The impact of the EU Emissions Trading System on low-carbon technological change: the empirical evidence

Abstract

This paper reviews the empirical literature analysing the effects of the EU Emissions Trading System (EU ETS) on low-carbon technological change. The emerging evidence is assessed, with references to both relevant economic concepts and the evolving regulation of the EU ETS through the years. The two most robust indications of the literature are: *a)* free allocation (grandfathering) tended to hamper low-carbon investments in Phases I (2005-2007) and II (2008-2012), and *b)* the EU ETS appears to have been more effective in stimulating innovation of low-carbon technologies than their adoption. Importantly, however, a complete general picture of the impact of the EU ETS on low-carbon technological change is missing. The main gap regards the lack of empirical evidence for Phase III (2013-2020). Especially econometric studies are few due to the lack of suitable databases accessible to researchers – a problem that the relevant public authorities are urged to address. Thanks to the recent reforms of the EU ETS, the incentives for innovation and adoption of low-carbon technologies are probably stronger today than ever before.

Keywords: EU ETS, low-carbon technological change, innovation incentives, free allocation, empirical evidence

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1. Introduction

As time ticks away for drastically reducing global greenhouse gas (GHG) emissions, low-carbon technological change is ever more important for meeting future emissions reduction targets and minimising the cost of the effort. The EU, which has been a leader in the fight against climate change for over two decades, is committed to achieving carbon neutrality by 2050 (European Commission, 2018), in line with the Paris Agreement objective to keep the global temperature increase within 2°C from pre-industrial levels. Since its adoption, in 2005, the EU Emissions Trading System (EU ETS) has been the cornerstone of the EU strategy for decarbonising the economy and the flagship of EU climate policy. The EU ETS is thus expected to have a central role in inducing low-carbon technological change as needed. However, whether and how the EU ETS has been playing this role is not obvious, as many are the factors internal and external to the system to consider.

The EU ETS imposes a cap on total emissions of carbon dioxide, nitrous oxide and perfluorocarbons from over 11,000 heavy energy-using and electricity-generating installations and aircrafts, covering about 45% of the EU's overall GHG emissions. The cap, and with it the emissions, decline over time. At the end of the current trading period, which is Phase III (2013-2020), the cap will reach a level 21% below that of 2005 emissions; by 2030, the final year of Phase IV (2021-2030), emissions will have decreased by at least 43% relative to the same year. Simply described, the cap of an emissions trading system (ETS) determines the supply of emission allowances, whereas the demand for emission allowances depends on output and emission intensity levels of regulated entities. The interplay between demand and supply determines the dynamics of the price of emission allowances, a.k.a. the carbon price. In theory, the carbon price established by an ETS guarantees that the cap is met at minimum cost, meaning that the ETS is cost-effective. In practice, there are various reasons (including, e.g., transaction costs, market power, investors' myopia, excessive discounting) for which the carbon price may deviate from the optimal path, in which case the ETS is not cost-effective.[1]

The EU ETS is a sophisticated policy instrument whose regulation has evolved considerably over the years, partly as a result of a learning-by-doing process and partly in response to unanticipated events. In 2009, the first major reform of the EU ETS, with effect from Phase III, made the system significantly more efficient than in Phases I (2005-2007) and II (2008-2012) through both its centralisation and a whole new set of rules for allowance allocation.[2] At the very same time, however, Europe was hit by the most serious economic crisis since the Great Depression, which for the EU ETS meant a sharp decline in the demand for emission allowances. In addition to the fall in production, the supply-demand imbalance in the allowance market was compounded by the inflow of international credits issued under the Kyoto Protocol's Clean Development Mechanism and Joint Implementation, effectively increasing allowance supply, and by effective renewable energy policies carried out by members states, resulting

[1] For a theoretical analysis of how an ETS should be evaluated, see Fuss *et al*. (2018).
[2] For an account of the regulatory changes of the EU ETS through the trading periods, with a focus on allocation rules, see Verde *et al.* (2019).

in further reduced allowance demand. The persistent excess supply, or market surplus, meant that the price of emission allowances stayed low for several years. As the level of carbon prices is the first determinant of low-carbon investment decisions, most analysts would probably agree that low carbon prices have been the main problem faced by the EU ETS since its inception. Steps were taken to address the market surplus. The surplus was first tackled through the withdrawal – originally intended to be temporary ("backloading") – of 900 million allowances and, then, in a structural way with the establishment of the Market Stability Reserve (MSR)[3]. In addition, the reform for Phase IV (European Parliament and Council, 2018) has (among other things) further tightened allowance supply and enhanced financial support for low-carbon investments through dedicated funds.

Given the importance of low-carbon technological change for attaining sustainable economic prosperity and the importance of the EU ETS – still the world's largest ETS in operation – as a policy expected to contribute to that end, empirical analyses examining whether and how the EU ETS has met this expectation are highly valuable. This paper reviews the empirical literature on the subject, assessing its findings and limitations. The review aims to cover all relevant studies published in specialised journals or as complete working papers up until December 2018.

The rest of the paper is organised as follows. Section 2 lays out the theoretical background of the review. Section 3 presents the studies. Section 4 discusses the emerging evidence. Section 5 concludes.

2. Theoretical background

This section recalls a few important concepts for evaluating the impact of an ETS, such as the EU ETS or other similar systems, on low-carbon technological change. We focus on: *a)* the distinction between innovation and adoption of low-carbon technologies as different responses to carbon pricing; *b)* the main properties of an ETS for its ability to spur low-carbon technological change; and *c)* the ways in which free allocation of emission allowances may affect low-carbon technological change.

2.1 Innovation vs adoption

In the wide and diverse literature on technological innovation, the word "innovation" can mean different things. Notably, it may refer to the process of technological change, encompassing the invention of a novel production process or product, its implementation and subsequent diffusion through progressive adoption. Or, it may more narrowly refer to the invention of a novel production process or product. The terminology of innovation is not more univocal in the more specific domain of environmental innovation, which is innovation benefiting the environment. As a matter of fact, different definitions of

[3] The MSR (European Parliament and Council, 2015) is a rule-based mechanism that limits the excess supply and excess demand of emission allowances. By introducing some flexibility in allowance supply, the MSR is intended to mitigate the impacts on the carbon market of macroeconomic shocks and, for that matter, of any unforeseen event or development affecting allowance demand. The MSR has started operating in January 2019. For in-depth analyses of the economics of the MSR, the reader is referred to the dedicated special issue of the Journal of Environmental Economics and Management (Hepburn *et al*., 2016).

"eco-innovation" add to ambiguity (Ekins, 2010). For example, the concept of eco-innovation is sufficiently wide to include adoption of a technology already used by others, which is, therefore, new for the acquiring firm ("new-to-the-firm") but not for the world ("new-to-the-market") (Kemp, 2010; Kemp and Pontoglio, 2011). In this paper, innovation is intended in the narrower sense just specified.[4]

With regard to technological change as a process that can be influenced by economic policy, John Hick's induced innovation hypothesis (IIH) underpins the idea that carbon pricing, whether in the form of carbon taxation or emissions trading, can spur novel low-carbon technologies. The IHH postulates that an increase in the relative price of a production factor spurs inventions aimed at reducing its use (Hicks, 1932). Considering carbon as a production factor, the IIH applies to carbon pricing.[5] Of course, investing in R&D is not the only way in which a firm may respond to carbon pricing. Most of the time, adopting an already existing technology will be the best option for minimising compliance costs.[6] From the policymaker perspective, however, only innovation (and not adoption) expands the technology set (Calel, 2018). This distinction is central in the context of climate change mitigation, as both innovation and diffusion (through adoption) of low-carbon technologies are needed for drastically reducing emissions.

2.2 Key properties of an ETS: stringency and predictability

Johnston *et al.* (2010) analyse the most important characteristics, or properties, of environmental policies for stimulating invention and diffusion of green technologies. By nature, emissions trading meets the highest standards for three of the five characteristics identified by the authors: flexibility, incidence and depth.[7] The same is not true for the other two properties, which are stringency and predictability. Whether or, rather, to what extent an ETS is stringent or predictable, depends on its specific design.

The stringency of an environmental policy refers to the ambition of its (explicit or implicit) target relative to the alternative ("baseline") scenario without the policy. For an ETS, this means how stringent the cap is relative to the total amount of emissions that would be produced if the ETS was not there. Since counterfactual emissions are not observed (they can only be estimated), the price of emission allowances, as an indicator of their scarcity, is a proxy for the stringency of an ETS. In general, the empirical literature clearly supports the hypothesis that a more stringent environmental policy gives economic agents stronger incentives to search for ways to avoid compliance costs, thereby promoting technological change (Barbieri *et al*., 2016).

[4] Jaffe *et al*. (2003) provide a thorough analysis of the literature on environmental innovation produced until then. For a comprehensive review of the empirical literature on environmental policy and innovation published during the past decade, see Popp (2019).
[5] The applicability of the IIH is general, beyond market-based policies and the environmental policy domain.
[6] The outcomes of R&D investments are generally highly uncertain (Scherer and Harhoff, 2000).
[7] "Flexibility" refers to whether the policy encourages novel solutions for reducing the pollutant; "incidence" refers to how closely the policy targets the pollutant; and "depth" refers to whether the policy provides continuous incentives to develop technologies ever more effective in reducing the pollutant.

The predictability of an environmental policy refers to the level of (un)certainty with which economic agents can expect the policy and its effects to unfold in the future. As technological change involves investment decisions, uncertainty can hamper technological change by affecting investors' expectations. Different types of uncertainty exist, however, with potentially different implications for technological change. With specific reference to an ETS, Hoffman *et al.* (2008) provide a taxonomy for different types of uncertainty. The authors first distinguish between regulatory and regulation-induced uncertainty. Regulatory uncertainty concerns: *a)* the basic direction of the ETS (related to, *e.g.*, future emissions reduction targets, the scope of the system, changes in international climate policy) and its very existence; *b)* the rules for allowance allocation; *c)* the implementation process (*e.g.*, allocation delays); and *d)* the interdependence with other policies. Regulation-induced uncertainty, by contrast, regards the state of the non-regulatory environment. For example, it can be uncertainty about competitors' strategies in the face of regulatory uncertainty or about the price of emission allowances. While regulatory uncertainty is considered detrimental to technological change, the same does not necessarily apply to regulation-induced uncertainty.

2.3 Free allocation and technological change

In an ETS, the emission allowances can be distributed to the regulated entities *a)* for free, in the form of grandfathering, benchmarking or output-based allocation, *b)* through auctions, or *c)* a mix of these methods.[8] Minimising the risk of causing market share losses to the advantage of foreign competitors and, thereby, minimising the risk of carbon leakage[9], is the economic rationale for using free allocation.

Among the most debated questions on the economics of emissions trading are whether grandfathering leads to output and emissions levels different from those achieved under auctioning (or a carbon tax) and, related, whether it alters the impact of the policy on technological change by affecting investment decisions. The standard answer is that the initial allocation makes no difference in these respects (Montgomery, 1972; Hahn and Stavins, 2011; Requate and Unold, 2003). This conclusion, however, rests on several assumptions about markets' structure and firms' behaviour. Among others, a key assumption is that firms fully value the opportunity cost of using free allowances for compliance[10] in the same exact way as if it was a real cost. Increasingly, this assumption has been questioned in light

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[8] With grandfathering, allowances are allocated in proportion to historical emissions. With benchmarking, allowances are allocated according to performance indicators. In practice, allocations are determined by multiplying the benchmarks (expressed in terms of emissions per unit of output) by recent output levels. With output-based allocation, allowances are allocated in proportion to current production levels.

[9] The displacement of GHG emissions due to differences in the stringency of climate mitigation policies is called carbon leakage. There are three main channels through which unilateral climate policy can result in carbon leakage: the trade balance (short-term impact), foreign direct investments (long-term impact) and changes in international fossil fuel prices. Deterioration of international competitiveness due to climate policy activates the first two channels. The third channel, by contrast, can come into play if the region strengthening its climate policy makes up a significant share of global fossil fuels demand.

[10] Since they have market value, using (preallocated) allowances for compliance carries an opportunity cost equal to the revenue that would be earned if (the corresponding emissions were avoided and) the allowances were sold.

of insights from behavioural economics, pointing to a negative impact of free allocation on low-carbon technological change (Venmans, 2016).[11] The same question applies to benchmarked allocation. The very purpose of benchmarking, however, is to promote low-carbon technological change by rewarding early movers investing in low-carbon technologies (Zipperer *et al*., 2017).

The literature identifies at least three other ways in which free allocation may alter the impact of an ETS on low-carbon technological change. One is the case of so-called new-entrant provisions, whereby a new plant entering the system is entitled to an allowance endowment for the duration of the trading period. The rationale for such arrangement – present in the EU ETS, not in other ETSs – is not to put new entrants at a disadvantage relative to the incumbents. However, the endowment could potentially change the relative convenience of alternative investments, thus affecting the investment decision. Unless allocations are determined on a fuel-neutral basis, allowance endowments to new entrants introduce a bias in favour of more emission-intensive investments (Åhman *et al*., 2007; Ellerman, 2008; Flues and van Dender, 2017). The second case is the situation where innovation or adoption of a low-carbon technology, by a firm holding a significant share of the allowance market, would result in a reduction of the allowance price (Fisher *et al.*, 2003). In this case – unlikely in the EU ETS given the low concentration of the allowance market –, free allocation may hamper low-carbon technological change because the price drop would reduce the value of the allowances hold by the firm and, hence, the convenience of the investment. The third case – not applicable to the EU ETS so far – refers to output-based allocation. In contrast to the previous cases, here low-carbon technological change may be strengthened as a result of greater production (output-based allocation effectively subsidises production) and higher allowance prices (Rosendahl and Storrøsten, 2015).

3. The empirical evidence

There are several empirical studies examining the effects of the EU ETS on firms' innovation or adoption of low-carbon technologies. Our search led to the identification of 22 such works, which here are first divided into two broad groups: the studies using econometrics (7) and those providing qualitative or descriptive analyses (15). In addition to this literature, five econometric studies provide evidence on the effects of the EU ETS on emission intensity of regulated manufacturing firms. Though not focused on technological change, these studies are potentially relevant in that variations in emission intensity may reflect changes in the technologies used.

The literature review below varies in format. In Section 3.1, the econometric studies focused on low-carbon technological change are described in detail, one-by-one. The literature providing evidence on emission intensity is summarised in the same section, but in a more concise way. In Section 3.2, the non-econometric studies are combined together in a single narrative.

[11] With reference to the EU ETS, Ellerman (2015) includes opportunity costs among the issues yet to be analysed seriously.

3.1 Econometric literature

3.1.1 Effects on low-carbon technological change

Calel and Dechezleprêtre (2016) estimate the impact of the EU ETS on low-carbon patenting. It is a study that stands out in the literature for at least four reasons. First, patent counts, while not without shortcomings,[12] are generally considered one of the most appropriate innovation indicators (Hagedoorn and Cloodt, 2003). Second, the firms in the estimation sample operate as many as 80% of all EU ETS installations. Third, the approach used, namely difference-in-differences (DiD), offers a clear-cut causal interpretation of the estimated effect.[13] Fourth, the authors find that the EU ETS was effective in spurring low-carbon technology innovation, more so than other studies show or suggest: it is estimated that the EU ETS caused an increase of up to 36% in the number of low-carbon patents granted to regulated firms, over 2005-2009. Other relevant results are: *a)* that no evidence of an indirect innovation effect on non-regulated firms is found; and *b)* that the surge in the total number of low-carbon patents observed over the study period was primarily driven by rising energy prices.

Martin *et al.* (2013) is a second important econometric study investigating the determinants of low-carbon innovation, here measured by any R&D activity aimed at curbing emissions or energy consumption or at developing products that can help customers reduce their emissions. It uses primary data from interviews conducted in 2009 with the managers of 770 manufacturing firms in six European countries. The study finds several interesting results. First, the responses indicate that most firms engaged in climate-related innovation, and that this effort was focused on process innovation rather than product innovation. Crucially, however, no statistically significant difference is found between firms regulated by the EU ETS and non-regulated ones. Second, significant differences in the propensity to innovate were found across sectors and countries. Third, low-carbon innovation is positively associated with firms' expectations about the stringency of their future allocation. Fourth, firms positioned just below the sectoral thresholds for receiving free allowances in Phase III[14] engaged more strongly in low-carbon innovation. This last result is presented as evidence of free allocation having a causal negative effect on low-carbon innovation.

Schmidt *et al.* (2012a) analyse the effects of the EU ETS and long-term emission reduction targets, as they are perceived (rather than as they are according to objective metrics), on both investments in technology adoption and in R&D. The study is based on interviews with managers of 65 electricity-producing firms and 136 firms providing technology for electricity generation, in seven European

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[12] Not all innovations are patented, not all patented innovations are eventually adopted.

[13] Typically, in the studies using the DiD approach, regulated firms are first paired through statistical matching with similar non-regulated counterparts. The model for the variable of interest is then fitted, including a binary regressor indicating whether the firm participates in the EU ETS. The coefficient of this variable measures the effect of the EU ETS. For a technical overview of this and similar methods for policy evaluation, see Imbens and Wooldridge (2009).

[14] The thresholds in question are based on sectoral trade and carbon intensities.

countries. The effects are measured by the respondents' answers to the questions about the intensity and the direction of innovation investments between two periods: 2000-2004 and 2005-2009. Among other results, the authors find evidence that not only did grandfathering of emission allowances hamper adoption of low-carbon technologies, but – as anticipated – new-entrant provisions promoted adoption of emitting technologies. A second important result is that long-term emission reduction targets are a powerful R&D trigger.

Focusing on Sweden and again using the DiD approach, Lofgren *et al.* (2014) test for whether participation in the EU ETS stimulated investment in low-carbon technologies. The estimation sample comprises some 706 Swedish firms, of which 229 are in the EU ETS, from all regulated sectors, plus five control non-regulated sectors: the study covers the years 2000 to 2008. Conducting separate but similar analyses for investment below and over €1 million (in a year), respectively, different logit model specifications are estimated, with the outcome of interest being the probability of low-carbon investment. The main result is that statistically significant effects of the EU ETS are not found, either for small or for large investments[15]. Though limited to Swedish firms, the study also reports some insightful descriptive statistics on low-carbon investment within and outside the EU ETS sector[16].

[TABLE 1]

Borghesi *et al.* (2015a) investigate whether the EU ETS affected the likelihood of climate-related investment (distinguishing between energy efficiency and emissions reduction as objectives) undertaken by Italian manufacturing firms, 2006-2008. Firm-level probit models are estimated, using Eurostat's Community Innovation Survey as the primary data source. Several explanatory variables are considered: some internal to the firm, some external to the firm (still, firm-specific) and policy factors. The effects of the EU ETS are specifically captured: *a)* by a dummy variable identifying regulated sectors; and *b)* (in regressions limited to observations of regulated sectors) by a stringency indicator given by the ratio of sectoral emissions to allocated allowances.[17] As expected, firms in regulated sectors are more likely to make climate-related investments.[18] The allocation stringency indicator, however, turns out to be negatively correlated with innovation. The authors suggest that this result may

[15] Considering the frequency of investment decisions, the analysis would have probably benefited in a significant way from longer time coverage.
[16] For example, over the period 2002-2008, out of 229 regulated firms, 70 (i.e., almost a third) made some low-carbon investment, 40 of which invested more than €1 million in a given year. With reference to the same firms, 46% of the large investments were in biofuels, 25% in district heating and 22% in energy efficiency; by contrast, over half of the small investments were in energy efficiency. The pulp and paper industry and the energy and heating sector had the highest shares of investors. Moreover, for regulated firms, fuel use was higher among investors compared to non-investors; the converse is true for non-regulated firms.
[17] Four regulated manufacturing sectors are analysed: coke and refining; ceramic and cement; paper and cardboard; and metallurgy.
[18] In the study, firms' participation in the EU ETS is defined at the sectoral level, however. This implies some measurement error, since not all firms in a regulated sector fall under the EU ETS.

be related to one or more of the following: firms' anticipatory behaviour; sectoral idiosyncratic factors as well as reverse causality between allocation and innovation. Yet, further investigation is not undertaken due to data limitations.

Focusing on firms in the UK, Calel (2018) estimates the effects of the EU ETS on three outcomes: low-carbon patenting, low-carbon R&D expenditure and emission intensity. The estimation sample, assembled by linking administrative data with business surveys and regulatory records, comprises about 400 regulated firms and about as many non-regulated matches (*i.e.*, non-regulated firms, very similar before the start of regulation), over the period 2000-2012. By comparing regulated firms after falling under the EU ETS and the respective non-regulated ones, the author infers that the EU ETS caused an average increase of low-carbon patents of about 25%. An effect similar in size is found for low-carbon R&D expenditure. By contrast, for emission intensity, no statistically significant difference between regulated and non-regulated firms is found. The results are interpreted as indicating that – contrary to what one may expect, based on past experiences with other ETSs – the EU ETS has been effective in spurring innovation of low-carbon technologies but not their diffusion, as this would have been reflected (had it taken place) in emission intensity improvements.

Compared to the studies above, Bel and Joseph (2018) address a partially different question, as they focus on the effect of allowance overallocation. The authors test for whether country-level oversupply of free allowances, as measured by allocated allowances exceeding verified emissions, had a negative effect on the number of filed low-carbon patents. Data for 28 countries are used, covering the period 2005-2012. Some interesting descriptive statistics are reported on the country distribution of low-carbon patents, showing Germany to be clearly the innovation leader in Europe. Country-level panel data models are then fitted for annual filed patent counts, explained by (lagged) allowance oversupply and a number of sectoral and economy-wide control variables (*e.g.*, GDP, sectoral activity indices, R&D spending, number of employees in the service sector, share of renewable energy). In all model specifications, allowance oversupply turns out to be negatively correlated with the number of patents.

3.1.2 Effects on emission intensity

Several econometric studies provide evidence on the effects of the EU ETS on firms' emission intensity. We focus on those dealing with manufacturing firms, as opposed to electricity producers, because variations in emission intensity of the former are more likely to reflect technology changes rather than fuel switching.[19] This literature is homogeneous in multiple ways. Firstly, the results on emission intensity, usually measured by emissions divided by output or by employment, accompany findings on other effects of the EU ETS on firms' economic and environmental performance. More important, the

[19] The empirical studies focusing on electricity generation highlight the effectiveness of the EU ETS in reducing emissions through fuel switching (from coal to gas). See, e.g., McGuinness and Ellerman (2008), Delarue *et al.* (2008) and Berghmans *et al.* (2014).

approach typically involves quasi-experiments under the DiD framework, where the average effect of the EU ETS is inferred by comparing the outcome of interest for regulated firms or plants and for similar non-regulated entities. Further, as is true for all other works reviewed in this paper, these studies too are limited to Phase I or Phase II. The most salient element of differentiation is the country for which the analysis is conducted. A summary of the results of this literature follows.

Focusing on Germany, Petrick and Wagner (2014) estimate that the EU ETS reduced emission intensity of regulated manufacturing plants by 18% and 20% in Phase I and in the first half of Phase II, respectively. Further investigations indicate that these changes in emission intensity are mainly explained by optimisation of onsite heat generation and fuel switching. Thus, no evidence is found of significant technological upgrades. In a similar application to French manufacturing plants, Wagner *et al.* (2014) find a reduction of emission intensity by 8-12%, again in the first three years of Phase II (not before). The effect vanishes, however, when the analysis is replicated at the firm level. Nil or very modest effects are found by other studies. Looking at regulated firms in Lithuania, Jaraite and Di Maria (2016) identify only a slight decrease in emission intensity for the year 2007 (not for 2006 or 2005), which appears to be mainly explained by the retirement of old physical assets. Klemetsen *et al.* (2016) find no statistically significant effects of the EU ETS on emissions intensity of regulated manufacturing plants in Norway, nor does Calel (2018) (as already said) for regulated firms in the UK.

3.2 Non-econometric literature

About two thirds of the studies dealing with the effects of the EU ETS on low-carbon technological change provide qualitative or descriptive analyses. We found 15 such works, of which 12 are based on primary information collected by the authors through ad-hoc interviews, typically with managers of regulated firms. These studies tend to be country- and sector-specific. Five of them focus on the electricity sector, five on the paper sector and one on the chemicals sector. The remaining four cover multiple sectors. Some of them are sufficiently narrow in scope to qualify as case studies.

Below, we first summarise the evidence from the studies exclusively looking at the electricity sector. We then turn to those analysing other sectors.

3.2.1 Electricity sector

Compared to other sectors, the impact of the EU ETS on technological change in the electricity sector has received more attention. There are multiple reasons for this: *a)* the electricity sector is by far the largest regulated sector, both in terms of emissions and number of installations; *b)* the electricity sector is expected to be fully decarbonised before any other major sector; *c)* certainly in the first years of the EU ETS, deployment of carbon capture and storage (CCS) for fossil fuel electricity generation was the main technology option in the EU's decarbonisation strategy; and *d)* the rules for free allocation in Phases I and II had particularly important implications for investment decisions concerning power plants. The most common research questions indeed relate to the consequences of specific allocation rules for new and closing installations and to the different factors influencing CCS deployment.

The literature highlights the perverse incentives associated with the free allocation provisions for new installations entering the EU ETS.[20] With reference to the first two trading periods, it is shown that new-entrant provisions (see Section 2.3) influenced investment decisions about the type of new plants to build. The emission allowances granted to new installations improved the economic attractiveness of investments in carbon-intensive electricity generation, notably coal-fired plants (Rogge *et al.*, 2011b). Most important, these perverse incentives vanished as of Phase III, as electricity producers (with the exception of those in lower-income member states) ceased to receive free allowances. In fact, already before the start of Phase III,[21] the expectation of auctioning is shown to have led to the cancellation of some planned investments in coal-fired power plants (Hervé-Mignucci, 2011).

The literature also clearly documents the initial interest in R&D activities related to CCS. However, this interest did not eventually translate into actual CCS deployment for various reasons, notably the low level of carbon prices but in some instances also social acceptability problems encountered at the local level (Hoffman, 2007; Rogge and Hoffmann, 2010; Rogge *et al.*, 2011b).[22] In general, the expectation of sufficiently high carbon prices in the future and regulatory predictability are the elements that seem to matter most for R&D decisions.

Overall, the impact of the EU ETS on low-carbon technological change in the electricity sector, during the first two trading periods, appears to have been moderate. Most often, what impact there was came in the form of small-scale investments with short amortisation times (*e.g*., three to five years) improving the efficiency of existing conventional plants (Hoffmann, 2007). Table 2 summarises the main features and the main results of this literature.

[TABLE 2]

3.2.2 Other sectors

Considering the large number of sectors covered by the EU ETS and the limited size of the literature at hand (summarised in Table 3), the pulp and paper sector has received a remarkable amount of attention. The five non-econometric studies that specifically look at this sector are concordant in concluding that the EU ETS only had a modest effect, if any, in driving low-carbon technological change. Carbon prices were too low and allocations of free allowances too generous to affect investment decisions. A second common conclusion is that other market factors, notably the cost of raw materials and especially energy

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[20] New-entrant and closure provisions characterise the EU ETS. Previous cap-and-trade schemes did not foresee such provisions (see, e.g., Ellerman *et al*., 2010).

[21] The new allocation rules for Phases III were set out by the second ETS Directive, in 2009: over three years before their entry into force. Thus, there was time for investor expectations and investment decisions to adapt to the new allocation regime.

[22] For a more in-depth discussion of why so far CCS projects have not been successful, see Ahman *et al.* (2018).

costs, were far more important factors in investment decisions. Gulbrandsen and Stenqvist (2013) document a case study of two Nordic pulp and paper companies that, because of the effect of the EU ETS on wholesale electricity prices, show greater interest in investing in own electricity generation. According to Pontoglio (2008) and Gasbarro *et al*. (2013) relevant investments mainly consisted in the adoption of existing technologies for improving core process efficiency. Evidence consistent with the limited effect that the EU ETS seems to have had on technological change in the pulp and paper sector is provided by Fontini and Pavan (2014). Performing an index decomposition of the sectoral emission trends in Italy with 173 Italian plants, the authors show that technological change was never a relevant contributor to emission reductions. For Phase I, a compositional effect is found, whereby emissions slightly declined thanks to a shift toward less carbon-intensive types of paper products. For the second trading period, the reduction in emissions was explained by lower output – the effect of the economic crisis.

[TABLE 3]

The other non-econometric studies bring additional evidence that is largely consistent with the results discussed so far. Using information on production costs from four Portuguese companies in the chemicals sector, Tomas *et al*. (2010) show that the EU ETS did not significantly change production costs (thus providing no investment incentives), partly because – the authors argue – the allowances were grandfathered. Based on interviews with managers from the ceramics, lime and cement sectors, in Belgium, Venmans (2016) concludes that *a)* uncertainty about very low or very high carbon prices in the future and *b)* allowance overallocation were the main factors hindering low-carbon investments. Based on interviews with representatives of different industries in eight European countries, Borghesi *et al*. (2015b) investigate whether and how policies and market factors affected eco-innovation. The EU ETS turns out to have had a relatively more significant role in the electricity sector than in manufacturing sectors, inducing fuel switching and CCS-related activities. Based on questionnaires administered to regulated firms in Ireland, Anderson *et al.* (2010) find that significant low-carbon technological change occurred during Phase I. Substantial shares of the respondents stated that they had undertaken some technology changes as well as fuel switching and behavioural change. However, it is unclear to what extent these were effects of the EU ETS. Finally, Petsonk and Cozijnsen (2007) document a few cases of firms in the agricultural sector benefitting from different process innovations brought about by the EU ETS.

4. Discussion

Some important indications emerge from the literature presented. We focus on: *a)* the effects of the EU ETS on innovation and on adoption of low-carbon technologies, and *b)* the effect of free allocation on low-carbon technological change. But, first of all, let us consider the limitations of the literature.

4.1 The general picture is incomplete

The empirical literature on the effects of the EU ETS on innovation and adoption of low-carbon technologies is significant in size and, taken together, offers some robust results. Nevertheless, it falls short of providing a complete picture of the impact of the EU ETS on low-carbon technological change. The main gap regards the lack of empirical evidence for the last six years or so, as none of the studies identified comes up to cover even the beginning of Phase III. This delay of empirical results is particularly unfortunate because major changes in the rules for allowance allocation, potentially affecting firms' investment decisions, came into operation in the third trading period. These changes, introduced by the second ETS Directive (European Parliament and Council, 2009), include: *a)* the switch from grandfathering to auctioning as default allocation method for the electricity sector, *b)* benchmarked allocation for all other sectors, plus *c)* progressive shrinking of free allocation (from 80% in 2013 to 30% in 2020) for those identified as at risk of carbon leakage. These regulatory changes point to a potentially stronger impact of the EU ETS on low-carbon technological change during Phase III – plausible given the evidence on the effects of free allocation in the previous trading periods (see below). On the other hand, again relative to Phases I and II, allowance prices have been lower most of the time, suggesting a weaker effect on low-carbon investments (Figure 1).

[FIGURE 1]

It is thus difficult to guess whether, in the period for which empirical evidence is missing, the EU ETS has had a greater or smaller impact on low-carbon technological change than it did in previous years. In this sense, the current situation is easier to interpret. The combination of Phase III allocation rules and – now – substantial carbon prices, which have much increased since the Reform for Phase IV was agreed, suggests that the incentives for innovation and adoption of low-carbon technologies are probably stronger today than ever before.

Other limitations of the literature are related to the small number of econometric studies and of sector-specific findings. The small number of econometric studies implies that there are few empirical results with statistical relevance, which is what allows drawing conclusions with some general validity. For this reason, econometric studies are usually of special interest and, consistent with this view, our summary of the econometric literature is more detailed than that of the non-econometric literature. This is not to say that econometric studies are superior to non-econometric ones in all respects. The second can offer important insights on, for example, agents' behaviour or specific situations, that the first are not able to capture through regression analysis. The scarcity of databases that are both suitable, meaning sufficiently large and with sufficiently detailed information on firms' investments, and usable or easily accessible for research purposes, is the main reason for the paucity of econometric works in this field.

The small number of sector-specific findings implies that the existing evidence is not very granular at the sector level. Most results, especially those of econometric applications, as they require sufficiently numerous observations for parameter identification, refer to aggregates of heterogeneous sectors. This is the case of estimated average effects for the regulated manufacturing sector, which in the given application may comprise several diverse subsectors, such as cement, steel, paper, glass, etc. With the exceptions of the electricity sector and of the pulp and paper sector, sector-specific evidence for the others is very limited or missing. This is a limitation of the literature, especially because sector-specific evidence can be useful for informing policy adjustments.

4.2 More innovation than adoption

Despite said limitations, the literature examined seems to give a rather clear indication on how the EU ETS has affected low-carbon technological change. Namely, so far the EU ETS appears to have been more effective in stimulating innovation of low-carbon technologies rather than their adoption. To our knowledge, Calel (2018) is the first to have pointed out this type of asymmetry. However, other studies shedding light on investments made by regulated firms, in response to the EU ETS, warn us against exaggerating Calel's interpretation.

Focusing on the econometric literature previously reviewed, Table 4 compares the direction of estimated effects on innovation and on adoption of low-carbon technologies.

[TABLE 4]

In two out of three applications relevant to technology adoption, the effect of the EU ETS on investment in existing low-carbon technologies is not statistically significant.[23] Borghesi *et al*. (2015a) find a positive effect, though it might be potentially affected by measurement error (see footnote 18). The situation is reversed for the effects on innovation. In four out of five applications with low-carbon R&D expenditure or low-carbon patent count as dependent variable, the effect of the EU ETS is positive and substantial in magnitude, especially for patenting.

This simple comparison of a handful of econometric results lends support to the hypothesis of an asymmetry between innovation and adoption effects. Moreover, as we have seen (Section 3.1.2), the few studies investigating how emission intensity improvements in manufacturing sectors were achieved do point to optimisation of energy use and fuel switching rather than technology changes. Nevertheless, the evidence of other closely related econometric literature indicates that dismissing the role of the EU ETS in pushing the diffusion of low carbon technologies would not be justified. Several studies find that the EU ETS had causal positive effects on tangible assets of regulated firms (aus dem Moore *et al*.,

[23] In our "innovation vs adoption" comparison, emission intensity improvements are not considered because they may not exclusively reflect adoption of low-carbon technologies. This does not alter the conclusion about the observed asymmetry between innovation and adoption effects.

2019; Dechezleprêtre *et al*., 2018; Löschel *et al*., 2018; Marin *et al*., 2018; Colmer *et al*., 2018; Jaraite and Di Maria, 2016). These recurring results suggest that the EU ETS, to some extent, induced adoption of low-carbon technologies.

4.3 Free allocation: a brake on low-carbon technological change

The effect of free allocation on technological change is a second important question, on which the literature examined gives an even clearer indication. Namely, free allocation (grandfathering) tended to hamper low-carbon technological change in Phases I and II. The most general explanation is that regulated firms undervalue the opportunity cost of using their own free allowances as compared to the real cost of purchasing allowances on the market. As a result, through both operational and investment decisions, they end up abating fewer emissions than they would if they had fewer or no free allowances.[24] A more specific mechanism whereby free allocation affected low-carbon technological change is that related to new-entrant provisions. The effect was salient in the electricity sector because, despite coal and gas can be close fuel substitutes, allowance allocations for new installations were determined based on emissions rather than output (KWh).

While evidence on how free allocation affected technological change is rather clear, the caveat that this result refers to the first two trading period could not be overemphasised. Both the rules for free allocation and the volume of free allocation have changed drastically with Phase III. Notably: *a)* auctioning has become the default allocation method for the electricity sector (thus solving the issue of new-entrant provisions in that sector); *b)* while 95% and 90% of all allowances were allocated for free in Phases I and II, respectively, the same share has dropped to about 57% (due to auctioning in the electricity sector and increasingly limited free allocation for the sectors not at risk of carbon leakage); *c)* the volume of free allowances has also shrunk due to the EU ETS cap declining over time; and *d)* benchmarked allocation has replaced grandfathering, introducing a potentially important incentive for undertaking technology upgrades.

In general, no definitive judgement on free allocation should be passed without considering the costs that may have been avoided thanks to free allocation. That is, one should consider how free allocation performed with respect to its own purpose, which is minimising the risk of carbon leakage. The relevant literature indicates that, certainly in the first two trading periods, the EU ETS had no significant negative effects on the competitiveness of regulated firms (Verde, 2018). On the other hand, while free allocation was sufficiently generous to prevent negative competitiveness effects, it enabled regulated firms (with differences from sector to sector) to gain substantial windfall profits – which is controversial for distributional reasons. However, while today it is safe to assume that there were margins for reducing free allocation in Phases I and II without negative consequences for

[24] For an analysis of the different ways in which the perception of free allowance allocations may lead to different investment decisions, the reader is referred to Venmans (2016).

competitiveness (Martin *et al*., 2014), the same judgment cannot be extended automatically to Phase III.

5. Concluding remarks

The review of the empirical literature on the effects of the EU ETS on low-carbon technological change has highlighted a few relatively robust findings as well as limitations of the same evidence. Concerning the findings, we have stressed: *a)* the negative effect of free allocation on low-carbon investments, in the first two trading periods, and *b)* the apparent stronger effect of the EU ETS on low-carbon innovation than on adoption. As of Phase III, both extensive auctioning and benchmarked allocation have strengthened the incentives for low-carbon investments. However, probably, the benefits of the new allocation regime were more than offset by very low allowance prices during most of Phase III. Recently, the establishment of the MSR mechanism and the Reform for Phase IV have addressed the problem of excessively low prices: the Reform by tightening the cap further, the MSR by (eventually) keeping allowance supply-demand imbalances within given boundaries. Though criticised by some for not being timely, the regulatory response has proved effective considering the evolution of allowance prices since early 2018.[25]

Current and prospective allowance prices combined with progressively shrinking free allocation (due to the cap declining over time) call for enhanced financial support to low-carbon investments. Carbon pricing is gradually spreading around the world (World Bank and Ecofys, 2018), but the achievement of a de facto global carbon price (whether through cooperative processes or controversial border adjustments) is not guaranteed or close in time. Support to low-carbon investments, towards both innovation and adoption, is thus an increasingly important lever to counter competitiveness deterioration (by reducing emission intensity) and mitigate carbon leakage risk.[26] Introduced as part of the Reform for Phase IV, the Innovation Fund and the Modernisation Fund promise to be useful tools in this sense. With reference to the Innovation Fund, many were the lessons learnt from the difficulties incurred with its predecessor NER300 (Åhman *et al*., 2018; European Commission, 2015, 2019), plus its size is expected to be almost five times as big, namely about €10 billion, compared to €2.1 billion.

As to the limitations highlighted by the literature review, the small number of econometric studies and the lack of results for the last few years have been stressed. At the root of the shortage of econometric studies is the scarcity of firm-level databases both suitable in terms of information content and accessible to researchers. Badly needed are firm-level data on climate-related investments, enabling analyses of the diffusion of low-carbon technologies in the economy. Ideal databases would contain

[25] Still, carbon prices currently prevailing in the EU ETS remain below the lower bound of the price range recommended by the High-Level Commission on Carbon Prices (2017), for 2020, to meet the 2°C objective of the Paris Agreement (US$40-80/t$CO_2$).

[26] In presence of international spillovers, not only can low-carbon innovation mitigate carbon leakage risk, but it could also result in negative carbon leakage, that is, lower emissions overseas (Fischer, 2015; Gerlagh and Kuik, 2014).

longitudinal data for both regulated and non-regulated firms, as this would facilitate econometric analyses identifying causal relationships. Administrative data and business surveys maintained by national statistical authorities already generate, or could generate, databases with such features. However, often access to these data for research purposes is not allowed or is heavily restricted for confidentiality reasons. Given the ever increasing importance of low-carbon technological change for society and, therefore, of monitoring whether and how the EU ETS or other policies affect it, the EU and MS relevant authorities are urged to improve said data and, while ensuring confidentiality as needed, make them usable for research purposes.

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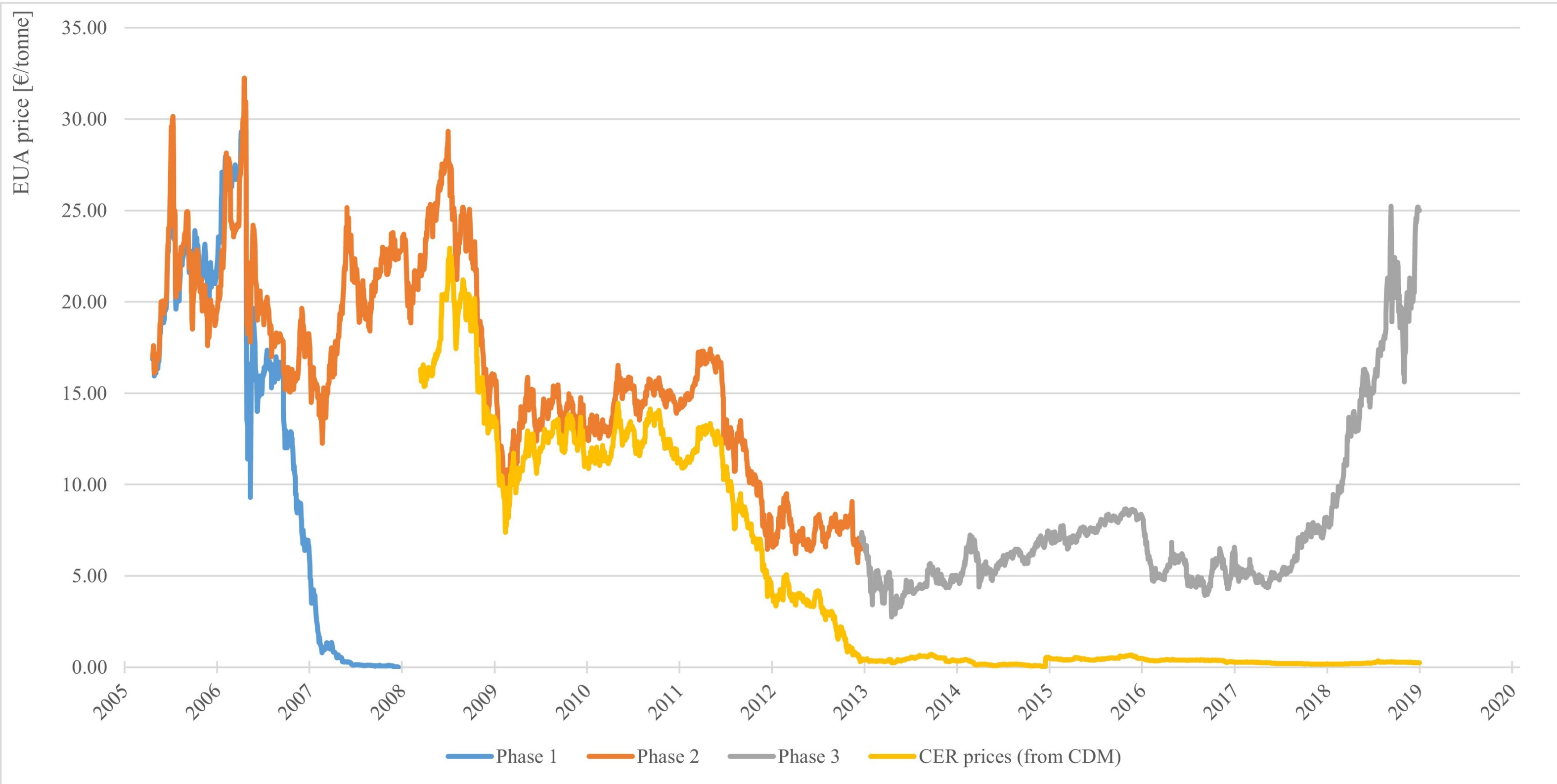

Source: ICE (for EUA prices) and Refinitiv Financial Solution (for CER prices).

Table 1 – Summary of econometric studies.

Study	Data	Countries	Sectors	Years	Approach	Innovation measure	Determinants of interest	Main results
Calel and Dechezleprêtre (2016)	Firm level (80% of EU ETS emissions covered)	18	All sectors	2005-2009	Difference-in-differences	Low-carbon patents	- Participation in the EU ETS (dummy)	Positive effect of the EU ETS on the number of low-carbon patents (+36% relative to counterfactual). No effect of the EU ETS on third parties' innovation (*i.e.*, no indirect effects).
Martin *et al*. (2013)	Firm level, primary data (770 firms interviewed)	6	Manufacturing	2009	Linear regression	Low-carbon R&D	- Participation in the EU ETS (dummy) - Expectation on EU ETS stringency (cap and price levels)	No difference in innovation effects between regulated and non-regulated firms. Positive effect of expected stringency (cap) on R&D decisions.
					Regression discontinuity design		- Exemption from permit auction post-2012 (dummy)	Negative effect of free allocation on innovation efforts.
Schmidt *et al.* (2012a)	Firm level, primary data (65 electricity producers and 163 technology providers)	7	Electricity	2009	Linear regression	Low-carbon technology adoption Low-carbon R&D	- Perception of EU ETS in Phase 1-2 /Phase 3	Negative effect of grandfathering on adoption. No effect of EU ETS perception on low-carbon technology adoption. Positive effect of perception of long term emission reduction target on low-carbon R&D.
Lofgren *et al.* (2014)	Firm level (776 firms, of which 229 regulated)	1 (SE)	All sectors	2000-2008	Difference-in-differences	Low-carbon technology adoption	- Participation in the EU ETS (dummy) - Proxy for allowance over-allocation (2)	No effect of the EU ETS on investment behaviour. No effect of over-allocation on investment behaviour.
Bel and Joseph (2018)	Country level	28	All sectors	2005-2012	Negative binomial panel data	Low-carbon patents	- Proxy for allowance over-allocation (2)	Negative effect of over-allocation on low carbon patents.

Borghesi *et al*. (2015a)	Firm level	1 (IT)	Manufacturing	2006-2008	Probit model	Any environmental innovation (Survey question: yes/no)	- Proxy for allowance over-allocation (2)	Negative effect of stringency on innovation (the authors relate this counterintuitive result to potential anticipatory behaviour of regulated firms or to reverse causality between allocation and innovation).
Calel (2018)	Firm level	1 (UK)	All sectors	YEAR?	Matching estimator	Low-carbon R&D Low-carbon patents CO_2 intensity (proxy for adoption)	- Participation in the EU ETS (dummy)	No effect of the EU ETS on regulated firms' carbon intensity (i.e. no effect on adoption). Positive effect on low-carbon patenting (+25% relative to counterfactual). Positive effect on low-carbon R&D spending.

Note*:* (1) Despite data was raised from interviews in 2009, the analysis can be understood to cover phase 1, 2 and 3; as the results focus on expectations (Martin et al 2013) or perceptions (Schmidt et al 2012a) about future EU ETS phases. (2) Proxies of allowance over-allocation refer to different set of similar indicators where allocated allowances are contrasted with verified emissions, but not with a counterfactual scenario where firms/countries are allocated differently. We, therefore, refer to this as a proxy to over-allocation rather than to actual over-allocation.

Table 2 – Summary of non-econometric studies specific to the electricity sector.

Study	**Data**	**Countries**	**Years**	**Research question**	**Main conclusions**	**Main reported effects**[(1)]	**Influence level of the EU ETS**
Hoffmann (2007)	Primary; Interviews with managers of five companies (making up 80% of sectoral CO_2 emissions)	1 (DE)	2006	How does the EU ETS affect low-carbon investment decisions?	- The EU ETS mainly drove small scale investments (€2-10 million) with short amortisation times (two-five years), and retrofits- Limited effect on R&D investment - Increased interest in CCS-related R&D, though considered too risky given the level and volatility of carbon prices - Limited effect on plant portfolio choices (fuel of new plants)	- CCS-related R&D - Retrofits	- Low to moderate
Rogge and Hoffmann (2010)	Primary; Interviews with 42 experts (in the EU ETS, the electricity sector and technological innovation)	1 (DE)	2006-2009	What changes in the innovation system (of the electricity sector) have been triggered by the EU ETS?	- Accelerated investment in new and existing plants (especially coal-fired) - Significant effects on CCS-related R&D and on linkages between utilities and technology providers - Additional driver for R&D in energy efficiency - Incremental increase in the optimal efficiency level of new and existing plants	- R&D - Retrofits	- Moderate
Rogge *et al.* (2011)	Primary; Interviews with 61 experts (electricity generators, technology providers and project developers)	1 (DE)	2008-2009	What are the effects of the EU ETS on R&D, adoption and organisational change?	- The EU ETS led to an intensification of R&D activities through three routes that can be differentiated in whether the emissions are captured before (IGCC), during (oxyfuel) or after combustion (post-combustion) - Strong increase in corporate CCS research - Heterogeneous effects on R&D for energy efficiency: high for coal plants, very little for gas plants and wind turbines - Before full auctioning, perverse incentives favouring new coal plants -The EU ETS contributed to increase retrofit activities for coal plants	- CCS-related R&D - Retrofits (strong for coal plants)	- Generally low, but significant effects on CCS-related R&D and on retrofits for coal plants
Schmidt *et al.* (2012b)	Primary; Survey with 200 firms (65 electricity generators and 135 technology providers)	7	2009	How do firms differ in their contribution to low-carbon technological change?	- Doubts as to whether the current policy mix is able to trigger the acceleration and redirection of technological change needed to meet the targets - Many firms appear to be behaviourally unaffected by climate regulation	-…	- Low

Hervé-Mignucci (2011)	Secondary; Official information on investment by five major utilities	EU	2004-2009	Has the EU ETS incentivised investment in low-carbon generation?	- Some investments were clearly for mitigating emissions, but they cannot be solely attributed to the EU ETS. - Expectations regarding Phase III triggered clear investment-related responses: highly carbon-emitting plants cancelled in favour of plants emitting less CO_2 or offset project mechanisms used to foster investments in lower carbon power plants	- Cancellation of already planned coal plants	- Moderate

Note*:* (1) Innovation activities presented as entirely or partially induced by the EU ETS.

Table 3 – Summary of non-econometric studies relevant to sectors other than electricity.

Study	Data	Countries	Sector	Years	Research question	Main conclusions	Reported effect of the EU ETS (1)	ETS influence level
Pontoglio (2008)	Primary (Survey with 38 respondents).	1 (IT)	Paper Industry	2006	Which is the role of EU ETS as driving factor for eco-innovations?	- The majority of the respondents (52%) declared not to have realized/planned to introduce technological innovations aimed at reducing emissions. The remaining (48%) already realized or developed projects for the coming years. As for the innovation typology, 38% were energy-efficient solutions; 24% were directed at the optimisation of the production process. - Italian paper plants are old on average, and hence there are significant margins for improving efficiency (in energy and the use of raw materials). -Energy prices are more relevant in driving energy efficiency than uncertain carbon prices.	-…	- Low or null impact.
Tomas *et al.* (2010)	Primary (Survey with 4 representative firms).	1 (PT)	Chemical Industry	2005-2012	How did the EU ETS affect the cost structure of the sector?	- The cost increases observed were found to be non-relevant. - Grandfathering and low prices cannot act as a stimulus for innovation.	-…	- Low or null impact.
Anderson *et al.* (2011)	Primary (Mail interviews to 27 firms, 70% of the Irish allowance allocation).	1 (IE)	All regulated sectors	2005-2007	How did to the ETS affect technological changes in terms of equipment adoption, behavioral change using existing equipment, fuel switching and R&D investments?	- 48% of the respondents report technology adoption. However the EU ETS, despite considered, is not the main driver (rising energy prices more important). - 74% report some form of process/behavioural change with current machinery, of which 30% admit some influence (marginal or strong) driven by the EU ETS. - 41% engaged in fuel switching "in order to reduce carbon emissions". - 46% report that the EU ETS had influenced the way in which capital and investments are analysed.	- Technology adoption. - Behavioural change. - Fuel switching.	- Moderate impact.
Rogge *et al.* (2011)	Primary (Survey among paper producers (19) and technology providers (17)).	1 (DE)	Paper Industry	2008-2009	How did the EU ETS affect the innovation activities of R&D, adoption (investment in new plants or modernization of existing ones) and organizational change (procedural, structural or vision change) in the sector?	- Innovation activities are mainly driven by market forces other than the EU ETS. - The EU ETS has a low relevance for R&D investment: It is considered the least relevant factor (More important are: the prices of paper, raw material and fuel, and public acceptance). 65% of paper producers consider the EU ETS has low relevance and only 21% high relevance (lower % for tech-providers). - Market factors are more relevant for adoption decisions. Although 37% considered the EU ETS of high relevance in adoption decisions. - Regulated companies have performed more CO_2-related organizational changes than non-regulated companies have.	- R&D. - Adoption. - Organizational.	-Null or very low impact. Only moderate for Organizational Innovations.
Gasbarro, Rizzi, Frey (2013)	Primary (6 case studies that include 24 installations).	1 (IT)	Pulp and paper Industry	2010-2011	How did the EU ETS influence companies' Environmental Management Systems (EMS) and to what extend did it affect investment planning of the pre-existing EMS program?	- Companies having an EMS better integrate GHG emission monitoring and compliance within the existing organization. - But cost reduction (and factors other than the EU ETS) is the main driver of investment decisions. - "Investments in technological innovation to reduce carbon emissions are still limited, and investments tend to be mainly focused on market-available technologies for core processes." In any case, not driven by the ETS.	-…	- Null effect

						- "The EU ETS has not been able to trigger additional investment in technological innovation, despite the presence of an EMS".		
Gulbrandsen and Stenqvist (2013)	Primary (2 case studies).	2 (SE, NO)	Pulp and Paper Industry	2012	How have the EU ETS influenced the climate strategies of two companies?	- The EU ETS had a rather limited effect on the climate strategies. - EUA price is too low and allowances too abundant to underpin investment decisions. - However, increase of energy prices (perceived as the strongest influence of the EU ETS) have reinforced some long-term commitments to improve energy efficiency and reduce emissions, i.e. greater interest for own power assets.	-…	- Low or null effect.
Borghesi *et al* (2015b)	Primary (29 interviews to industry associations, other experts or *industry* representatives).	8 (CZ, PL, IT, DE, UK, ES, FR, NL)	6 sectors: energy, ceramics, cement, paper, coke and refinery	2013	Did policy support drive eco-innovations in terms of (i) technological and (ii) organizational innovations?	- Energy: The EU ETS did not contribute much to technology innovation in large combustion plants, but promoted fuel switching, CCS related innovations and organizational innovations. - Ceramics and cement: innovations driven by market factors, not by policy. - Paper: innovation driven by energy costs. Possible incremental influence of the EU ETS on already ongoing innovation projects. - Coke and refinery: Past policies were more relevant for innovation than the EU ETS.	- Fuel switching. - CCS projects.	- Moderate effect (energy). - Very low or null effect (the remaining sectors)
Venmans (2016)	Primary (In-depth interview to 16 managers).	1 (BE)	Ceramics, lime and cement	2012	How do managers perceive (free) allowance allocation above emissions in terms of incentives to invest in abatement?	-The vast majority of them thought that allocation below emissions was a greater incentive to invest. "Companies combusting natural gas stated the availability of excess permits as the main reason for not including the carbon advantage of efficiency investments when assessing payback values." - Price uncertainty was perceived as a risk to be minimized, and hence, an incentive for low carbon investment. "Avoiding uncertainty from the EU ETS was an important motivation to invest in energy efficiency, certainly for future projects when companies are likely to be allocated below emissions". However, when the price volatility is faced directly, certain price vs uncertain price, most perceived uncertainty as a disincentive.	-…	-…
Petsonk and Cozijnsen (2007)	Secondary data (3 case studies that were possible because of the EU ETS).	3 (NE, DE, FR)	-Several	2005-2007	How does the EU ETS stimulate the technological and process innovations?	- Carbon emissions from a refinery are used by horticulture farmers, who otherwise would have needed to burn gas (to generate fertilizer). This already known technology only became economical once carbon had a price. - Methane captures and generation of renewable energy are becoming more profitable thanks to the EU ETS.	- …	- Strong effect.
Fontini and Pavan (2014)	Secondary data (173 Italian paper plants).	1 (IT)	Paper and pulp industry	2005-2010	Index decomposition of the variation in emission in terms of composition, technic and scale effects.	- In phase I, there was a reduction emission via composition effect: shift in production towards products that cause less carbon emissions. This trend could be driven by either change in production or change in demand. - In phase II, technological change played a contribution, but the scale effect (decrease in overall output) always dominated emission reduction, in both phases I and II.	-…	- Low effect (potentially only, as the method does not allow to identify the EU ETS effect).

Notes: (1) Only reported innovation activities that according to the study were entirely or partially induced by the EU ETS.

Table 4 – Effects of the EU ETS on innovation and adoption of low-carbon technologies (econometric literature).

	Effect of the EU ETS	
Study	**Innovation (Low-carbon R&D or patenting)**	**Adoption (Investment in existing low-carbon technologies)**
Schmidt *et al*. (2012a)	+ (R&D)	
Schmidt *et al*. (2012a)		0
Martin *et al.* (2013)	0 (R&D)	
Lofgren *et al.* (2014)		0
Borghesi *et al.* (2015a)		+
Calel and Dechezlepretre (2016)	+ (Patenting)	
Calel (2018)	+ (R&D)	
Calel (2018)	+ (Patenting)	