Hamamoto (2006) studied the effect of the stringency of environmental regulations on innovative activity and the productivity enhancement effect of environmental regulations in Japanese manufacturing industries. This paper concludes that stricter environmental regulations may encourage researchers to develop new technologies that contribute to both environmental benefits and productivity enhancement. This suggests that environmental regulation can substantively influence the direction of innovation.

Many studies have examined the effect of the EU-ETS on various economic outcomes, with particular focus on the effect of the EU-ETS on innovation. Relevant studies can be divided into those on the first phase of the EU-ETS, those on the second phase, and those that cut across the first and second phases.

With regard to several studies targeting the first phase, three main research approaches are adopted: empirical prediction, mail survey and interview, and econometric analysis. Early studies on the effect of the EU-ETS on innovation take the approach of analyzing empirical cases from other regions as well as specific details of policies. Gagelmann and Frondel (2005) and Schleich and Betz (2005) examined the effect of the first phase of the EU-ETS on innovation and predicted its effect on innovation to be minimal. The former used the experience of the US-ETS to appraise the potential innovation effect that may be spurred by the EU-ETS. The latter explored the rules provided in the National Allocation Plans (NAPs) of the EU Member States (EU-MS) for the first period of the EU-ETS with respect to their effect on innovation and technology variety. In several subsequent studies, researchers tend to use surveys and interviews to examine this topic. In a case study of the German electricity sector, Hoffmann (2007) finds that technology investments by companies in this sector induced by the EU-ETS are moderate and limited, and play a role in lower-risk short-term investments, but not in long-term large-scale investments. Pontoglio (2008) conducted a survey of plant operators in the Italian pulp and paper industry participating in the EU-ETS between May and June 2006 and received responses from 38 of them. The study finds that most operators have taken a cautious approach to decision-making, with only 13% of operators investing so far in technological innovations to reduce CO_2 emissions and 35% indicating that they are developing energy-saving and emission-reducing innovations. The author concludes that the EU-ETS does not, or only moderately, encourage technological innovation during the pilot phase. In a similar finding, Anderson et al (2011) conducted a mail survey and interviews with participating firms in all EU-ETS covered sectors in Ireland. They find that the EU-ETS has a positive albeit moderate effect on the adoption of low-carbon technologies and the development of new technologies during its pilot phase. For the first phase of the study, there are also some studies that use data sets for empirical analysis. Jaraite (2012) used a panel dataset of Swedish industrial firms from 1999 to 2008, estimated using a two-stage Heckman selection model. The author finds that firms participating in ETS are more likely to act on environmental R&D expenditures and investments. Lofgren et al (2014) analyzed the effect of the EU-ETS on firms' decisions in low-carbon technologies by using detailed firm-level data from the Swedish industry from 2000 to 2008. Based on differences-in-differences estimation, the author concludes that the EU-ETS has no significant effect on firms' decisions to invest in low-carbon technologies. Lundgren (2015) empirically analyzed how the Swedish CO2 tax and the EU-ETS affected productivity development in the Swedish pulp and paper industry from 1998 to 2008. Total factor productivity, technological development, and technological efficiency change were used as indicators. The results show that climate policy has had little effect on technological development in the pulp and paper industry. Borghesi et al (2015) studied various factors that influence the adoption of environmental innovation (EI). They examined the effect of the EU-ETS on emissions reduction and energy efficiency innovations by applying the Italian Community Innovation Survey Data (CIS) from 2006 to 2008. The results show that sectors participating in the EU-ETS are more likely to be innovated than those not. Calel and Dechezlepretre (2015) investigated the effect of the EU-ETS on technological change by comparing applications of low-carbon technologies across both EU-ETS and non-EU-ETS firms. They find that the EU-ETS has increased low-carbon innovation among regulated firms by as much as 10%, and also accounted for nearly a 1% increase in European low-carbon patenting. Overall, these studies show that the first phase of the EU-ETS has had a positive but moderate effect on environmental R&D expenditures and the development of low-carbon technologies. This effect widely occurs across multiple sectors in several countries.

There are also several studies on the second phase of the EU-ETS, which are conducted mainly in the form of interviews. Rogge (2011) conducted a case study of the German power sector between June 2008 and June 2009 through on-site and telephone interviews to verify whether the EU-ETS affected firms' environmental technology innovation. The author finds that the EU-ETS has a limited effect on innovation. In the same year, based on interviews and a survey of German pulp and paper producers and technology suppliers conducted between June 2008 and September 2009, Rogge (2011) concludes that the EU-ETS has had little effect on firms' innovation activities. Similar conclusions are reached using the same interview and survey methodology by Gasbarro (2013) and Gulbrandsen and Stenqvist (2013). Based on interviews with six Italian companies between December 2010 and March 2011, Gasbarro (2013) finds that pulp and paper producers do not undertake any additional technological innovation investments in response to the EU-ETS. Gulbrandsen and Stenqvist (2013), on the other hand, interviewed two pulp and paper producers in Sweden and Norway. They determine that the effect in the pulp and paper sector is weaker or even non-existent compared to the limited effect of the EU-ETS in the electricity sector. Therefore, this paper finds that for the second phase, researchers have focused more on its effect on low-carbon technology innovation, while the exploration of the effect on environmental R&D expenditures is lacking. Moreover, the evidence on the effect of the second phase of the EU-ETS on innovation activities is less positive than expected, or even minimal.

The following studies cover the first and second phases of the EU-ETS. Martin et al. (2013) analyzed the effect of the EU-ETS on clean innovation in processes and products. They used responses from manager interviews for both process and product innovation, and ranked firms on a scale from one to five to capture the firm's innovation input. They find this effort is mainly focused on process innovation[1] rather than product innovation.[2] To illustrate the transnational characteristics of the EU-ETS as well as to attempt to examine longer implementation periods, Bel and Joseph (2015) constructed a dataset covering the 27 EU member states plus Norway for the period 2005 to 2011. The study assessed the effect of excessive supply of EUAs under the EU-ETS on green patents. The results show that the excessive supply of EUAs negatively affects technological change during the first and most of the second phase of the EU-ETS. In the same year, Inoue (2015) studied the effect of the EU-ETS on R&D intensity (R&D expenditure divided by net sales). The author used firm-level panel data constructed from the EU Industrial R&D Investment Scoreboard and corporate CSR reports. The author finds that corporations that have a policy or a strategy to comply with the EU-ETS are more likely to encourage R&D investment. Following this, Lennart (2019) investigated the effect of the first two phases of the EU-ETS on eco-patent output using firm-level data through propensity score matching and the differences-in-differences approach. The results of this analysis show that the first phase of the EU-ETS does not have significant results while the second phase increased the eco-patent output of regulated firms by 1.8%. Through these studies, we can learn that existing studies differ in their conclusions about how the first two phases of the EU-ETS affect environmental R&D expenditures and low-carbon technology development.

Although many studies have been conducted on the effect of EU-ETS on innovation at different phases, according to Teixido et al (2019), the effect of the EU-ETS has not been fully examined over a long period covering the first, second, and third phases of the system by means of empirical analysis. Moreover, there is a lack of research on the effect of the EU-ETS on R&D expenditure. Therefore, our study extends the time period and examines the effect of all phases of the EU-ETS. Also, we believe that R&D expenditure is a better proxy of a company's determination to innovate than the number of patents, R&D expenditure is used as the dependent variable in our study.

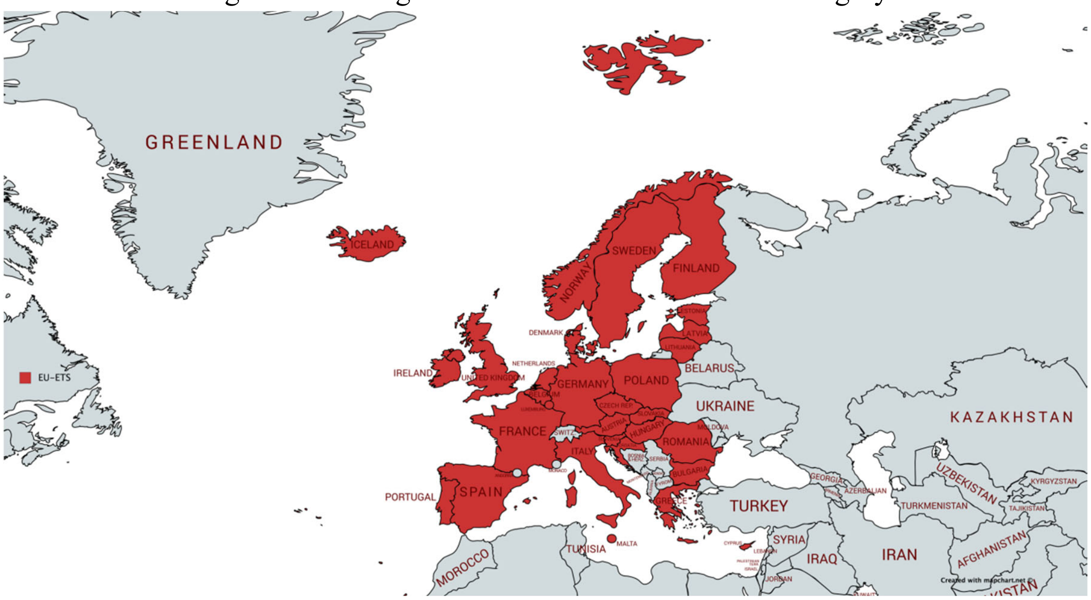
1 Investing to find cleaner production processes that help to reduce emissions on site.

2 Developing new products that are cleaner and thereby reduce emissions of the customer.

3. EU-ETS

The EU-ETS[3] is an environmental policy of the EU to deal with climate change. The purpose of this policy is to reduce greenhouse gas emissions through cost-effective principles. This system is the world's first major carbon market and is still the largest one. The EU-ETS began in 2005 and has been implemented in three phases so far. It covers 11,000 power stations and industrial plants in 31 countries (Figure 1). In addition, it covers around 45% of the EU's greenhouse gas emissions.

Figure 1 The Region under the EU Emissions Trading System



The EU-ETS requires corporations that emit carbon dioxide (CO_2), nitrous oxide (N_2O), and perfluorocarbons (PFCs) to join this system, and subsequently cover aviation corporations. However, in some sectors, only plants above a certain size are included.

The EU-ETS operates on the principle of "cap and trade." That is, the facilities covered by the EU-ETS have a cap on the total amount of emissions, which is reduced year by year, so that the total amount of emissions can also be reduced. Within this cap, corporations obtain or purchase emission allowances, which they can trade among themselves on demand. At the end of each year, corporations must pay sufficient allowances to cover all their emissions; otherwise

[3] The discussion on the EU-ETS in this section is heavily dependent on the description by the European Commission (https://ec.europa.eu/clima/policies/ets_en).

heavy fines are imposed.[4] If a corporation reduces its emissions, the saved emission allowance can be stored for future use, or can be sold to other corporations that require emission allowances.

The first phase, from 2005 to 2007 (Figure 2), was the trial operation phase to accumulate experience through actual operation and to prepare for the second phase. In the first phase, only carbon dioxide (CO_2) emissions from power generators and energy-intensive industries were covered, and almost all emission allowances were allocated free of charge to businesses. Since emission data cannot be obtained at the beginning, the emission allowance is more than the actual emissions. In addition, because the allowances in the first phase cannot be used in the second phase, the price of emission allowance fell to zero in 2007.

The system began to operate officially in the second phase, from 2008 to 2012 (Figure 2), a time period consistent with the first commitment period of the Kyoto Protocol. EU countries needed to achieve emission reduction targets at this stage. In the second phase, the cap of emission allowances was reduced by 6.5%, and thus was lower than the 2005 level. The proportion of free allocations fell slightly to around 90%, and many countries began to use auctions to allocate emissions. After accumulating carbon emissions data for many years, the EU decided to reduce the cap for the second phase based on actual emissions data collected. However, the global financial crisis of 2008 resulted in excess emissions allowances, and the carbon price went down.

The third phase is from 2013 to 2020 (Figure 2). Unlike in the previous phases, a single, EU-wide emission cap was adopted during this period to replace the national caps. At the same time, the auction was used as a cap allocation method. In addition, this phase covers more sectors and more types of greenhouse gases.

Figure 2 The Phases of the EU-ETS

(Source: EU-ETS Handbook)

The EU-ETS ensures a reduction in carbon costs by promoting carbon trading. At the same time, we believe that this system also encourages corporations to increase their expenditure on research and development.

4 In the first phase of the EU-ETS, the penalty for non-compliance was 40 euros per metric ton, which was increased to 100 euros per metric ton from the second phase.

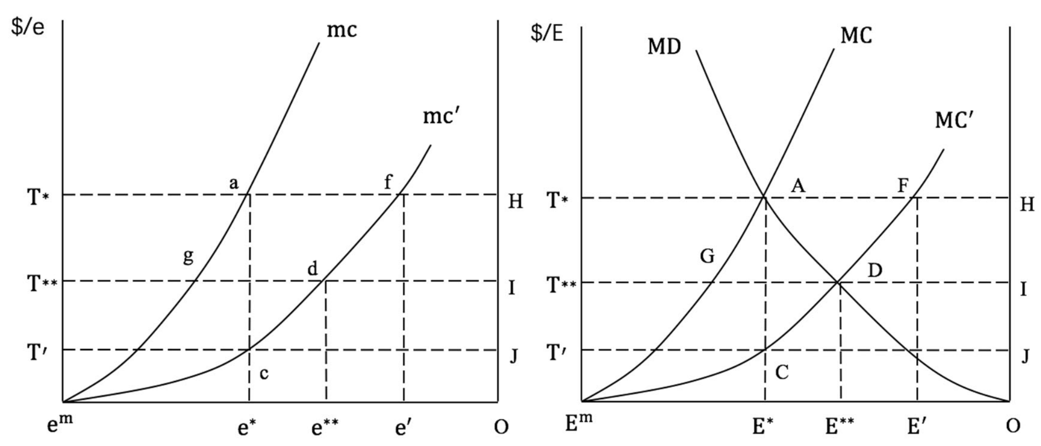
4. The relationship between environmental regulation and innovation

In this section, we discuss the theoretically expected effects of the EU-ETS on innovation, following Milliman and Prince (1989). Assume that a large number (N) of identical firms in a competitive industry are discharging homogeneous emissions into the air. The public regulator, being a social gain maximizer, can reduce these emissions to the optimal rate of E^* per time period by

- Imposing a direct emission control of e^* per time period on each firm, where $N \times e^* = E^*$;
- Giving away E^* marketable permits at frequent, regular intervals, with each firm receiving e^* permits, valued at T^* per permit;
- Auctioning off E^* marketable permits at price T^* at frequent, regular intervals.

Milliman and Prince (1989) argues that firms are divided into innovative firms and non-innovative firms. Meanwhile, innovation has a diffusion process. Here, we assume that all firms have the ability to innovate and ignore the process of diffusion. In addition, E refers to the emissions and T refers to not the tax but the price of the emission permit. MD is the marginal damage. mc and MC mean the marginal cost of reducing the cost of reducing emissions

Figure 3 A Simple Model of Pollution Control



(a) Firm (b) Industry

If a single firm develops an innovation, the firm's marginal cost curve will change from mc to mc' (Figure 3 (a)), and the industry's marginal cost curve will also change from MC to MC' (Figure 3 (b)). In order to restore efficiency, we can reduce the allowed emission levels to e^{**} per firm under direct controls or reduce total permits to E^{**} under free permits and auctioned permits.

Table 1 Relative Ranking of Firm Incentives to Promote Innovation

	Regulatory regime		
	Direct controls	Free permits	Auction permits
Pre-innovation costs:			
1. Direct costs	$e^m ae^*$	$e^m ae^*$	$e^m ae^*$
2. Transfer losses	–	–	$e^* aHO$ x
3. Transfer gains	–	–	–
4. Total (1 + 2 − 3)	$e^m ae^*$	$e^m ae^*$	$e^m aHO$
Post-innovation costs:			
5. Direct costs	$e^m ce^*$	$e^m fe'$	$e^m fe'$
6. Transfer losses	–	–	$e' fHO$ x
7. Transfer gains	–	$e^* afe'$ y	–
8. Total (5 + 6 − 7)	$e^m ce^*$	$(e^m ce^* - caf)$	$e^m fHO$
9. Cost Δ (8 − 4) z	$-e^m ac$	$-e^m af$	$-e^m af$
10. Relative ranking	2	1	1

x Permit payments to the regulator.

y Permit revenues (sales to other firms).

z Negative sign indicates cost reduction.

Firm incentives to promote innovation are determined by firm abatement costs. Firm abatement costs include direct costs, transfer losses, and transfer gains. Table 1 represents the results of abatement cost changes. The highest rank represents the greatest cost reduction. The EU-ETS adopts the mechanism of free permits and auction permits. This ranking suggests that the incentive provided by the emissions trading system is stronger than other policies for environmental regulation.

5. Empirical analysis

5.1 Model

In order to estimate the effect of the EU-ETS on corporate innovation, we employ a DID methodology combined with fixed effects. The DID methodology compares the change in R&D expenditure between corporations that participate in the EU-ETS and those that do not. The fixed effects estimation allows us to control for time-invariant and time-varying unobservable corporation characteristics that may be correlated with the corporation's decision whether to participate in the EU-ETS.

This study uses unbalanced panel data for 606 EU corporations from 2000 to 2017. The specification for the regression model is as follows:

$$R\&D_{it} = \alpha + \beta_1 C_{it} + \beta_2 X_{it-1} + \delta_i + \gamma_t + \varepsilon_{it}$$

where $R\&D_{it}$ indicates the research and development expenditure of corporation i in year t. C_{it} is the treatment indicator, which takes the value of one in the year the EU-ETS policy was implemented in corporation i, as well as in subsequent years, and zero otherwise. The baseline year is set to 2004. X_{it-1} is a set of time-varying corporation characteristics. R&D expenditure and X from the same period could be interrelated. Although R&D expenditure of a later period cannot possibly affect the corporation characteristics of an earlier period, the operating status of the earlier period could be an important reference for future R&D expenditure. Therefore, the corporation characteristics are lagged by one year. Corporation fixed effects are captured by δ_i, with control for unobserved heterogeneity across corporations. Year fixed effects, represented by γ_t, are included to control for trends that affect the development of corporations such as changes in policies and regulations at the EU level. ε_{it} is the error term.

We use R&D expenditure to measure innovation because it is an input to innovation. It can reflect the corporation's commitment to innovation.

5.2 Data description

To examine the effect of the EU-ETS on the corporation's R&D expenditure, we used the Osiris database of the Bureau van Dijk. The Osiris database includes financial data for global listed companies. Then, we selected corporations belonging to the EU 28 countries and related to the EU-ETS sectors. We found 606 corporations that meet these requirements. In order to distinguish between corporations that participated in EU-ETS and that did not, we also compare these 606 corporations with the EU official document (compliance data for 2017). This document records the list of corporations that have participated in EU-ETS after 2005. Finally, we identified 139 corporations as the treatment group and 467 corporations as the potential control group. The sample period for this study is from 2000 to 2017.

Table 2 Descriptive Statistics

	Main variables	Unit	Observation	Mean	Standard deviation	Min	Max
Control group	R&D	Million euros	8399	67.73	385.9	0	6337
	Number of employees	Person	7878	9124	27276	1	450000
	Net profit	Million euros	8398	161.6	895.1	-9099	42285
	Market capitalization	Million euros	6490	3144	10709	0.300	180000
Treatment group	R&D	Million euros	2502	403.7	1005	0	8591
	Number of employees	Person	2416	42163	70395	1	640000
	Net profit	Million euros	2502	857.0	2339	-15000	23895
	Market capitalization	Million euros	2039	12846	23320	2.650	190000
Total	R&D	Million euros	10901	144.8	605.5	0	8591
	Number of employees	Person	10294	16878	43910	1	640000
	Net profit	Million euros	10900	321.2	1399	-15000	42285
	Market capitalization	Million euros	8529	5464	15308	0.300	190000

Table 2 reports the descriptive statistics of the variables used in our analysis. Corporations that participated in the EU-ETS in 2005 and in subsequent years are included in the treatment group. By contrast, corporations that did not participate in the EU-ETS are included in the control group. The average R&D expenditure is about 67.73 million euro in the control group, and 403.7 million euro in the treatment group. In particular, the average R&D expenditure in the baseline year is about 59.39 million euros in the control group and approximately 342.63 million euros in the treatment group. Therefore, we need to employ a matching technique to avoid selection bias.

Corporation characteristic variables, including number of employees, net profit, and market capitalization, are used to control for the size and value of corporations.

5.3 Matching techniques

In this study, we adopt the PSM methodology to reduce potential bias by pairing treatment corporations with control corporations that have similar observed properties from the control pool. The PSM methodology was developed by Rosenbaum and Rubin (1983). The objective of PSM is to identify units from the control group that have similar covariates X with the treatment group units. This method gives each unit of the control group and the treatment group a propensity score $p(X_i)$ and matches units based on the score. The propensity score $p(X_i)$ is the probability that unit i is assigned to treatment, defined as $p(X_i) \equiv \Pr(T_i = 1|X_i)$.

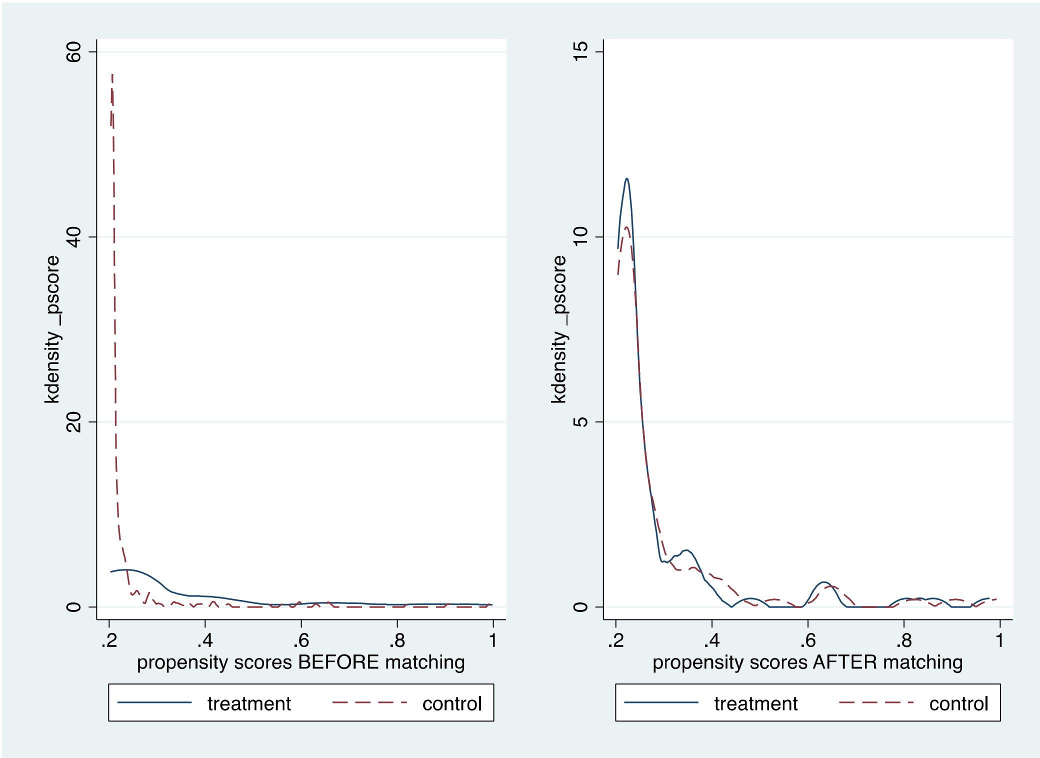
We employ the logit model and complete the PSM method in three steps. First, we use covariates X to determine the probability that a corporation participates in EU-ETS in order to obtain a propensity score. Covariates employed in this study are number of employees, net profit, and market capitalization. Second, we use the estimated propensity score to match the control group and the treatment group in the baseline year. The baseline year is set to 2004 because the EU-ETS started in 2005. At the same time, a one-to-one matching method without replacement was adopted while using the nearest-neighbor PSM algorithm. The observations decreased from 10,901 to 3,024 after the adoption of the PSM method, as observations out of the common support were dropped from the sample. Lastly, we compare the matched control and treatment groups to confirm whether the matching method successfully balances the two groups. We present the balancing test results for the PSM method in Table 3. The results show statistically significant differences between the mean values of the estimated propensity scores of the treatment and control groups before matching. For instance, in the first row of Table 3, we find that the numbers of employees in the treatment and control groups differ by nearly 58.5%. However, the second row shows that the difference between these two groups drops to 0% when the sample is matched. In addition, the t-test results indicate that except for market capitalization, the matched groups do not have statistically significant differences in the mean value of covariates. These results reveal no statistical difference between the matched treatment and control groups.

Table 3 Nearest-Neighbor Propensity Score Matching (PSM) by Logit Model

	Unmatched/	Mean				t-test	
Outcome var: R&D	Matched	Treatment	Control	%bias	%bias reduction	t-value	p-value
Number of employees	U	38419	9128.3	58.5		6.15	0.000
	M	23493	23481	0.0	100.0	0.00	0.999
Net profit	U	772.29	164.78	44.6		5.05	0.000
	M	276.26	437.4	-11.8	73.5	-1.54	0.126
Market capitalization	U	9175.1	2107.9	47.1		5.34	0.000
	M	3309.6	5233.3	-11.9	74.7	-1.65	0.100

The balancing test results are also shown in Figure 4, which depicts the differences between the distributions of propensity scores for the treatment and control groups. The figure shows that the kernel density of the propensity score is similar for selected observations in the control and treatment groups after matching. This suggests that the difference between the distributions of the two groups has significantly reduced after the PSM was applied.

Figure 4 Distribution of Propensity Scores for Treatment and Control Groups: before and after the Nearest-Neighbor PSM (Matching by Logit Model)



6. Results

The estimation results of the EU-ETS's effect on corporations' R&D expenditure are reported in Table 4. Since the EU-ETS has had three phases so far, we divided the time scale into three periods for the regression analysis.

Table 4 The Effect of the EU-ETS on R&D Expenditure (Matching by Logit Model)

	2000-2007		2000-2012		2000-2017	
	(1)	(2)	(3)	(4)	(5)	(6)
ETS∗Time	68.01**	51.77*	93.71**	79.21**	114.6**	90.87**
	(2.12)	(1.94)	(2.09)	(2.39)	(2.06)	(2.40)
Time	-18.53	-13.24	-15.16	-32.43	-2.060	-37.73
	(-0.76)	(-0.75)	(-0.55)	(-1.51)	(-0.08)	(-1.40)
Number of employees		0.00760**		0.00982***		0.0119***
		(2.25)		(3.64)		(3.75)
Market capitalization		-0.00181		-0.00266		0.00545**
		(-0.38)		(-1.36)		(2.23)
Net profit		0.0139		0.0577**		0.0187
		(0.39)		(2.17)		(0.88)
_cons	159.2***	-13.86	159.2***	-71.15	152.6***	-151.3*
	(19.84)	(-0.20)	(10.25)	(-1.02)	(7.18)	(-1.78)
N	1344	978	2184	1806	2854	2456

t statistics in parentheses
* p<0.1, ** p<0.05, *** p<0.01

Note: All columns are estimated by DID with robust standard errors.

Columns 1 and 2 show the results for the years 2000 to 2007, which include the pre-EU-ETS period and phase 1 of the EU-ETS. The results in Column 1 suggest a positive relationship between EU-ETS and R&D expenditure. The coefficient of the treatment indicator *ETS∗Time*[5] is positive and statistically significant at the 5% level. However, when we add control variables such as corporation characteristics to the regression, the result is positive and statistically significant at the 10% level as shown in Column 2. This result shows that the first phase of the EU-ETS may have some effects, but the statistical significance is weak. Since the European Commission hopes to promote the ETS during the trial phase, most of the allowances can be obtained free of charge. Although the implementation of the ETS will encourage corporations to increase investment in R&D expenditure and thereby reduce carbon emissions, obtaining free allowances will still weaken their willingness to invest.

Columns 3 and 4 show results for the years 2000 to 2012, which include the pre-EU-ETS period and phases 1 and 2 of the EU-ETS. The coefficient of the treatment indicator *ETS∗Time* is positive and statistically significant at the 5% level. After we add the control variables, the result is still positive and statistically significant at the 5% level as shown in Column 4. The result shows that the EU-ETS increases the corporations' R&D expenditure by EUR 79.21 million. After passing the trial period and entering the formal period, corporations increase their

[5] ETS refers to corporations that participated in the EU-ETS and Time refers to the time period following the implementation of the EU-ETS.

willingness to invest in R&D expenditure due to the reduction of free allowances and the emergence of the auction method.

Columns 5 and 6 show the results for the years 2000 to 2017, which include the pre-period and all three phases of the EU-ETS. The coefficient of the treatment indicator *ETS∗Time* is positive and statistically significant at the 5% level. After we add the control variables, the result is still positive and statistically significant at the 5% level as shown in Column 6. The result shows that the EU-ETS increases the corporations' R&D expenditure by EUR 90.87 million. The increase in the estimated effects is about 62.75% of the corporations' average R&D expenditure.[6] Because the European Commission continues to increase the auction allowances for carbon emission rights, and the allocation will no longer be controlled by member states but will be developed by the European Commission to formulate a unified allowances allocation plan. Based on the above two reasons, corporations have further increased R&D expenditure.

7. Conclusions

In this study, we examine whether the EU-ETS promotes corporate innovation, by focusing on corporations' R&D expenditure. This study used corporate financial panel data for EU corporations from 2000 to 2017 based on the Osiris dataset and an official EU document. Through an empirical analysis, we investigate whether environmental regulation promotes corporate innovation and enhances the competitiveness of corporations.

Previous studies focus on the first and second phases of the EU-ETS, without a complete analysis of the three phases. In addition, most of the focus is on low-carbon patents. In contrast, our study focuses on the effect of all phases of the EU-ETS on firms' R&D expenditure.

The regression results show that corporations regulated by the EU-ETS generally encourage R&D activities. It is worth noting that the first phase of the EU-ETS has only a little effect on the corporations' R&D expenditure. However, the second and third phases increase the corporations' R&D expenditure by 79.21 million euros and 90.87 million euros, respectively. We argue that the first phase of the EU-ETS has only a little effect probably because almost all allowances were given to the corporations free of cost, as the first phase was a trial period.[7] This study differs from previous empirical studies in that our study concludes that the first phase of the EU-ETS is not completely ineffective, but has a relatively weak effect. Also, our study extends the study period and finds a positive effect in the third phase of the EU-ETS.

The results of this study show that environmental regulation could promote innovation and

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6 This calculation is based on the assumption that the corporations' average annual R&D expenditure is 144.8 million euros.

7 According to the conclusions of the previous theoretical research in section 4, the free permits and auction permits have the same relative ranking of firm incentives to promote innovation. In reality, free permits emissions may have less transfer gains because all firms also have sufficient emissions permits, which may reduce the incentive for innovation. Therefore, we believe that the first phase of the EU-ETS has a weaker effect on corporations' R&D expenditure.

enhance the competitiveness of corporations. A better understanding of the relationship between environmental regulation and corporate innovation is important to achieve economic development in the face of climate change. Although our study confirms the positive role of the EU-ETS in promoting corporate innovation, further research using different empirical methods could supplement our results. In addition, future research might consider adding more corporate innovation indicators to increase the rigor of the analysis, such as patents. Furthermore, test for heterogeneity among corporations belonging to different sectors are also studied.

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Appendix

In this study, we also employ the probit model when we adopt the PSM methodology to reduce potential bias. In the same way, we adopt a one-to-one matching method without replacement when we use the nearest-neighbor PSM algorithm. Because of the common support, the observations decreased from 10,901 to 3,132.

Table 5 Nearest-Neighbor Propensity Score Matching (PSM) by Probit Model

	Unmatched/	Mean				t-test	
Outcome var: R&D	Matched	Treatment	Control	%bias	%bias reduction	t-value	p-value
Number of employees	U	38419	9128.3	58.5		6.15	0.000
	M	23374	25853	-5.0	91.5	-0.36	0.720
Net profit	U	772.29	164.78	44.6		5.05	0.000
	M	481.86	479.93	0.1	99.7	0.01	0.992
Market capitalization	U	9175.1	2107.9	47.1		5.34	0.000
	M	5313.5	5914.6	-3.7	92.1	-0.33	0.745

The balancing test results are presented in Table 5. The results show statistically significant differences between the mean values of the treatment group and control group before matching. For example, in the third row of Table 5, we find that the bias of net profit between the treatment group and control group is 44.6%. However, the fourth row shows that the bias between the two groups drops to 0.1% after matching. Meanwhile, results of the t-test also reflect no statistically significant differences in the mean value of covariates after matching.

Figure 5 Distribution of Propensity Scores for the Treatment and Control Groups: before and after the Nearest-Neighbor PSM (Matching by Probit Model)

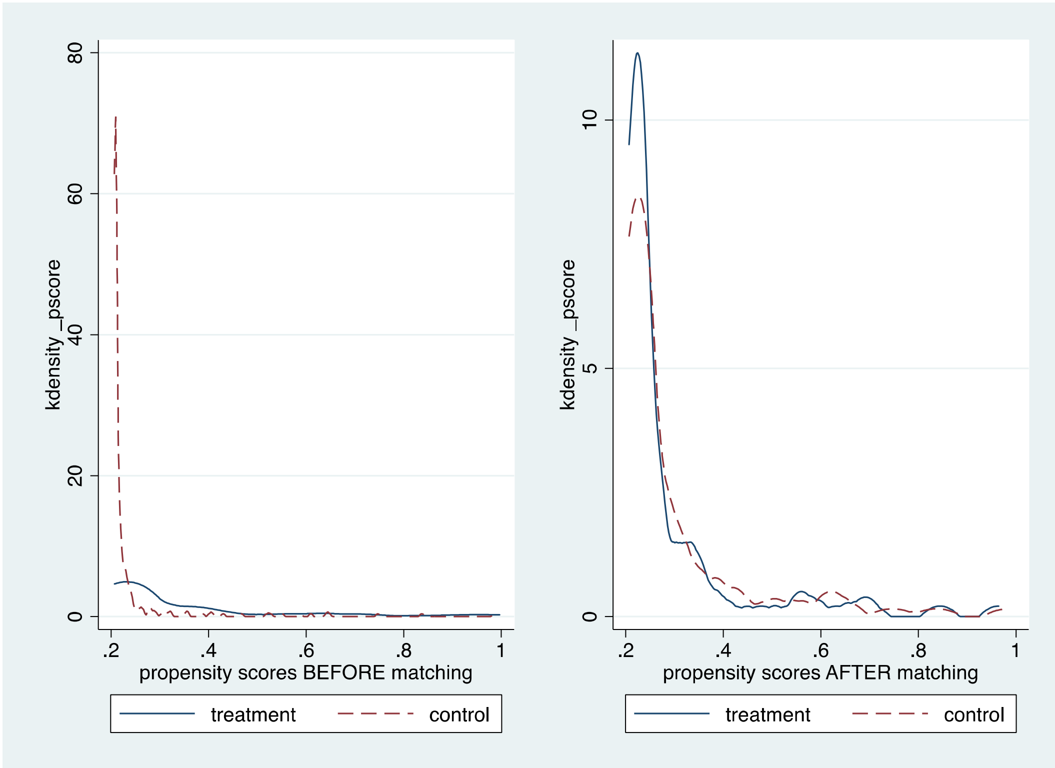

Figure 5 depicts the distribution of the propensity scores for the treatment and control groups. The figure also shows that the kernel density of propensity scores of these two groups is similar after matching. These results reflect that the bias in the distribution of the two groups have reduced after adoption of the PSM methodology.

The estimation results of the EU-ETS's effect on the corporations' R&D expenditure are provided in Table 6.

Table 6 The Effect of the EU-ETS on R&D Expenditure (Matching by Probit Model)

	2000-2007		2000-2012		2000-2017	
	(1)	(2)	(3)	(4)	(5)	(6)
ETS∗Time	53.35*	50.27*	63.24*	58.15*	55.80	58.09
	(1.78)	(1.97)	(1.73)	(1.91)	(1.42)	(1.63)
Time	-8.419	-3.155	3.601	2.297	25.23	-4.579
	(-0.34)	(-0.21)	(0.13)	(0.10)	(0.85)	(-0.17)
Number of employees		0.00775***		0.00690***		0.00548***
		(3.08)		(3.27)		(2.94)
Market capitalization		-0.00256		-0.0000831		0.0105***
		(-0.63)		(-0.03)		(2.90)
Net profit		0.0250		0.0129		-0.0221*
		(0.79)		(0.82)		(-1.75)
_cons	166.5***	-27.20	166.5***	-13.74	166.4***	-20.85
	(22.25)	(-0.51)	(13.17)	(-0.27)	(11.06)	(-0.37)
N	1392	1020	2262	1876	2958	2558

t statistics in parentheses
* $p<0.1$, ** $p<0.05$, *** $p<0.01$

Note: All columns are estimated by DID with robust standard errors.

Columns 1 and 2 show the results for the years 2000 to 2007, which include the pre-EU-ETS period and phase 1 of the EU-ETS. The results in Column 1 suggest a positive relationship between the EU-ETS and R&D expenditure. The coefficient of the treatment indicator *ETS∗Time* is positive and statistically significant at the 10% level. The result is still positive and statistically significant at the 10% level after we add control variables as shown in Column 2. These results show that the EU-ETS increases the corporations' R&D expenditure by EUR 50.27 million.

Columns 3 and 4 show the results for the years 2000 to 2012, which include the pre-EU-ETS period and phases 1 and 2 of the EU-ETS. The coefficient of the treatment indicator *ETS∗Time* is positive and statistically significant at the 10% level. After we add control variables, the result is still positive and statistically significant at the 10% level as shown in Column 4. The result shows that the EU-ETS increases the corporations' R&D expenditure by EUR 58.15 million.

Columns 5 and 6 show the results for the years 2000 to 2017, which include the pre-period and all the three phases of the EU-ETS. The coefficients of the treatment indicator *ETS∗Time* are not statistically significant as shown in Columns 5 and 6.