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The creative response of energy-intensive industries to the Emissions Trading System in the European Union

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ABSTRACT

There is a broad consensus on the contribution of the so-called eco-innovations to the sustainability transition of economic activity and on the power of policy instruments to redirect innovation towards solving environmental challenges over time. However, despite remarkable academic efforts in this direction, there is a shortage of studies empirically analysing the link between environmental policy and innovation activities. Using firm-level data gathered from the Community Innovation Surveys of two specific years, 2008 and 2014, from eleven European countries, we apply a difference-in-difference approach to provide a clear-cut test of the effects of Phase III of the EU's Emissions Trading System on low-carbon innovations of energy-intensive firms. Our results suggest that environmental policy may affect firms' environmental performance by improving eco-innovating efforts. In fact, the new environmental policy not only induced an *adaptive response*, in which firms adjust their level of emissions to this new cost scheme, it also induced a *creative response*, leading companies to move outside of the range of their existing practices.

1. Introduction

Globalisation has undoubtedly boosted innovation by facilitating the exchange of new knowledge and ideas (e.g., Archibugi and Iammarino, 2002; Crescenzi et al., 2020; Baloch et al., 2021). At the same time, environmental and natural resources have been seriously threatened because of a persistent sectoral dependence on capital-intensive factors since the beginning of the First Industrial Revolution. To overcome this problem, an institutional response has arisen in terms of increasing environmental stringency, so that firms need to readapt their production strategies to initiate the transition towards production processes with fewer polluting resources. However, this process of readaptation is not exogenous and can be managed by firms using technology. The recent globalisation process is also governed by rapid and disruptive changes in technology (McAfee, 2019; Baldwin and Forslid, 2020; among others), which can be used by firms not only to exchange information, but also to decrease the environmental impact of the production process or even to create newer ones. A deeper study of the impact of environmental policies on the adoption of technology may contribute to providing a suitable framework for ex-post environmental policy review.

Among all the existing ways to mitigate the environmental impact of production processes using technology, we pay special attention to the impact exerted by innovation. In the last twenty years, the role of innovation in the transition towards sustainability has received increasing attention from academics (Mowery et al., 2010; Geels, 2014; Fagerberg, 2018). In this vein, recent evidence confirms the existence of a positive causal relation between innovation and sustainability and, more importantly, this evidence has recently started to mount rapidly (e.g., Fernández-Fernández et al., 2018; Mensah et al., 2018; Silvestre and Ţîrcă, 2019; Nguyen et al., 2020). However, specific purposes of innovation have been left out of the discussion. This issue is particularly relevant, as innovation could be oriented to facilitate the sustainability transition. In line with these findings, the idea of mission-oriented innovation emphasises the role of policy in redirecting innovation towards major social, environmental, and economic challenges (Jaffe et al., 2005; Foray et al., 2012; Mazzucato, 2018; Schot and Steinmueller, 2018). Eco-innovation contributes to shedding light on this type of innovation, where firms orient their innovation strategies to reduce the use of natural resources and decrease the release of harmful substances (James, 1997; Díaz-García et al., 2015). Globalisation without considering the dimension of eco-innovation is not expected to be aligned with environmental purposes (Ahmad and Wu, 2022).

Despite these remarkable academic efforts, we find an important shortage of studies analysing general patterns on the link between

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environmental policy and eco-innovation (Kiefer et al., 2017). Some quantitative studies analyse the existing causal relation exerted by environmental regulations, measured by public funding of eco-innovation efforts (Peñasco et al., 2017; Jové-Llopis and Segarra-Blasco, 2018; Fernández et al., 2021). Although public funding can be considered as a good proxy to in an institutional setting, it does not indicate the impact of specific environmental regulatory changes on eco-innovation. To this end, reframing the context towards a proper ex-post policy analysis, which requires resorting to experimental evidence, may be desirable.

In addition, we acknowledge that eco-innovation efforts may be unequal across territories and that focusing on a specific area may help formulate specific policies. When studying the evolution and dynamics of eco-innovations, the European Union emerges as one of the most critical areas of interest for several reasons. First, it is ranked among the largest emitters of CO_2, with around one-third of the population being potentially exposed to noise and pollution. Second, the European Union has been highly proactive in making several institutional efforts and arrangements to cope with sustainability issues and decouple CO_2 emissions from economic growth. Specific regulations and initiatives can be argued to act as a major driver to accomplishing these goals, as they may facilitate a cleaner, sustainable transition of production processes (European Commission, 2020). More specifically, the European Commission regulation on auctioning for allocation of greenhouse gas (GHG) emission allowances, the European Union's Emissions Trading System (EU ETS), launched in 2005, opened an important research stream to fill this gap. However, to the best of our knowledge, academics have largely ignored evidence on the evaluation of the EU ETS.

At the same time, it is important to pay attention that the implementation of the EU ETS has taken place during different temporal phases (we are currently situated at the beginning of the fourth phase) and the impact of such phases on eco-innovation efforts may differ. While the first two phases gave firms almost free allowances, the third (2013–2020) began to incorporate an ambitious progressive plan of decreased free allocations, moving from 80% of the allowances being free of charge at the level of a "benchmark" in 2013 to 30% in 2020. Therefore, firms are expected to increase their eco-innovation efforts to comply with the more stringent requirements. Hence, a proper evaluation of the effects induced by the third phase may be an appropriate context to determine whether European firms have benefited from such a policy or not.

Nevertheless, academic efforts to address the environmental impact under a policy domain seem to be absent for Europe. While most of the literature has focused on the impact of environmental policy in China (Almond et al., 2009; Zhao et al., 2015; Cai et al., 2016; Xu et al., 2019; Chen et al., 2022; Wang et al., 2022, among others), few studies have shifted to the context of the European Union by analysing the impact of the EU ETS on eco-innovation via low-carbon technological changes. Although previous work has analysed the impact of the EU ETS on technological change (Schmidt et al., 2012; Martin et al., 2013; Borghesi et al., 2015; Calel, 2020), this has been at the cost of omitting the later phases of the EU's ETS. This statement is particularly relevant, as the later stages incorporate growing levels of environmental stringency and allow us to evaluate more accurately firms' eco-innovational response to the most stringent phases of the EU ETS.

In this paper, we analyse the effect of the changes in the EU ETS, introduced in Directive 2009/29/EC, on the propensity of firms to introduce low-carbon innovations. Our main argument is that this new policy encourages this type of innovation, particularly in the case of energy-intensive industries, since the regulation allows them to cover all their needs through free allowances if they achieve greenhouse gas efficiency. Using data from the Community Innovation Survey (CIS) gathered for two specific years, 2008 and 2014, for eleven European countries, we performed an empirical study to analyse the impact of this environmental policy on firms' eco-innovational performance. We have resorted to well-established methods of analysing the impact of a policy, such as the difference-in-difference approach (e.g., Athey and Imbens, 2006; Doudchenko and Imbens, 2016) and propensity score matching techniques (e.g., Caliendo and Kopeinig, 2008; Abadie and Imbens, 2016).

The Schumpeterian "creative response" provides a framework for understanding the link between environmental policy and the low-carbon innovations of energy-intensive firms in the EU. Schumpeter (1947) suggested that agents' reactions to changes in data (e.g., prices, income, etc.) could be of two types. On the one hand, there is the "adaptive response," which is none other than that predicted by conventional economic theory. For example, changes in the cost of inputs lead to suboptimal behaviour of firms (e.g., the marginal rate of technical substitution will differ from the relative prices for some pairs of inputs). As a consequence, companies will reconsider their allocation of resources. This adjustment can be seen as adapting to these new conditions by economising costs through substitution.

On the other hand, there is also the possibility of "creative response," in which agents devise new ways of carrying out their activities. In this sense, changing conditions leading to sub-optimal performance might be the source of innovative efforts of companies. This approach has also been used recently to explain the effect of regulatory changes on innovation (Antonelli and Feder, 2022).

According to recent studies, the EU ETS managed to reduce the EU's emissions from 2008 to 2016 (Dechezleprêtre et al., 2018; Bayer and Aklin, 2020). Our main findings show that the new environmental regulation has induced a higher propensity for eco-innovation in those firms belonging to energy-intensive industries. This new regulation has not only induced an adaptive response, in which firms adjust their level of emissions to this new cost scheme, but it has also induced a creative response, leading companies to move outside of the range of existing practice. The Schumpeterian "creative response" provides a framework for understanding the link between the European Union's environmental policy and the low-carbon innovations of energy-intensive firms.

The remainder of this article is organized as follows. Section 2 presents a literature review of eco-innovation and provides the framework for our analysis. Section 3 sketches the data and method followed for the empirical analysis, after which, Section 4 describes the results. Finally, Section 5 is focused on conclusions.

2. Literature review

2.1. Eco-innovation and environmental regulation

New evidence on the factors that drive and push eco-innovations is flourishing and can be considered of growing interest (De Jesus and Mendonça, 2018; Arranz et al., 2020; Frigon et al., 2020). The literature classifies these drivers into two categories: internal and external drivers. Internal usually refers to innovative and environmental capabilities, while external drivers include factors such as competitive pressure, customer green demand, or regulation. Since our study aims at analysing the impact of a regulatory change on eco-innovation, we can limit our contribution to this latter debate on external drivers.

A business-friendly regulatory environment can defy certain barriers that may dampen innovation efforts, favouring the transition to innovation (Carrillo-Hermosilla et al., 2010). Peñasco et al. (2017) analyse the impact of regulation on eco-innovation, as proxied by public subsidies from national and international sources, for Spanish eco-innovating firms. Evidence reported is countervailing, as public subsidies from international sources are not positively related to eco-innovation efforts, while national sources have a positive and significant effect. Others have addressed the impact of regulation on eco-innovation but focusing solely on developing countries. Aloise and Macke (2017) analyse the impact of the regulatory framework on eco-innovations in a Brazilian region, where they confirm a significant relation between both variables. Jové-Llopis and Segarra-Blasco (2018) obtain similar results for Spanish firms using subsidies to measure the impact of regulation. In contrast, Fernández et al. (2021) consider Chilean firms during 2009–2016 and find that the regulatory framework, measured using public support, has only a weak association with eco-innovation. Although this strand of research has aimed at shedding light on the impact of regulation, efforts have focused on the impact of specific regulatory measures rather than on the effect of regulatory changes.

2.2. The European Union's Emissions Trading System and technological change

Over the last decade, the concern about climate change has been increasing. Hence, the proliferation of international arrangements, like the Kyoto Protocol, the Paris Agreement, or the 2030 Agenda for Sustainable Development from the United Nations, has represented a significant effort driven by countries to mitigate harmful environmental practices. In addition, the EU has been highly proactive in promoting the diffusion of sustainability, with specific initiatives such as the European Green Deal, the Just Transition Mechanism, and the climate neutrality target by 2050, among others.

The EU ETS is the first international market for greenhouse gas emissions, and it is one of the most ambitious initiatives of the European Commission to combat climate change. The trading system works as follows. Each installation (a firm might have one or more installations) has free allowances for emissions of greenhouse gases. Once the limit of these allowances (called the "cap") is exceeded, the installation must purchase allowances from others. On the contrary, if the installation has emitted gases below its limit, it can sell its leftover credits to other installations. Fig. 1 provides a general overview of the different phases of the EU ETS and places a substantial emphasis on Phase 3. This is the most stringent phase with available existing data to evaluate its policy impacts.

There is much scepticism about the effectiveness of the EU ETS and its impact on technological change. However, these perceptions are changing. Despite the low prices for carbon emissions, recent studies show that the EU ETS managed to reduce the EU's emissions during the period 2008–2016 (Dechezleprêtre et al., 2018; Bayer and Aklin, 2020). Meanwhile, the empirical literature shows a moderate impact of the early stages (2005–2012) of the EU ETS on low-carbon innovation.

In a different research stream, other studies have analysed the impact of the EU ETS on technological change (e.g., Teixido et al., 2019). Generally speaking, the empirical literature shows that the impact of the early stages (2005–2012) of the EU ETS on low-carbon innovation was moderate. Schmidt et al. (2012) compared the periods 2000–2004 and 2005–2009 in seven European countries using interviews with managers from the electricity sector to show that the free allocation allowances of emissions hampered the adoption of low-carbon technologies. Using primary data from interviews carried out in 2009 in six European countries, Martin et al. (2013) found that firms positioned below the benchmark engaged more strongly in low-carbon innovation. Löfgren et al. (2014) found no significant effects of the EU ETS on investment in low-carbon technologies in Sweden from 2000 to 2008. Using Community Innovation Survey (CIS) data covering 2000–2008, Borghesi et al. (2015) found that sectors regulated by the EU ETS were more likely to make climate-related investments. Calel and Dechezleprêtre (2016), show that the EU ETS caused an increase of 36% in the number of low-carbon patents over 2005–2009. Calel (2020) found for the case of the UK that the ETS caused an increase of low-carbon patents by about 25% in the period 2008–2012.

However, an important shortcoming in these studies is that, as stated before, they analyse only the early stages of the EU ETS (phases I and II), where almost all allowances were given to businesses for free. But phase III (2013–2020) incorporated important regulatory changes: as the percentage of free allowances decreases significantly, there may be potentially more substantial incentives for firms to implement low-carbon technological change. One of these changes was the regulation associated with the so-called carbon leakage list, which is more restrictive by including a more significant number of sectors. A further policy evaluation of this transition from phase II to phase III is precisely the object of our empirical study.

To the best of our knowledge, the only study on the link between eco-innovation and phase III of the EU ETS (Silva et al., 2021) does not provide a clear-cut causal interpretation of the estimated effect of the new policy, since it does not include information on the situation before the regulatory change. Unlike those studies aiming to find a causal relation between variables, our efforts focus on assessing the impact of Phase III of the EU ETS. In particular, we aim to identify the existence of specific mechanisms to differentiate the policy response of firms considering different scenarios, such as activity, country and policy. That is expected to be our contribution to this growing and important academic debate.

At the same time, this policy evaluation needs to cope with the problem of data paucity. Our study combines the only two editions of the Community Innovation Survey (CIS) that include specific questions on the development of eco-innovations: CIS-2008 and CIS-2014. Given that each wave of the CIS covers the innovations of the last three years, our

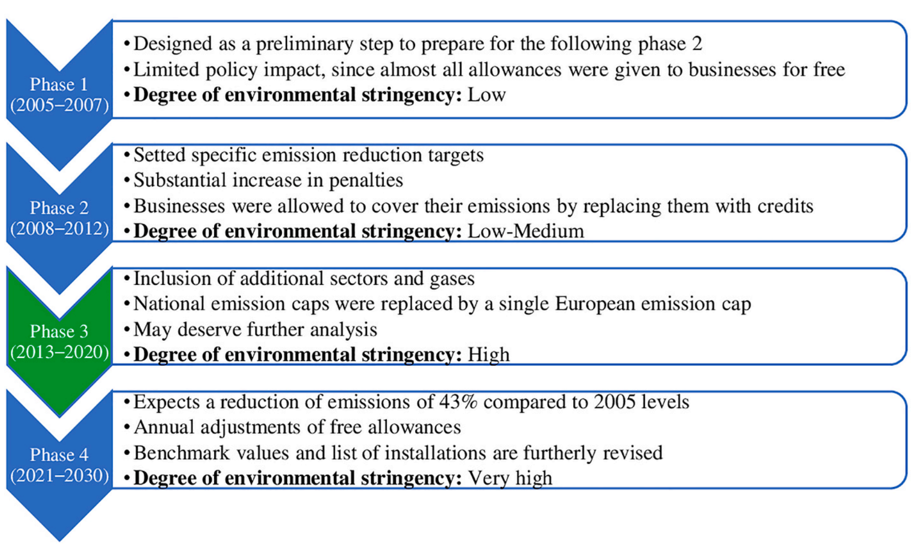

Fig. 1. General overview of the European Trading Scheme, phases 1 to 4
Source: The European Union.

study compares the periods 2006–2008 and 2012–2014. In this sense, from the point of view of the EU ETS, our study compares the last two years of the first phase and the first year of the second phase, with the last year of the second phase and the first two years of the third phase. However, as we will explain in the methodology section, the significant change in eco-innovation incentives goes back to 2009, when the new EU policy framework for the third phase of the EU ETS was announced.

2.3. The carbon leakage list

The implementation of the EU ETS has been developed in different phases (we are currently at the beginning of the fourth phase). Almost all allowances were given to businesses in the early stages for free. But the third phase (2013–2020) incorporated an ambitious progressive plan to decrease the free allocations, going from 80% of the allowances free of charge at the level of a "benchmark" in 2013 to 30% in 2020.

This benchmark, which is calculated for each product, is based on the average greenhouse gas emissions of the best performing 10% of the installations producing that product in the EU and European Economic Area-European Free Trade Agreement states. Installations that do not reach the benchmarks will receive fewer allowances than those meeting the benchmarks.

Another important change in the framework of the EU ETS introduced in the third phase was precisely the Carbon leakage list, following Directive 2009/29/EC (European Commission, 2009). Carbon leakage occurs when businesses transfer their production activities to other countries with laxer emission constraints. In the paradigm of international business, lower emissions constraints can be seen as a location advantage and hence become a useful factor to explain firms' internationalisation (e.g., Dunning, 1977). Consequently, this location advantage could increase firms' total emissions, since many developing countries could be used as pollution havens. This problem is more acute for firms where the additional costs induced by the implementation of the regulation would lead to a substantial increase in their production costs. The risk of carbon leakage may be higher in certain energy-intensive sectors. The carbon leakage list identifies these sectors, at the level of 3 or 4 digits in the NACE classification. In the case of these sectors, the regulations allow free emissions for 100% of the benchmark.

More specifically, we suggest that Directive 2009/29/EC introduced differentiated incentives for eco-innovations aimed to reduce the CO2 footprint, since the regulation allows the most efficient firms of the sectors included in the Carbon Leakage List to cover all their emission needs through free allowances, while the firms in other sectors could only reach a maximum of 30% discount rate in the medium term. Thus, eco-innovation became more profitable for firms deemed to be exposed to a significant risk of carbon leakage.

The new rules of Directive 2009/29/EC were applied in 2013. However, they were set out in 2009: over three years before they entered into force. Thus, there was time for investment decisions to adapt to the new allocation regime. This makes the 2008–2014 period relevant for analysing the effects of this change in regulation.

2.4. The importance of time for evaluating technological response

Beyond regulation, the literature has also found it important to analyse diffusion patterns of eco-innovations and convergence. In this regard, there is ample evidence that the diffusion of innovations takes place over time, so firms may need to accommodate their production processes to the innovation (Rogers, 2003). Concerning the diffusion of eco-innovations, we acknowledge that the literature has strictly focused on drivers rather than diffusion, which has been gaining more importance because some eco-innovations can be already found at a mature stage (Karakaya et al., 2014) and hence be less attractive for those firms seeking potential benefits from early stages.

Neglecting diffusion patterns across the business cycle entails certain shortcomings mainly derived from omitting dimension of time and hence considering eco-innovation as just a static phenomenon. The assumption of a static framework implies that the benefits of eco-innovation are only analysed during a specific time period, which may not necessarily be consistent with the theoretical outcomes. In fact, existing theoretical findings show that when adopting an innovation, firms may be subject to decreasing returns to scale at least during the initial stages (Helpman and Trajtenberg, 1998). According to this statement, firms may improve their propensity to eco-innovate over the business cycle in response to growing environmental stringency to reap convergence. The aim for firms is to move towards not a slow change, but to a continual one (Termeer et al., 2017) when eco-innovating.

To the best of our knowledge, the evidence provided is still limited compared to previous topics and offers preliminary evidence to be considered for further research. Durán-Romero and Urraca-Ruiz (2015) focus on adopting environmentally sound technologies to prevent climate change. Using patent data from 1978 to 2010 for developed and developing countries, their evidence is twofold: while developed countries specialise in environmental patents and regulations, emerging countries diffuse eco-innovation from their participation in international agreements. From a more general point of view, Mazzanti (2018) examines the increasing growth of green patenting activities from 1990 to 2010 in the European Union and concludes that different channels, among which we find technology, human capital and social capital, may be relevant to explain this growth. Finally, Karman et al. (2020) provide quantitative evidence on diffusion patterns of eco-innovation at a macroeconomic level. Using data from 38 countries during the years 2012–2017, they obtain not only the existence of absolute convergence per se, but also spatial spillovers that may induce country collaboration.

To sum up, we propose the importance of the temporal dimension when evaluating how firms adapt their technological response to a given change. However, this has not received further attention from academics when analysing firms' efforts directed to eco-innovation.

All these prior considerations lead us to propose the following research hypothesis:

Hypothesis. The propensity to introduce low-carbon innovations grew more rapidly between 2008 and 2014 in companies deemed to be exposed to a significant risk of carbon leakage

3. Data and methods

To analyse the empirical content of our hypothesis, we construct a test based on the Difference-in-Difference strategy, using two waves from the Community Innovation Survey (CIS-2008 and CIS-2014) of 11 European countries. The strategy compares the change in the propensity to introduce low-carbon innovations between 2008 and 2014 in two groups. The first group contains companies belonging to sectors included in the Carbon leakage list (treated group), and the second contains companies from the rest of the industries (control group). Since these groups have different average profiles from the point of view of their innovative activities (i.e., R&D intensity, size.), we will use the propensity score matching technique to deal with the problem of a systematic difference between groups. Although this problem is usually addressed by testing the parallel trend assumption (Dimick and Ryan, 2014), as we explain below, the information provided by CIS does not allow this. In this section, we describe the methodological strategy proposed in this study.

Another challenge for our analysis is that it exclusively evaluates the first two years of the third phase of the EU ETS (2013 and 2014), which might seem like a brief period to observe its effects. However, as we will explain in the next paragraph, the empirical evidence indicates that its impact on eco-innovation incentives is prior to the year of its implementation.

The first two phases of the EU ETS (2005–2007 and 2008–2012, respectively) are considered "trial periods" with marginal changes between stages, a low level of restrictions from the point of view of allowances, and few incentives aimed at promoting eco-innovations. (Ellerman, 2010). The EU introduced the most substantial changes in the third phase of EU ETS (2013–2020). Although this phase began in 2013, its effects on the incentives to produce eco-innovation started much earlier in 2009. A decisive change in the policy against climate change in the European Union was the Climate and Energy Package which made the EU ETS the critical tool for cutting greenhouse gas emissions. Within this framework measures, the EC Directive 2009/29 introduced the most substantial changes in the EU ETS since its creation (Borghesi et al., 2016). This Directive announced measures aimed at a more stringent emissions market (free emission rights would go from 80% to zero in the 2013–2020 period), and a more significant boost to the eco-innovation.

Our study combines the only two editions of the Community Innovation Survey (CIS) that include specific questions on the development of eco-innovations: CIS-2008 and CIS-2014. Given that each wave of the CIS covers the innovations of the last three years, our study compares the periods 2006–2008 and 2012–2014. In this sense, from the point of view of the EU ETS, our study compares the last two years of the first phase and the first year of the second phase, with the last year of the second phase and the first two years of the third phase. In this sense, although, at first glance, it might seem premature to analyse the effects of a policy implemented in 2013 by comparing the periods 2006–2008 and 2012–2014, as we stated before, we conjecture that 2009 is the critical year for the change in GHG emissions policy with the publication of Directive 2009/29. In fact, consistently with this idea, previous studies using CIS-2008 find a weak relation between eco-innovations and the EU ETS measures in its first stages (Aghion et al., 2009; Borghesi et al., 2015), while some studies show a positive impact of this policy on R&D effort (Martin et al., 2012).

3.1. Data

The CIS database, developed by the European Commission, is considered the most relevant microdata source to measure innovation efforts for European firms (Popp, 2019), and its use has become widespread. It consists of a voluntary and harmonised survey whose aim is to collect data broken up by countries, type of innovators or objectives of innovation, among others. Hence, CIS provides a very accurate effort to capture not only differences in innovation between firms, but also to find such differences between sectors of countries, and its use has become widespread.

In 2008 and 2014, most countries implementing the CIS introduced questions regarding eco-innovations (thirteen out of sixteen countries in 2008, and thirteen out of fifteen in 2014). Therefore, to conduct a stable test of changes in the patterns of eco-innovations, we have selected the eleven countries that captured information on the environmental benefits of innovation simultaneously in 2008 and 2014.

The sample contains firms from the industrial sector (including mining, quarrying, and construction). The firms from the agriculture, hunting and forestry sectors were removed from the sample, since none declared eco-innovations in the two years analysed. To obtain more stable results, and comparable between periods, we also ruled out service companies from the sample (which are not included in the list of sectors deemed to be exposed to a significant risk of carbon leakage). Although services produce two-thirds of the European GPD, they generate only around one-third of greenhouse gas emissions. Finally, the variables on eco-innovation are available only, as is obvious, for firms that have introduced an innovation (whether technological or non-technological). Therefore, to avoid trivial correlations, the analysis focuses on companies that have introduced any type of innovation in each period. These selection criteria resulted in a sample of 17,365 companies for 2008, and 13,313 for 2014. To perform the test of this research, we have merged these two sets into a single database.

One of the limitations of our study is that the CIS does not allow us to identify the companies that participate in the EU ETS. Participation in this market is limited to a group of sectors that are intensive in the emission of gases such as carbon dioxide, nitrous oxide and perfluorocarbons. However, the participation of these sectors within the members of the EU is mandatory, and the objectives of the successive phases of the EU ETS clearly point to a growth in the number of companies involved. On the other hand, although some companies in these sectors could be excluded from the ETS, governments will have to replace this participation through fiscal or other measures that will cut their emissions by an equivalent amount. Finally, companies from other sectors less intensive in the emission of polluting gases will be included in the EU ETS if their emissions exceed a certain volume. Hence, it seems clear that the effects of the EU ETS extend beyond the set of companies that actually participate in the system.[1]

The dependent variable of our analysis is a binary response variable indicating whether the company has introduced low-carbon innovations (more specifically, innovations to reduce the CO_2 footprint). The main explanatory variables are *Time* (2008 = 0; 2014 = 1) and a dummy variable identifying the firms belonging to sectors included in the Carbon leakage list of Directive 2009/29/EC. We also use a set of control variables typically included in the analysis of innovation propensity, and dummy variables to control for country effects. Table A1 in the Appendix presents the main descriptive statistics of the variables included in the study.

3.2. Method

Evaluation research methods have been gaining importance to exploit the impact of policy interventions (e.g., Card and Krueger, 1994; Abadie and Imbens, 2006; Arkhangelsky et al., 2021). Following this background, our empirical strategy is an attempt to mimic an experimental research design using observational data, to obtain the effect of a "treatment" on an outcome variable. The treatment is the European Commission regulation on auctioning for allocation of greenhouse gas emission allowances (EU ETS), and the outcome variable is the propensity of firms to introduce eco-innovations. Our treatment group, *T*, is the set of firms that belong to sectors deemed to be exposed to a significant risk of carbon leakage by Directive 2009/29/EC, and the control group, *C*, is the set of firms from the rest of the industrial sectors. Both groups are subject to the same set of incentives in the initial period (2008). In the second period, the treatment group is affected by a new set of incentives.

To run this test, we depart from previous empirical research (Athey and Imbens, 2006; Doudchenko and Imbens, 2016). We also note that this method has been proven successful in evaluating the impact of environmental policy (e.g., Cai et al., 2016). Following these prior advances, we propose the following difference-in-differences (DID) model:

$$eco_i = \alpha + \beta_1 t_i + \beta_2 cl_i + \beta_3 (t_i \cdot cl_i) + \varepsilon_i \quad (1)$$

where eco_i is the binary response variable indicating if the *i*th firm has introduced a low-carbon innovation. The variables t_i and cl_i are dummy variables indicating the year 2014 and the treatment group (i.e., firms included in the Carbon leakage list), respectively, while α, β_1, β_2 and β_3 are parameters to be estimated by the regression analysis. Finally, ε_i is the error term.

This model allows comparing the innovation propensity in both groups and periods: $T_0 = \alpha + \beta_2$ and $C_0 = \alpha$ are the innovation propensities in the year 2008 for the treated and control groups, respectively, while $T_1 = \alpha + \beta_1 + \beta_2 + \beta_3$ and $C_1 = \alpha + \beta_1$ are these propensities for the period 2014.

Thus, to accept the hypothesis that the effect of the policy introduced

[1] A detailed description of the sectors included in the EU ETS can be consulted in the following link: https://ec.europa.eu/clima/eu-action/eu-emissions-trading-system-eu-ets_en.

in 2014 was an increase in the propensity to introduce eco-innovations of the treated group, we should observe the following inequality, as described:

$$T_1 = \alpha + \beta_1 + \beta_2 + \beta_3 > \alpha + \beta_2 \cdot \left(1 + \frac{\beta_1}{\alpha}\right) = S \quad (2)$$

The left-hand side of (2), T_1, represents the eco-innovation propensity of the treated group after the implementation of the new policy instrument (i.e., 2014), while the right-hand side, S, is that same propensity assuming no effect of the new policy (i.e., the rate of change in eco-innovation propensity is equal in both the control and treated groups). Fig. 2 shows three hypothetical cases: $T_1 > S$, $T_1 < S$, and $T_1 = S$. It is important to note that line $\overline{T_0S}$ shows the case in which the rate of change of the treated group is equal to that of the control group.

Since both groups, treated and control, might have different average profiles from the point of view of their innovative activities, since they differ in certain strategic variables such as R&D intensity, size, among others, we will use the propensity score matching technique in the conformation of the treated and control groups, to avoid the possible bias due to confounding variables. Propensity score matching has been widely used in many contexts to estimate causal treatment effects (e.g., Caliendo and Kopeinig, 2008; Abadie and Imbens, 2016), and it has also been helpful to estimate the impact of environmental policies (List et al., 2003; Xu et al., 2019).

Equation (3) presents the method to select the two comparable samples for treated and control groups.

$$Pr(cl_i = 1) = \gamma + \sum_{k=1}^{K} \delta_k z_{ik} \quad (3)$$

Here z_{ik}, for $k = 1, \ldots, K$, is a vector containing conventional control variables when analysing the innovation propensity, such as size, R&D intensity, collaboration with external partners in innovative projects, public funds, and country effects, while γ and δ_k (for $k = 1, \ldots, K$) are parameters to be estimated by the regression analysis. Table 1 provides the results of the propensity score matching.

The matching adjusts the sample of the treated group, selecting the set of companies that most closely resembles the control group sample. It can be seen that after matching, the differences in characteristic features of the companies (such as the intensity of R&D, the size of the company, the propensity to collaborate in innovation projects and the raising of public funds) of both groups disappear. Thus, we can say that we have two comparable sets, reducing the possibility of bias due to confounding variables.

Robustness can be considered as a major empirical challenge for this study. To this end, robustness tests for the DID model are typically based on pre-treatment trends (Lechner, 2011; Dimick and Ryan, 2014; Slusky, 2017). However, our data do not allow this analysis since at least two periods would be required before treatment when we only have one. For this reason, we will take the path suggested by Gertler et al. (2016), performing an additional DID estimation using a "fake" treatment group, that is, a group not affected by the policy analysed. This procedure is

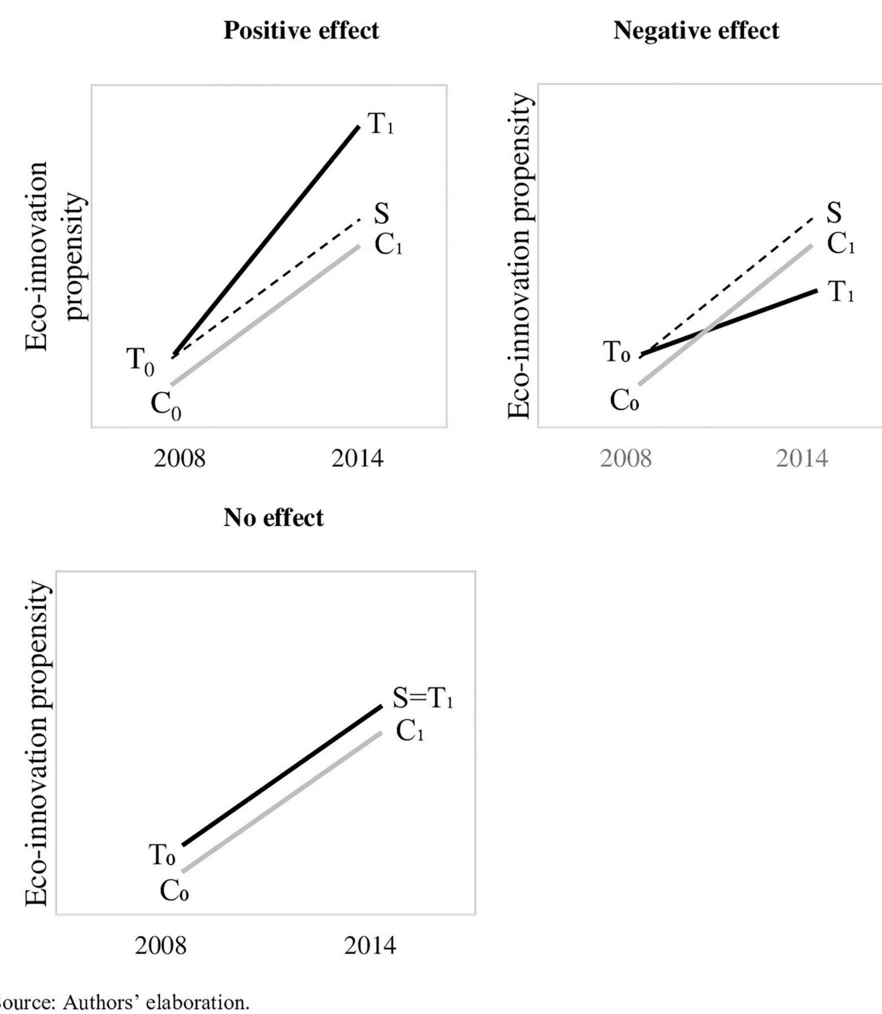

Fig. 2. Testing the impact of environmental policy on eco-innovation
Source: Authors' elaboration.

Table 1
Propensity score matching results.

Variables	Treated group		Control group
	Before matching	After matching	
Carbon leakege risk	1	1	0
Time (2014 = 1)	0,410	0415	0,467
Size (N. log. of sales)	15,1	15,7	15,7
R&D	0,321	0440	0,429
Collaboration	0,244	0320	0,331
Public funds	0,188	0244	0,246
Countries			
Bulgaria	0,221	0045	0,115
Cyprus	0,016	0023	0,016
Czech Republic	0,117	0164	0,152
Germany	0,150	0210	0,228
Estonia	0,058	0081	0,070
Hungary	0,073	0102	0,083
Lithuania	0,023	0026	0,062
Latvia	0,010	0014	0,023
Portugal	0,192	0143	0,121
Romania	0,112	0155	0,086
Slovakia	0,026	0037	0,044
Num. of Obs.	17830	12848	12848

Source: Authors own elaboration with data from CIS-2008 and CIS-2014

also known as the "placebo test" and has been used in previous experimental studies (e.g., Abadie and Gardeazabal, 2003; Abadie et al., 2010; Arkhangelsky et al., 2021).

With the aim of demonstrating the robustness of our method, we proceed to split the sample in three different groups: treatment group, control group, and "fake" treatment group. Unlike the previous step, the last of the groups is not affected by the policy impact analysed. Accordingly, we expect to find a zero impact of the environmental policy by performing a DID estimation using these two groups.

At the same time, we acknowledge the potential existence of an ad hoc partition of the non-treatment group, which may affect the robustness test. Therefore, we wonder whether it is possible to find a partition of the non-treatment group for which the placebo test yields significant differences between the fake and the control group. To analyse this question we resort to the bootstrapping technique (Efron, 1979) by repeating our estimation procedure with one hundred random samples in both the "true" and "placebo" models (i.e., we run our models with one hundred bootstrap different samples). A negative answer to this question will confer robustness to an eventual confirmation of our main research hypothesis.

4. Results

The results are reported in Table 2. As explained in the previous section, these estimated coefficients are used to compare the propensity to introduce low-carbon innovations of treated (T) and control (C) groups, respectively. Model 1 presents the test grouping firms of all sectors included in the Carbon leakage list. Model 2 performs the same test disaggregating this list into six sectors. Models 3–6 show the variety of results among countries, focusing on the four countries with the most considerable sample size.

For ease of exposition, we present these comparisons graphically. Fig. 3 presents the results of Model 1. For the case of the eleven economies analysed, it can be seen that the evidence is consistent with our hypothesis, given the fact that the propensity to introduce low-carbon innovations after the implementation of the new policy instrument (i.e., T_1) is above the level that would have been achieved if there were no impact from the new regulation (i.e., S).

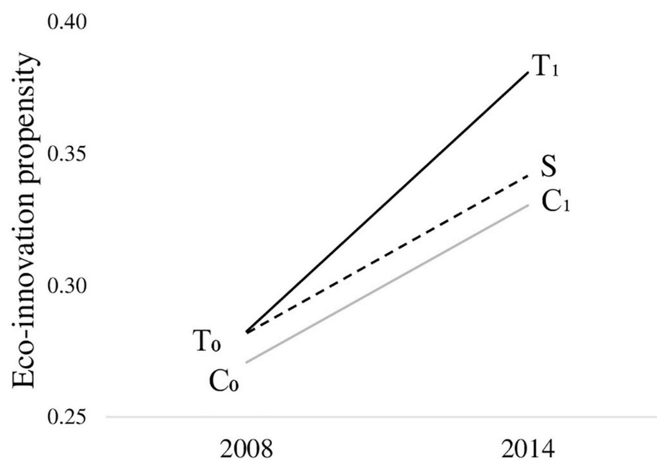

Fig. 3. The effect of EU EST on low-carbon innovation
Source: Authors own elaboration with data from CIS-2008 and CIS-2014.

Table 2
Regression analysis on the effect of the EU EST on low-carbon innovation.

Explanatory variables	Model 1		Model 2 (by industry)		Model 3 (Czechia)		Model 4 (Germany)		Model 5 (Portugal)		Model 6 (Romania)	
	Coef.	Pr > t	Coef.	Pr > t	Coef.	Pr > t	Coef.	Pr > t	Coef.	Pr > t	Coef.	Pr > t
Time	0.060	0.000	0.060	0.000	0.104	0.000	0.006	0.741	0.036	0.146	−0.209	0.000
Carbon leakage risk	0.012	0.126	–	–	0.009	0.654	0.031	0.114	0.006	0.815	−0.017	0.383
Carbon leakage risk (desagregated)												
Mining and quarrying	–	–	0.065	0.033	–	–	–	–	–	–	–	–
Food products, beverages and tobacco products	–	–	0.011	0.397	–	–	–	–	–	–	–	–
Textiles, wearing apparel and leather	–	–	−0.080	0.000	–	–	–	–	–	–	–	–
Wood, paper, printing and reproduction	–	–	−0.014	0.341	–	–	–	–	–	–	–	–
Chemical, pharmaceutical, rubber and plastic	–	–	0.034	0.003	–	–	–	–	–	–	–	–
Basic metals and fabricated metal products	–	–	0.055	0.000	–	–	–	–	–	–	–	–
Interaction with Time												
Carbon leakage risk*Time	0.039	0.001	–	–	−0.011	0.718	0.076	0.004	0.088	0.008	0.076	0.047
Mining and quarrying*time	–	–	0.006	0.911	–	–	–	–	–	–	–	–
Food products, beverages and tobacco products*time	–	–	0.005	0.820	–	–	–	–	–	–	–	–
Textiles, wearing apparel and leather*time	–	–	0.114	0.000	–	–	–	–	–	–	–	–
Wood, paper, printing and reproduction*time	–	–	0.073	0.002	–	–	–	–	–	–	–	–
Chemical, pharmaceutical, rubber and plastic*time	–	–	0.031	0.066	–	–	–	–	–	–	–	–
Basic metals and fabricated metal products*time	–	–	0.003	0.863	–	–	–	–	–	–	–	–
Cons.	0.271	0.000	0.271	0.000	0.268	0.000	0.395	0.000	0.359	0.000	0.323	0.000
Num. of obs.	25,696		25,696		4062		5632		3409		3100	
R-squared	0.0082		0.0111		0.011		0.0085		0.0118		0.025	

Source: Authors' own elaboration with data from CIS-2008 and CIS-2014.

As expected, these changes are not uniform across sectors or countries. According to Fig. 4, we find sectoral differences in the evolution of the propensity to eco-innovate. The sectors of Mining and quarrying, food products, beverages and tobacco products, and basic metals and fabricated metal products (represented by the grey lines) do not show a significantly different evolution compared to other industries not included in the Carbon leakage list. On the contrary, textiles, wearing apparel and leather, wood, paper, printing and reproduction, and chemical, pharmaceutical, rubber and plastic (represented by the grey lines) present a greater slope, something that is consistent with the hypothesis that their propensity to introduce eco-innovations is significantly higher.

We also find substantial differences by analysing whether our research hypothesis displays differences by country. For the sake of homogeneity, we select four countries with the largest data availability. These countries constitute a remarkable example, given that they were either members of the Iron Curtain (the Czech Republic and Romania) or belong to strategic areas of the European Union (Germany and Portugal). In Fig. 5, we can see no significant effect in the case of the Czech Republic, since the evolution of the treated group is not significantly different from its evolution assuming no effect of new regulation (i.e., $T_1 \approx S$).

On the contrary, we do find significant differences in the other three countries analysed. In the case of Germany and Portugal, the innovation propensity grew at a faster rate in the case of the treated group. In the case of Romania, this propensity fell in both groups, but less in the treated group. This difference can be explained due to the theoretical outcomes derived from the innovation systems approach, which recognises that innovation is a result of the interaction between different agents and factors. Consequently, substantial differences in innovational performance between and within countries are reported (Asheim et al., 2016), and eco-innovation is not going to constitute an exception. Concerning the lowest performance exhibited by the Czech Republic, we rely on Blažek and Žížalová (2010). They analyse regional innovation patterns in the Czech Republic and conclude that Prague's innovation system is highly fragmented because of low local networking.

Finally, in Table 3 we present a robustness check performing a "placebo test," following Gertler et al. (2016), as previously explained in the Methods section. It can be seen that, while the true model reproduces the results presented in Model 1 of Table 2, the fake one detects a growing and parallel trend between the fake and the control group. These parallel trends confirm that the non-parallel trends found in the true model are significant. Furthermore, the high *p*-values of the coefficients associated with the carbon leakage variables in the placebo model, which are obtained with the bootstrapping technique, show interesting findings. Indeed, the probability of finding a partition for which the placebo test finds significant differences between the fake and the control group can be considered statistically equal to zero.

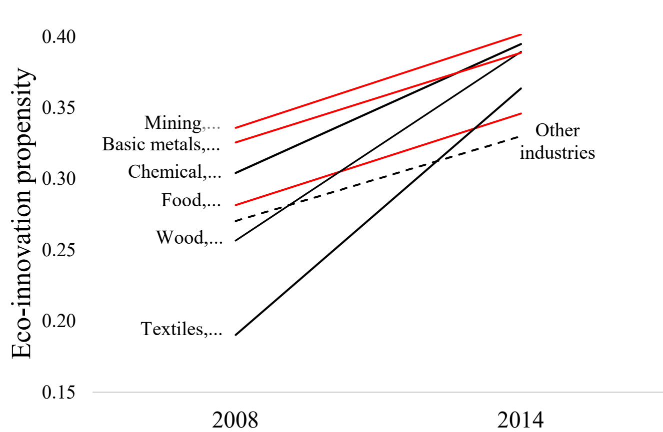

Fig. 4. The effect of EU EST on low-carbon innovation, by industry
Source: Authors own elaboration with data from CIS-2008 and CIS-2014.

5. Conclusions

The contribution of this result to the scientific debate is twofold. On the one hand, our research provides a clear-cut causal interpretation of the estimated effect of the regulatory change. Thus, it reduces the shortage of studies analysing the effect of changes in environmental policy on innovative activity, since most of the work in this area study the link between innovation and certain environmental policies, such as subsidies. However, such analyses have been implemented in a static context, which evaluates the policy impact for a single year and neglects the fact that firms can improve their environmental performance due to a learning process that may take place over time. On the other hand, we note that study of environmental policy impacts on eco-innovation has been scarce and oriented to other territories different from the EUnion. To the best of our knowledge, our research provides the first empirical test of the effect on low-carbon innovation of the most stringent phase of the world's largest emissions market, the EU ETS, Phase III. Although our data only consider the beginning of Phase III, results could be extended to the whole phase, since we are comparing this phase with prior phases I and II, whose distinctive characteristic is the number of free allowances (Silva et al., 2021) and they remain unaltered over time during a whole phase. More specifically, we shed light on how European firms adapt their eco-innovative strategies to regulatory changes in environmental policy, so that we have identified specific mechanisms to differentiate the policy response of firms by activity, country and policy.

According to recent studies, the EU ETS managed to reduce the EU's emissions during the period 2008–2016 (Dechezleprêtre et al., 2018; Bayer and Aklin, 2020). Our results suggest that this performance cannot be considered exclusively an adaptive response to an increase in the cost of greenhouse gas emissions, but also a Schumpeterian creative response to the challenge of achieving greenhouse gas efficiency.

Shedding light on how firms react to specific environmental policy changes may be a subject of further interest for policymakers to study the underlying factors behind firms' attitudes towards greening principles. The EU ETS has placed particular emphasis on increasing environmental stringency to avoid pollution havens and may constitute a significant attempt to induce deglobalisation for European firms. However, due to the current extent and coverage of globalisation, the complexity of the production process has increased and the creation of global production networks involving different countries can be considered as a must. In this context, European firms have experienced a substantial rise in their offshoring activities to reduce their operating costs. To reduce the probability of offshoring, it is imperative to create an ambitious funding scheme. In this context, current initiatives such as Just Transition Mechanism or REPowerEU may constitute a remarkable approach, but they may need to be more committed for European firms to develop cleaner production techniques. Otherwise, there will not be real incentives for European firms to deglobalise.

While this article has fulfilled all the research objectives, it has not been without limitations. The most important limitation is concerning the data, since the CIS is not collected every year, and also impedes the evaluation of innovation propensity by taking into account improvements over time in eco-innovating efforts. In addition, it would also be important to include recent years to capture increasing trends in innovation efforts conducted by firms. This research could be extended in several ways to undertake future research goals: first, one could address whether eco-innovators and general innovators display substantial differences, as in Halila and Rundquist (2011). This analysis could be implemented by means of a causal relation. Second, this analysis could be extended to the subnational level in the European Union, in line with the analysis from Chen et al. (2022) for Chinese cities, so that the geography of innovation has been reported to affect the spatial distribution of activities (e.g., Audretsch and Feldman, 1996). Third, we believe our analysis could be enriched by incorporating results for the current phase

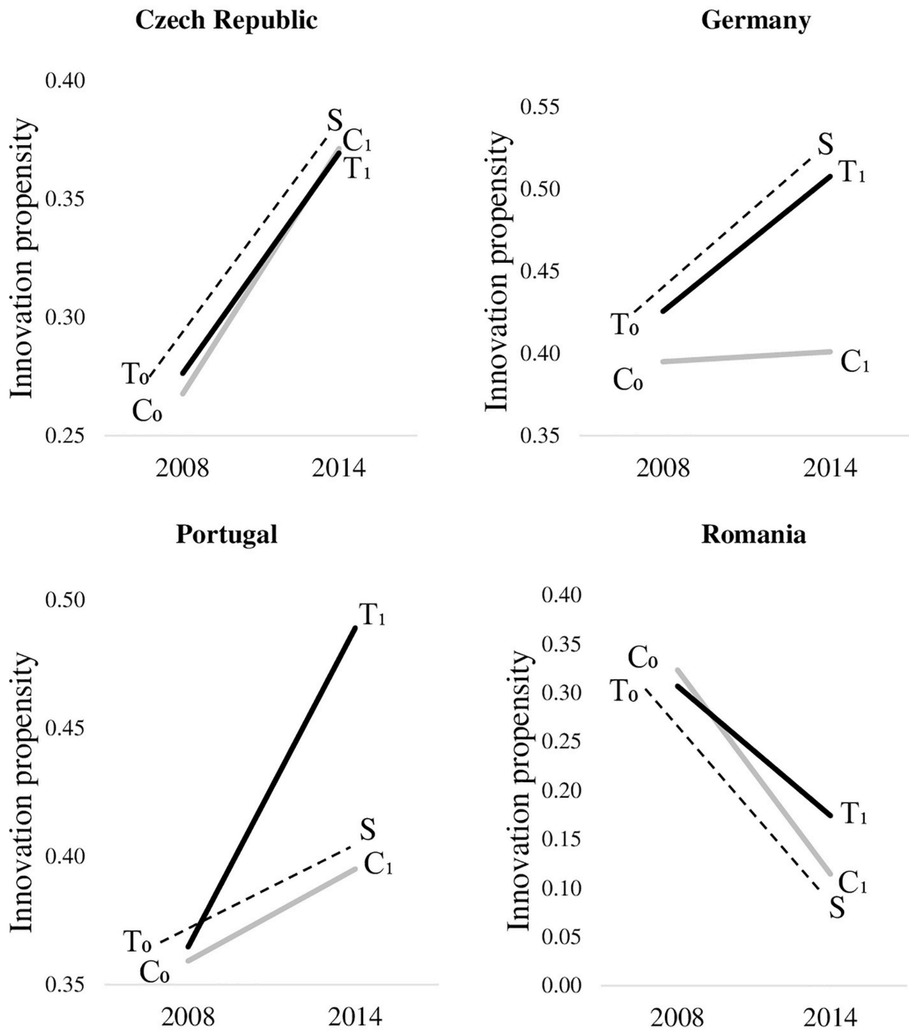

Fig. 5. The effect of EU EST on low-carbon innovation by country
Source: Authors own elaboration with data from CIS-2008 and CIS-2014.

Table 3
Robustness check for differences-in-differences model.

Explanatory variables	True model		Placebo test	
	Coef.	Pr > t	Coef.	Pr > t
Time	0.060	0.000	0.059	0.000
Carbon leakage risk	0.013	0.096	−0.0004	0.970
Carbon leakage risk*Time	0.023	0.047	0.0006	0.969
Cons	0.271	0.000	0.271	0.000
Num. of obs.	12,800		12,800	
R-squared	0.007		0.004	

Source: Authors' own elaboration

4 of the EU ETS as soon as available data exist.

Disclaimer

The authors declare the existence of no compelling conflicts of interest.

CRediT authorship contribution statement

Javier Lucena-Giraldo: Conceptualization, Writing – review & editing, Formal analysis, Writing – original draft, Investigation. **Ernesto Rodríguez-Crespo:** Conceptualization, Writing – review & editing, Formal analysis, Writing – original draft, Investigation. **Juan Carlos Salazar-Elena:** Data curation, Writing – review & editing, Formal analysis, Methodology, Software, Writing – original draft.

Declaration of competing interest

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

Data availability

The authors do not have permission to share data.

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Appendix

Table A1
Descriptive statistics of the sample

Variables	Mean	Std.	Min.	Max.
Low-carbon innovation	0.280	0.003	0	1
Time	0.434	0.003	0	1
Carbon leakage risk	0.581	0.003	0	1
Carbon leakage risk (desagregated)				
Mining and quarrying	0.015	0.001	0	1
Food products, beverages and tobacco products	0.118	0.002	0	1
Textiles, wearing apparel and leather	0.092	0.002	0	1
Wood, paper, printing and reproduction	0.082	0.002	0	1
Chemical, pharmaceutical, rubber and plastic	0.157	0.002	0	1
Basic metals and fabricated metal products	0.117	0.000		
Control variables				
Size (N. log. of sales)	15.366	0.012	0	25.02
R&D	0.366	0.003	0	1
Collaboration	0.281	0.003	0	1
Public funds	0.212	0.002	0	1
Countries				
Bulgaria	0.176	0.002		
Cyprus	0.016	0.001	0	1
Czech Republic	0.132	0.002	0	1
Germany	0.184	0.002	0	1
Estonia	0.063	0.001	0	1
Hungary	0.078	0.002	0	1
Lithuania	0.036	0.001	0	1
Latvia	0.016	0.001	0	1
Portugal	0.163	0.002	0	1
Romania	0.101	0.002	0	1
Slovakia	0.034	0.001	0	1
Num. of firms	30,678	–	–	–

Source: Authors' own elaboration with data from CIS-2008 and CIS-2014.

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