Environmental Policy and Directed Technological Change: Evidence from the European carbon market

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Abstract

The European Union Emissions Trading Scheme (EU ETS) launched in 2005, and has aimed to encourage the development of low-carbon technologies by putting a price on carbon emissions. We investigate whether the EU ETS has been successful in this regard, using a newly constructed data set that records firms' regulatory status with respect to the EU ETS, key firm characteristics, and patenting activities. A casual look at patent records reveals a surge in low-carbon patenting in Europe since 2005, especially among EU ETS regulated firms. We then employ a matched study design to eliminate explanations that depend on systematic differences in the characteristics of regulated and unregulated firms, and a difference-in-differences estimate to account for firm-level heterogeneity. Our estimates imply the EU ETS is responsible for increasing low-carbon patenting among our matched sample of EU ETS firms by 36.2%. If applied to all EU ETS firms in our study area, however, our treatment effect implies an increase of just 8.1%. Both of these numbers translate into an increase in European low-carbon patenting by no more than 1%, or less than a third of the naive difference-in-differences estimate. In addition, our results show that the EU ETS has not crowded out patenting for other technologies. Finally, we find indicative evidence that the EU ETS has not significantly impacted patenting beyond EU ETS regulated firms.

JEL: O31, Q55, Q58
Keywords: Directed technological change, EU Emissions Trading Scheme, Policy evaluation

1 Introduction

Over the course of the last decade, emissions trading programs have assumed an ever more prominent role in efforts to curb greenhouse gas emissions. In the US, the Chicago Climate Exchange (CCX), the Regional Greenhouse Gas Initiative (RGGI), and California's cap-and-trade program are all examples of this trend. In New Zealand, a national carbon market opened in 2008. Australia has also recently launched their own carbon market. A new carbon market becomes legally binding in 2013 in the Canadian province of Quebec, China is laying the groundwork for several province-level trading schemes, and Japan, South Korea, Brazil, and Kazakhstan have all enacted legislation laying the foundations for their own markets. Today, global carbon markets are worth over $175 billion a year (Kossoy and Guigon, 2012), and with so many new markets in the works, this number will likely grow much larger in years to come.

At present, most of the $175 billion a year is accounted for by the European Union Emissions Trading Scheme (EU ETS). It launched in 2005, allocating tradable emissions permits to over 12'000 power stations and industrial plants in 24 countries, accounting for over 40% of the EU's total greenhouse gas emissions.[1] It is today the world's largest carbon market. Like all of the new emissions trading initiatives around the globe, the primary aim of the EU ETS is to reduce carbon emissions, but to do so through innovation rather than output reduction. When regulated firms expect to face a higher price on emissions relative to other costs of production, this provides them with an incentive to make operational changes and investments that reduce the emissions intensity of their output. The "induced innovation" hypothesis, dating back to Sir John Hicks (1932) and restated in the context of environmental policy by Porter (1991), suggests that part of this new investment will be directed toward developing and commercializing new emissions-reducing technologies. According to this theory, the EU ETS can be expected to spur development of new low-carbon technologies. This vision has been articulated many times by EU policy makers, who envisage the EU ETS to be a driving force of low-carbon economic growth.

In fact, technological change may be the single most important determinant of the long-run cost of emissions abatement. Consequently, the ability of an environmental policy to influence technological change is perhaps one of the most important criteria on which to judge its success (Kneese and Schultze, 1975; Pizer and Popp, 2008). In light of this, it is not surprising that there are ongoing efforts from both theoretical and empirical economists to better understand the capacity of environmental policies to induce clean

[1] 24 countries were included from the beginning. 6 countries have joined since then.

innovation. On the theoretical side, the past few decades have seen the emergence of a considerable literature further developing the induced innovation hypothesis, especially in the context of climate change mitigation (Goulder and Schneider, 1999; van der Zwaan et al., 2002; Popp, 2004, 2006a; Gerlagh, 2008; Acemoglu et al., 2012). On the empirical side, a large and growing research enterprise is trying to understand and quantify the link between environmental policies and directed technological change (Lanjouw and Mody, 1996; Newell et al., 1999; Brunnermeier and Cohen, 2003; Popp, 2002, 2003, 2006b; Arimura et al., 2007; Lanoie et al., 2007; Johnstone et al., 2010 and many others. See Popp et al., 2009, Popp, 2010, and Ambec et al., 2010, for recent surveys). Our study contributes to this literature.

In this paper we investigate the impact of the EU ETS on low-carbon technological change in the first 5 years of the Scheme's existence. The EU ETS offers a unique opportunity to investigate the impact of environmental policy on technological change. It is the first and largest environmental policy initiative of its kind anywhere in the world, which by itself would make it an interesting case to study. But more important is the fact that, in order to control administrative costs, the EU ETS was designed to cover only large installations. Firms operating smaller installations are not covered by EU ETS regulations, although the firms themselves might be just as large as those affected by the regulations.[2] Because innovation takes place at the level of the firm, we can compare firms with similar resources available for research and similar patenting histories, but which have fallen under different regulatory regimes since 2005. This provides an opportunity to apply the sort of quasi-experimental techniques most suited to assessing the causal impacts of environmental policies (List et al., 2003; Greenstone and Gayer, 2009). To the authors' knowledge, this is the first time these methods have been employed to study the link between environmental policy and directed technological change.

We use a newly constructed data set that records firms' regulatory status with respect to the EU ETS, key firm characteristics, and patenting activities. The low-carbon patent classification recently developed by the European Patent Office (EPO) allows us to identify emissions reduction technologies. Our data set includes information on over 30 million firms across 23 countries, 18 of which took part in the 2005 launch of the EU ETS. We identify over 5'500 firms operating more than 9'000 installations regulated under the EU ETS, accounting for over 80% of EU ETS-wide emissions. Using this data set, we are

[2]Although the EU ETS regulations are applied at the level of the installation, we will often use 'EU ETS firms' or 'regulated firms' as shorthand for firms operating at least one EU ETS regulated installation.

able to compare unregulated and would-be regulated firms both before and after the EU ETS launched. A matched difference-in-differences study design enables us to control for confounding factors that affect both regulated and unregulated firms (input prices, sector- and country-specific policies, etc.), as well as firm-level heterogeneity (Heckman et al., 1998b,a; Smith and Todd, 2005; Abadie, 2005). Our estimates provide the first comprehensive empirical assessment of the impact the EU ETS on directed technological change.

A casual look at aggregate patent data reveals a rapid increase in low-carbon patenting since 2005. Moreover, this increase seems to have disproportionately affected EU ETS regulated companies. Our matched difference-in-differences estimate of the treatment effect implies that the EU ETS is responsible for a 36.2% increase in low-carbon patenting among our matched sample of 3'428 EU ETS firms, or an increase of 8.1% across all of the 5'500 EU ETS firms. This would account for less than a 1% increase of low-carbon patenting at the EPO. By way of comparison, naive estimates obtained by comparing EU ETS and non-EU ETS firms, en masse, suggest that the Scheme may be responsible for increasing low-carbon patenting at the EPO by 2.6%. Such an optimistic number, however, appears to stem largely from systematic differences in firm characteristics that can be measured even before the EU ETS launched. With respect to concerns that low-carbon innovation would crowd out development of other technologies (Popp and Newell, 2012), we find evidence that the EU ETS has in fact encouraged patenting for other technologies, but by a very small amount. We investigate several challenges to the internal and external validity of our results—e.g. omitted variable bias and a failure of 'selection on observables'—but our conclusions appear to be remarkably robust.

For fear that a focus on EU ETS firms would have blinkered us to a broader indirect impact of the EU ETS, we identify a group of likely third-party technology providers and purchasers and test whether these firms have also responded to the EU ETS. The estimates are only indicative, but we find no compelling evidence that the EU ETS has had either a net positive or net negative impact on the patenting activities of third parties. Taken together, our findings suggest that, while EU ETS regulated firms have responded strongly, the Scheme so far has had at best a very limited impact on the overall pace and direction of technological change.

The EU ETS is expected to remain an integral part of the EU's strategy for building a low-carbon Europe (European Commission, 2011). Our results indicate, however, that the impact of emissions trading programs on innovation may be concentrated to a relatively small set of firms. The EU ETS in its current form might not be providing incentives for low-carbon technological change on a large scale. Debates about the relative costs and benefits of different environmental policy instruments already consider the impacts on pace and direction technological change to be of central importance (Kneese and Schultze, 1975; Pizer and Popp, 2008), but our results highlight another potentially important dimension in which environmental policy instruments may differ. If it is recognized that the distribution of impacts on directed technological change differ across environmental policy instruments, this might change the economic, or indeed the political calculus of instrument choice.

The paper proceeds as follows. Section 2 surveys the evidence on environmental policy and directed technological change, especially in the context of emissions trading. Evidence from the US Acid Rain Program and early studies of the EU ETS inform us about how the EU ETS is likely to have impacted technological change. In section 3 we familiarize ourselves with our newly constructed data set, and use it to begin unpacking the characteristics of low-carbon technological change. In section 4 we turn our eye to estimating the impact of the EU ETS on regulated firms, and in section 5 we examine its indirect impact on third-party technology providers and purchasers. Section 6 summarizes and discusses the evidence in light of the broader empirical literature. We conclude by considering some of the potential policy implications of our findings, and directions for future research.

2 Emissions trading and directed technological change

In 2005, the EU ETS launched in 24 countries across Europe, covering roughly 40% of the EU's total greenhouse gas emissions. First, power stations and industrial plants across Europe were classified according to their main activity: "combustion", "cement", "paper and pulp", etc. For each category, installations had to meet certain criteria to be included in the EU ETS. For instance, only combustion installations historically consuming more than 20 MWh a year were covered. The Scheme would then be implemented in 3 trading phases, with successively more stringent emissions caps for each phase. Phase 1, which ran from 2005–2007, was insulated from later phases by prohibiting banking and borrowing of permits across the phase boundary. Phase 2 (2008–2011) and Phase 3 (2012–2020) allow firms to bank unused permits for later use, as well as a limited form of borrowing against future emissions reductions. For each year in Phase 1, over 2 billion tons-worth of tradable emissions permits were allocated to the more than 12'000 qualifying power stations and industrial plants, and a legal requirement was instituted that each installation surrender enough permits at the end of each year to cover their emissions. Prior to the compliance date, however, installation operators could freely trade permits with each other (as well as with financial intermediaries and private citizens).[3] The price of emitting one ton of CO_2 would be set in this newly created marketplace. Since 2005, the spot price has varied between €0 and €30, spending more time in the lower part of that range. The price of forward contracts has remained steadily above the spot price, though, suggesting firms are taking the progressive stringency of the cap into account. With the price of carbon revealed in the market, installations (or rather the firms that operate them) can then make abatement and investment decisions accordingly.

Several studies have found evidence that environmental policy does impact the direction of technological change (Lanjouw and Mody, 1996; Brunnermeier and Cohen, 2003; Popp, 2002, 2003, 2006b; Arimura et al., 2007; Lanoie et al., 2007). Popp (2006b) finds an almost immediate patenting response to domestic clean air regulations in the US, Germany, and Japan. Johnstone et al. (2010) find that renewable energy patents have increased dramatically as national and international climate change policies have multiplied. But while policy makers continue making this argument, and though there is empirical evidence to support a general link between environmental policy and directed technological change, a more careful reading of the literature yields three cautionary observations relating specifically to emissions trading.

Firstly, when examining the impact of emissions trading programs specifically, rather than environmental policies more broadly construed, the conclusions about its impacts are more modest. Most studies concern the US Clean Air Act's Acid Rain Program, launched in 1995. Early estimates suggested nearly half of the emissions reductions were achieved by installing scrubber technology, and the remainder by switching to coal with a lower sulphur content (Schmalensee et al., 1998). The scrubber technology existed before 1995, but had in many instances not been economically viable. The innovation resulting from the Acid Rain Program thus appears to have been focused on operational rather than technological change (Burtraw, 2000). Yet there is some evidence of very narrowly directed technological change. Popp (2003) detects an increase in patents that improved the efficiency of scrubbers.[4] This effect was confined to early years under the new regime though, and the Program has not provided ongoing incentives for technological advancement (Lange and Bellas, 2005). This squares with findings that the use of scrubber technology as an emissions abatement strategy has actually declined over time (Burtraw and Szambelan, 2009). To put it simply, past emissions trading programs like

[3] See Ellerman et al. (2010) for a more comprehensive review of the design and implementation of the EU ETS.

[4] It is worth noting that Title IV of the Clean Air Act, which establishes the Acid Rain Program, also includes special provisions that reward firms specifically for the use of scrubbers. It is not entirely clear, therefore, how much was 'the market's doing'.

the Acid Rain Program do not provide a precedent for the kind of induced technological change EU policy makers are hoping the EU ETS will provide.

Secondly, since it launched in 2005, there has been vigorous debate about whether the EU ETS would induce firms to develop new emissions-reducing technologies, many arguing that an overly generous allocation of emissions permits would largely undermine the incentives to innovate (Schleich and Betz, 2005; Gagelmann and Frondel, 2005; Grubb et al., 2005). Indeed, a few early case studies summarized by Petsonk and Cozijnsen (2007) indicate that rather than developing new technologies, firms have been introducing well-known technological solutions that had simply not been economically viable before the EU ETS imposed a carbon price on regulated firms. A growing literature of case-studies and expert interviews now provides further support for this conclusion. Tomás et al. (2010) study four large EU ETS regulated Portuguese chemical companies, suggesting that the EU ETS may have encouraged some emissions reducing innovation, but largely in the form of energy efficiency improvements. Martin et al. (2011) conduct semi-structured interviews with nearly 800 European manufacturing firms, of which almost 450 operated some EU ETS regulated installations, finding a positive effect of the EU ETS on process innovation, but not on product innovation. It is the latter category we would expect to be more fully captured in patenting records. Few studies have inquired directly about R&D efforts, or about patenting. A survey of Irish EU ETS firms tentatively suggests that almost no resources were available for low-carbon R&D in Phase 1 of the trading program (2005–2007), while many of the firms had pursued more operational innovations like installing new machinery or equipment, making process or behavioral changes, and employing fuel switching to some degree (Anderson et al., 2011). Hoffmann (2007), reporting on the German electricity sector, find that the EU ETS has had an effect on decisions about small-scale investments with short amortization times, but not on R&D efforts. Neither study, however, provides a sufficiently large or representative sample of EU ETS firms to provide a reliable picture of the innovation response to the EU ETS, especially since innovation tends to be relatively concentrated to a small group of firms. Moreover, neither study offers for comparison a group of non-EU ETS firms.

What evidence there is suggests that the practice of fuel switching appears to have been very important so far. Fuel switching requires neither capital investment nor R&D, only that power providers bring less polluting gas-fired plants online before coal-fired ones as demand ramps up. This changes the average fuel mix in favor of natural gas, and therefore reduces the carbon intensity of output. Fuel switching is a purely organizational innovation. Macroeconomic estimates suggest that the EU ETS reduced total emissions by roughly 50–100 million tons of CO_2 annually in Phase 1, or roughly 3–6%, compared with a "business-as-usual" scenario (Ellerman and Buchner, 2008; Anderson and Di Maria, 2011). Meanwhile, model-based estimates of power sector emissions abatement from fuel switching alone range from 26–88 million tons per year (Delarue et al., 2008, 2010). These estimates suggest that fuel switching very likely accounts for the lion share of emissions reductions in the EU ETS so far. This is not a problem in and of itself, of course. The US Acid Rain Program, for instance, achieved its emissions targets in large part by analogous fuel switching strategies, and with little technological change. However, one should be conscious that in the case of the EU ETS, the capacity for emissions reductions through fuel switching is far more limited compared to the EU's longer term targets. Delarue et al. (2008) estimate that fuel switching has the potential to reduce emission by up to 300 million tons per year, which is no more than a tenth of what is needed to meet the EU target to cut emissions by 80% by 2050 against 1990-levels.[5]

Thirdly, even if firms are developing new low-carbon technologies in response to the EU ETS, extrapolating estimates from historical studies suggests the impact should be very small. Though most of the evidence so far suggests companies are chiefly employing fuel switching and other short-term strategies to reduce emissions, it is entirely conceivable that they have simultaneously started to develop new technologies that will facilitate future emissions reductions. There is little systematic evidence of this so far, of course, but if we expected the incentives for technological development to be mediated primarily by augmenting energy prices, we can use historical estimates of the energy price elasticity of energy-saving technology patents to aid our expectations of the potential effect the EU ETS might be having. Popp (2002) suggests that, even at the height of the energy crisis of the late 1970s, energy prices only boosted patenting by 3.14%. The carbon price in the EU ETS, having ranged from a peak of near €30 to a low of near €0 (and spending more time in the lower part of that range), does not imply anything close to the energy price hikes of the late 1970s. One might expect the patenting response, if any, to be barely perceptible. This back-of-the-envelope comparison comes with serious health warnings, of course, not the least of which is that innovation may be driven more by expectations than currently prevailing prices (Martin et al., 2011).

So while policy makers envisage the EU ETS as the engine of low-carbon innovation, and though there is empirical evidence that supports a positive link between environmental policy and directed technological change generally, the three observations above—the

[5]The EU target amounts to reducing annual emissions by roughly 4'500 million tons compared to 1990, or roughly 3'500 million tons compared to current emission levels.

weak patenting response in previous emissions trading programs, the overwhelming reliance on fuel switching and other short term strategies in the EU ETS so far, and the meager patenting response to be expected from the diluted price signal—invite a degree of skepticism about strong claims for the ability of the EU ETS to motivate innovation. These three observations motivate a special interest in obtaining direct empirical evidence on whether or not the EU ETS is encouraging firms to develop new low-carbon technologies.

3 Unpacking low-carbon technological change

While EU ETS regulations apply at the level of the installation, innovation takes place at the level of the firm, and recent advances in linking patent data with company data makes it possible to construct firm-level patent portfolios. This paper exploits a newly constructed patent data set—linking patent portfolios to key firm characteristics, including whether or not the firm operates any installations covered by EU ETS regulations.

Patents have been used extensively as a measure of technological change in the recent induced innovation literature (Popp, 2002, 2006b; Johnstone et al., 2010), and the advantages and drawbacks of patents are well understood (see OECD, 2009, for a survey). Patents provide a useful measure of the output of innovative activity and are available at a highly disaggregated technological level. Having said that, it is also worth noting that a number of studies have found that patent counts (output) are highly correlated with R&D expenditures (input) in cross section (Griliches, 1984), and shift concurrently over time and in response to shocks (Kaufer, 1989). Our main measure of technological change uses patents filed with the European Patent Office (EPO). EPO patents provide a common measure of innovation for all of Europe, unlike self-reported innovation measures or patents filed with national patent offices, for which the standards vary from firm-to-firm or country-to-country. In addition, EPO patents provide a useful quality threshold as only high value inventions typically get patented at the EPO.[6] Nevertheless, as a robustness test we also repeat our analysis to using quality-weighted patent counts.[7]

[6]Evidence shows that the highest value technologies are patented in several countries (Harhoff et al., 2003), and indeed, one of the methods used to measure the value of patents is to count the number of countries is which they are filed (van Zeebroeck, 2011). Patents filed at the EPO get patented in 6 EPO member countries on average.

[7]Although the EPO provides a common measure of minimum patent quality, the value of patents is still known to be heterogeneous. We use two ways to account for the quality of patents: forward citations and family size. Citation data have been widely used in the literature to control for the quality of patents. With this method, patents are weighted by the number of times each of them is cited in subsequent patents (see Trajtenberg, 1990; Harhoff et al., 1999; Hall et al., 2005). The family of a patent is the set of patents protecting the same invention in various countries (patent family information comes

All patents filed at the EPO are categorized using the European patent classification (ECLA), which includes a recently developed class pertaining to "technologies or applications for mitigation or adaptation against climate change", or "low-carbon technologies" for short. This new category (the "Y02" class) is the result of an unprecedented effort by the European Patent Office, whereby patent examiners specialized in each technology, with the help of external experts, developed a tagging system of patents related to climate change mitigation technologies. The Y02 category provides the most accurate tagging of climate change mitigation patents available today and is becoming the international standard for clean innovation studies[8]. These low-carbon technologies include, to name a few, efficient combustion technologies (e.g. combined heat and power generation), carbon capture and storage, efficient electricity distribution (e.g., smart grids) and energy storage (e.g. fuel cells). This class helps us measure the direction of technological change.[9] A complete description of the various sub-classes for low-carbon patents used in the paper can be found in appendix C.

The EPO was set up in 1978. Since then, over 2.5 million patents have been filed with the EPO, of which just over 50'000 (or 2%) have been classified as low-carbon inventions. Our newly constructed data set includes the patent portfolios of over 30 million firms located in 23 countries (22 EU countries, plus the US). 18 of these countries launched the EU ETS in 2005. The other 5 (Norway, Switzerland, Romania, Bulgaria, and the US) have either joined later or have remained outside of the EU ETS altogether. While our data is somewhat more geographically restricted than the EPO, the firms in our data set account for just over 95% of all patents filed at the EPO, so we are confident that we have managed to include the patent history of the vast majority of companies.[10]

The share of patents protecting low-carbon technologies shows a distinct pattern over

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from the DOCDB family table in PATSTAT). Counting the number of countries in which a patent is filed is another common measure of patent quality (Harhoff et al., 2003; van Zeebroeck, 2011). Family data also presents the advantage of being more rapidly available than citations (patents are typically mostly cited two years after their publication, hence four years after they are first filed), which is especially valuable when dealing with very recent patents as we do. Finally, in some of our robustness tests we also consider on patents filed with national patent offices to gauge whether our findings depend on how narrowly we define the patents of interest.

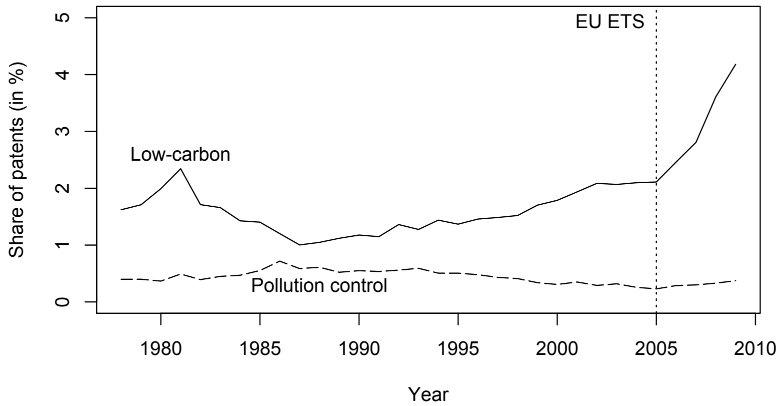
[8]See (Veefkind et al., 2012) for more details on how this category was constructed.

[9]Because the EPO low-carbon classification is not comprehensive, we also test the robustness of our results to the inclusion of additional patents that other authors have considered low-carbon, in particular patents pertaining to energy-efficient industrial processes. An updated list of environment-related patent classification codes is available from the OECD's Environmental Policy and Technological Innovation (EPTI) website: www.oecd.org/environment/innovation.

[10]We have also conducted extensive manual double-checking, so we can reasonably assume that companies for which we were unable to find any patent data have actually not filed any patent at the EPO. It is well documented that only a fraction of companies ever file patents, and this is likely to be especially true of the EPO that has high administrative costs.

time (figure 1). There was a surge in patenting for these technologies in the early 1980s, often attributed to the second oil price shock in the late 1970s (Dechezleprêtre et al., 2011). The share of low-carbon patents filed each year then stayed roughly level until the mid-1990s, after which it began to rise again. The share of low-carbon patents has increased rapidly in recent years, as is particularly evident after 2005, with the share doubling from 2% to 4% in just a few years. A simple Chow test strongly rejects the hypothesis that there is no structural break in 2005 ($P < 0.001$).

Figure 1: Share of low-carbon patents (1978–2009)



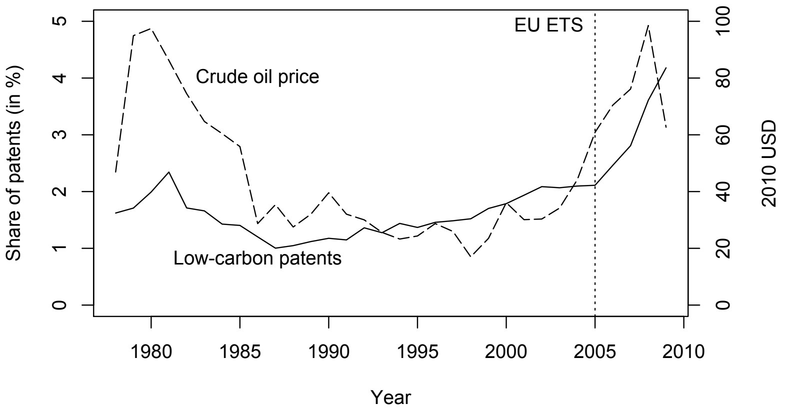
While this pattern is robust to using an expanded definition of "low-carbon technologies", it is not present for any set of environmentally friendly technologies. To see this, figure 1 also plots the share of patents protecting non-greenhouse gas "pollution control technologies", as defined by Popp (2006b),[11] which does not display the same structural break (one cannot reject the hypothesis of no structural break in 2005 at conventional significance levels). The sudden surge in patenting activity, therefore, appears to be specific to low-carbon technologies and to coincide with the launch of the EU ETS. Could the structural break in low-carbon patenting, then, be a consequence of the EU ETS?

Just like the increase in low-carbon patenting in the early 1980s has been attributed to the oil price shock, the recent surge might be due to rising oil prices. When comparing the share of low-carbon patenting with the evolution of oil prices (see figure 2), one notices that the present upsurge in patenting follows immediately on the heels of rapid oil price increases in the early 2000s. Patenting for pollution control, on the other hand, was not responsive to the oil price in the 1980s, and so it is not surprising it has stayed flat recently. Looking at the aggregate trends over time, clearly, is not enough to

[11]These technologies pertain to reduction of local pollutants including SO_2 and NO_X.

determine whether the increase in low-carbon patenting since 2005 is the result of the EU ETS, oil prices, or some other factor. In order to isolate the impact of the EU ETS we must compare the experience of firms regulated under the EU ETS with those not covered by the regulation. Both groups will have faced the same oil prices and other macroeconomic conditions, but starting in 2005 they were subject to different regulatory regimes.

Figure 2: Share of low-carbon patents and Crude oil price(1978–2009)



It is important to stress that the EU ETS regulates installations (not firms) by applying certain inclusion criteria. For instance, installations for which the main activity is "combustion of fuels" are included only if their annual thermal input exceeds a threshold of 20 MW. For steel plants, the relevant inclusion criterion is instead that the installation have a production capacity exceeding 2.5 tonnes per hour. Installations manufacturing glass and glass fibre are included only if their melting capacity exceeds 20 tonnes per day. These are only three examples from a longer list, but the upshot of this configuration is that what we refer to as EU ETS and non-EU ETS firms can in principle be virtually identical in all other respects relevant to their patenting behaviour, except for the size of a single installation.

Our data set also records the regulatory status of 30 million firms—5'568 firms in our data set operate at least one installation regulated under the EU ETS. Together they operate 9'358 EU ETS regulated installations, accounting for over 90% of regulated installations and emissions in Phase 1 in the 18 EU ETS countries we are studying, and roughly 80% of installations and emissions EU ETS-wide (see table 1).[12]

[12]See appendix A for more details on how the link between firm data and regulatory data was constructed.

Table 1: Coverage of the EU ETS – The first two columns of this table show the number of Phase 1 installations in each of the 18 countries in our sample, and their allocated emissions (source: CITL). The following two columns show the percentages of installations and emissions for which the operating firm has been identified. The two rows at the foot of the table summarise our data set's EU ETS coverage for our 18 countries as well as as a proportion of the EU ETS as a whole.

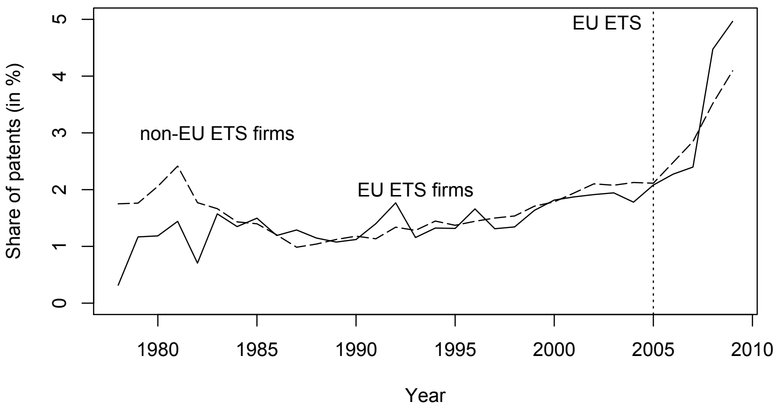
	Number of installations	Mton of emissions	Percent of installations covered	Percent of emissions covered
Austria	217	97.8	92.2	100.0
Belgium	345	178.7	98.6	100.0
Czech Rep.	415	290.8	92.5	96.9
Denmark	399	93.1	92.7	95.2
Estonia	54	56.3	77.8	99.9
Finland	637	133.9	84.6	100.0
France	1100	450.2	97.5	99.6
Germany	1944	1486.3	98.6	99.6
Ireland	121	57.7	76.9	94.7
Lithuania	113	34.4	87.6	91.4
Luxembourg	15	9.7	100.0	100.0
Netherlands	418	259.3	87.1	95.6
Poland	869	712.7	90.0	98.6
Portugal	265	110.7	99.2	99.9
Slovakia	191	91.4	90.6	99.9
Spain	1072	498.1	98.5	99.9
Sweden	774	67.6	93.9	98.8
UK	1107	628.0	83.3	97.0
Total	10056	5256.6	93.1	98.7
Total EU ETS	12122	6321.3	77.2	82.0

Having identified the subset of firms directly affected by the EU ETS, we can now look separately at the EU ETS and non-EU ETS trends in low-carbon patenting. Figure 3 shows that the share of low-carbon patents was roughly the same among EU ETS and non-EU ETS firms in the 5 years before the EU ETS launched. Economic theory then predicts that environmental regulations would produce greater incentives to develop new technologies for a regulated firm than for an unregulated firm (Milliman and Prince, 1989; Fischer et al., 2003), because the latter is not discharging costly emissions itself and therefore receives no additional benefit reducing its own emissions. After 2005, the share of low-carbon patents among EU ETS firms looks to have risen faster than among non-EU ETS firms.[13] The difference does not become apparent until the start of the second trading phase in 2008, which was widely expected to constrain emissions more tightly than Phase 1 had done. Could the post-2005 surge in low-carbon patenting, after

[13] One might be concerned that the surge in patenting activity by EU ETS firms compared to non-EU ETS companies might have been accompanied by a concurrent drop in the relative average quality of inventions patented by EU ETS companies. However, the average number of citations received by low-carbon patents filed by EU ETS companies since 2005 does not significantly differ from those filed by non-EU ETS companies. Similarly, the size of low-carbon patent families is the same for EU ETS and non-EU ETS companies.

all, be a consequence of the EU ETS?

Figure 3: Comparing the share of low-carbon patents (1978–2009)



Let us naively suppose for a moment that the differences visible in figure 3 are entirely due to the EU ETS. This permits us to calculate a simple estimate of the impact of the EU ETS on low-carbon patenting. Since 2005 EU ETS firms have filed 2'189 climate related patents, compared to 972 patents in the 5 preceding years (an increase of 125%). Non-EU ETS firms filed 19'841 and 12'037 patents protecting low-carbon technologies in the corresponding periods (an increase of 65%). Low-carbon patenting grew at similar rates among EU ETS and non-EU ETS firms in the pre-EU ETS period. If we then were to assume that the number of low-carbon patents filed by EU ETS firms, had they not been regulated, would have grown at the same rate experienced by non-EU ETS firms, we can calculate a naive estimate of how many low-carbon patents the EU ETS has added so far: 2'189 - 1.65 $\times$ 972 = 585.2. If 585.2 of the low-carbon patents filed at the EPO in 2005–2009 were additional, this amounts to a 2.6% increase in the number of low-carbon patents at the EPO compared to what we expect it would have been without the EU ETS.

This is clearly a very naive estimate. It assumes that the patenting of non-EU ETS firms provides an accurate counterfactual estimate of how EU ETS companies would have behaved had they not become regulated. This assumption may be problematic in case non-EU ETS firms are also responding to the new regulations. A more pressing concern, though, is that the two groups of firms appear to be very different even before the EU ETS. Just looking at the patenting of these two groups reveals that while only 1 in about 5'500 firms is EU ETS regulated, they account for roughly 1 in 12 low-carbon patents filed in the 5 years before the EU ETS launched. Clearly, EU ETS companies do not appear to be representative of the population of firms as a whole. One could quite easily imagine, then, that some unobserved change or shock (other than the EU ETS) would have had systematically different impacts on these two sets of firms. The naive calculation above cannot isolate the impact of EU ETS in such a case. To begin to address this shortcoming, it is better to restrict our view to a subset of companies that are more similar on pre-2005 characteristics. For such a group of firms, it would be more difficult to imagine post-2005 changes (apart from the EU ETS) that would have systematically different impacts on the patenting activities of EU ETS and non-EU ETS firms. Rather than comparing all EU ETS firms with all unregulated firms, this more restricted comparison is likely to yield a better estimate of the impact of the EU ETS. Let us now turn, therefore, to the task of constructing such a comparison.

4 The direct impact of the EU ETS

4.1 Matching

We face a difficult identification problem. Looking at changes over time is not sufficient to identify the impact of the EU ETS because it is not possible to adequately control for things like oil price fluctuations and changes in macroeconomic conditions. Comparing EU ETS firms with non-EU ETS firms at a given time allows us to better control for these time-variant factors. On the other hand, as we have discovered, the typical EU ETS firm appears very different from the typical unregulated firm even before the EU ETS launched in 2005. This comparison may therefore wrongly attribute some low-carbon patents to the EU ETS that are really the result of other systematic differences between EU ETS and non-EU ETS firms.

Comparing the changes over time for two groups of firms that are more similar prior to 2005 would make it more difficult to explain away any difference in outcomes by factors other than the EU ETS. Ideally one would like to match each EU ETS firm with a group of non-EU ETS firms with similar resources available and facing similar demand conditions, regulations (other than the EU ETS), input prices, etc. In this section we perform just such a matching exercise. As we restrict ourselves to more closely matched firms there will inevitably be a number of EU ETS companies for which no good match can be found. What is lost in sample size, however, is regained in terms of accuracy and robustness (see, for instance, Dehejia and Wahba, 1999).

Along with patent portfolios, our data set contains information on the country and economic sector in which firms operate,[14] as well as other firm-level information such as turnover and employment. Using this data, we have tried to assign to each of the 5'568 EU ETS firms a group of similar but unregulated firms (setting aside all companies with ownership ties to EU ETS firms, see appendix A). Though, this has not always been possible, for two main reasons. Firstly, the records of turnover become less and less complete further back in time. In fact, we only have pre-2005 records on the turnover for 3'564 out of the 5'568 EU ETS firms. Secondly, though EU ETS regulations were applied at the installation level rather than directly to the firm, one might expect two very similar firms to receive the same regulatory treatment more than occasionally. Different regulatory fates are possible if, say, an EU ETS firm operates an installation just large enough to be covered by EU ETS regulations, while the matched control operates one or more installations just below the threshold. But even though we have a very large pool of firms to start with, sometimes there will be no such comparators available within the same country and sector. Due to lack of suitable comparators, the sample of EU ETS firms is further reduced to 3'428. We return to the omitted firms below in section 4.3, to consider the possible consequences of dropping them from our sample.

For each of the 3'428 matched EU ETS firms we have found at least one unregulated firm that operates in the same country and economic sector. This means that they are likely exposed to much the same business and regulatory environment, input prices, country and sector specific shocks and trends. The firms are also matched to have similar pre-2005 turnover, patenting records, and age, since their available resources and capacity for R&D and patenting are likely important determinants of a firm's response to the EU ETS.[15] The resulting matched sample consists of 3'428 EU ETS firms and 4'373 non-EU ETS firms.

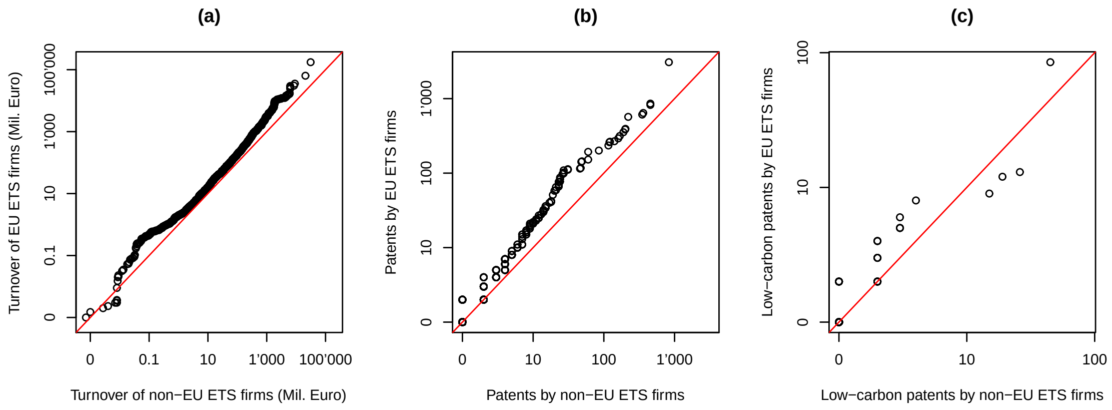
Figure 4 compares the empirical distributions of EU ETS and non-EU ETS firms in our matched sample on a few key variables used to construct the match. EU ETS regulated firms have slightly greater pre-EU ETS turnover on average, and filed slightly more patents. However, as can be seen in table 2, we reject the hypotheses that the empirical distributions differ between the EU ETS and non-EU ETS firms.

Because firms look similar within each match, the firms' pre-2005 observable characteristics do not help us predict (better than chance) which firm in each matched group

[14]Economic sectors are defined at the 3-digit level for the NACE Rev. 2 industry classification. A few examples of these sector definitions will illustrate how narrowly sectors are defined: "electric power generation, transmission, and distribution", "steam and air conditioning supply", "manufacture of glass and glass products", "manufacture of plastic products", "manufacture of rubber products".

[15]See appendix B or technical details about how the matching was implemented.

Figure 4: Comparison of matched EU ETS and non-EU ETS firms



Panel (a) displays the empirical quantile-quantile (e-QQ) plot for average turnover in the 4 years before the EU ETS (2001–2004). Each dot gives the value for one EU ETS firm and the average for a group of matched non-EU ETS firms, shown on logarithmic scales. 2001 is the first year for which turnover is recorded in our data set for any firm. Panels (b) and (c) show the e-QQ plots for the total number of patents and the number low-carbon patents filed 2000–2004, respectively, once again shown on logarithmic scales.

would become regulated after 2005 and which firm in each group would file more low-carbon patents. Conditional on pre-EU ETS observable characteristics, the assignment of firms to the EU ETS appears random. In a naive sense, we have recovered the identifying conditions present in a randomized experiment (though we subject this claim to further scrutiny below).

4.2 Results

For each firm we measure the change in the number of low-carbon patents from 2000–2004 to 2005–2009. This means that, even after matching, we take account of any additional time invariant firm-level heterogeneity. The outcomes of the matched control firms are then subtracted from the outcomes of the EU ETS firms to obtain the difference-in-differences. A striking feature of the patent counts used to calculate these difference-in-differences is the large number of zeros. It is a very common feature of patent data that most firms do not file any patents at all, and this arises from a similar censoring problem that usually motivates the use of the Tobit estimator. We can imagine there being a latent variable that can take any value, but we can only observe numbers of zero or greater.

To implement Tobit estimator in our case, though, we would have to explicitly model

Table 2: Equivalence tests for matched EU ETS and non-EU ETS firms

	Median difference between EU ETS and non-EU ETS firms	Equivalence range	Critical equivalence range (5% sign. lev.)
Turnover (in Mil. Euro)	1.60	± 523.39	± 13.25
Patents	0	± 9.30	± 1.99
Low-carbon patents	0	± 0.25	± 1.99
Year of incorporation	0	± 5.97	± 0.49
Any pre-2005 patents (binary)	Exactly matched	–	–
Economic sector	Exactly matched	–	–
Country	Exactly matched	–	–

The first column from the left reports the median difference between EU ETS firms and non-EU ETS firms in our sample for the key matching variables. Apart from those variables shown in figure 4, matched on the year of incorporation interacted with other variables, since turnover and cumulative patent filings mean different things for an old and new firms. We have also matched exactly for whether (1) or not (0) a firm filed any patents before 2005, for country of operation, and for economic sector (defined at the 3-digit level for NACE Rev. 2). The empirical distributions of EU ETS and non-EU ETS characteristics are judged to be substantively equivalent if the location shift parameter (as defined for Wilcoxon's signed-rank test) lies within the 'equivalence range' reported in the second column. We follow the convention of letting this range be ± 0.2 standard deviations of the distribution of the pooled sample (Cochran and Rubin, 1973; Ho and Imai, 2006). Using Wilcoxon's signed-rank test, we are just unable reject at the 5% significance level the hypothesis that the location shift parameter lies within the the 'critical equivalence range' reported in the final column. (The signed-rank test has been adjusted to account for the fact that our variables are censored at zero, using a method outlined by Rosenbaum (2009, ch. 2). More details in section 4 below.) As can be seen by the fact that the range in the third column is contained within that in the second column, we can reject the hypotheses of substantive differences for all variables, except for low-carbon patents. This last failure to reject is because of the small number of firms that filed any low-carbon patents prior to 2005, as is evidenced by the fact that the same test also fails to reject the hypothesis that the difference is zero. Standard t-tests for differences in means reject the hypotheses of substantive differences for all variables (not reported).

the propensity of firms to file at least one patent. This is by no means a straightforward exercise, and getting the model wrong carries with it the risk of introducing new biases. The analogous maximum likelihood estimator will likewise generally be inconsistent, especially when applied to panel data (Chay and Powell, 2001). Instead, we can account for the censoring at zero using a Tobit-modified empirical-likelihood estimator, as outlined by Rosenbaum (2009, ch. 2). The idea is as follows. We observe the low-carbon patents filed by EU ETS firms and non-EU ETS firms. In estimating a treatment effect, we would normally search for a number that, if subtracted from each of the observations in one of our two samples, would as nearly as possible equate the distributions of the two samples (using some metric of similarity). The problem, of course, is that this assumes a constant treatment effect that applies even to firms with zero patents. Instead, we can adjust our observed difference-in-differences in a way that takes the censoring into account, and then re-calculate our similarity measure. Each of the difference-in-differences, Δ, is adjusted according to the formula:

$$\Delta = \begin{cases} \max((T_t - T_{t-1}) - \tau, -T_{t-1}) - (C_t - C_{t-1}) & \text{if } \tau \geq 0 \\ (T_t - T_{t-1}) - \max((C_t - C_{t-1}) + \tau, -C_{t-1}) & \text{otherwise} \end{cases}$$

where T_t and T_{t-1} are the numbers of low-carbon patents filed by an EU ETS firm in the treatment period t (2005–2009) and the pre-treatment period $t-1$ (2000–2004), respectively. C_t and C_{t-1}, are the corresponding numbers for the matched non-EU ETS firms, and τ is the treatment effect. The point estimate of the treatment effect is then the value of τ for which the similarity measure is maximized, and the $(1-\alpha)\%$ confidence interval is the set of values of τ for which we cannot reject the alternative of difference at the $\alpha\%$ level of significance. We implement this estimator using as our similarity measure the p-value calculated from the Wilcoxon signed-rank test. This provides a non-parametric alternative to the Tobit estimator.

We estimate a treatment effect of $\tau = 2$ additional low-carbon patents for our EU ETS firms, with a 95% confidence interval of $(1, 5)$. The matched EU ETS firms filed a total of 316 low-carbon patents in the period 2005-2009. Subtracting 2 low-carbon patents from each of our matched EU ETS firms (and accounting for censoring at zero) tells us that these firms together would have filed 232 low-carbon patents in the absence of EU ETS regulations. Our estimated treatment effect therefore implies that EU ETS has prompted 84 $(53, 129)$ additional low-carbon patents amongst our sample of EU ETS firms, or an increase of 36.2% (20.2%, 69.0%) compared to what we expect would have happened in the absence of the EU ETS. Because these firms only account for a small portion of all patents, however, this remarkable impact translates into an increase of low-carbon patenting at the EPO of only 0.38% (0.24%, 0.58%) compared to what we expect it would have been in the absence of the EU ETS. If we think our estimate applies to all of the 5'568 EU ETS firms, we can use their patenting records to calculate that, once we account for censoring at zero, the EU ETS is responsible for 188 $(114, 319)$ additional low-carbon patents. This amounts to a 8.1% (4.7%, 14.5%) increase in their low-carbon patenting, or a 0.85% (0.51%, 1.45%) increase in the total number of low-carbon patents filed at the EPO in 2005–2009. The first thing to note about these numbers is that they are substantially smaller than what was suggested by our naive calculations above (585.2 additional low-carbon patents, or a 2.6% increase in low-carbon patents at the EPO, see table 3). Second, because these numbers are so small relative to the totals, it is likely we would not have recognized the impact to be anything different from zero, had we been studying patent counts at a more aggregated level.

To address the issue of the *direction* of technological change, we must compare this with the impact on patenting for other technologies. Environmental regulations like the EU ETS increase the cost of production and can in principle encourage patenting for any technology that reduces it, be it a low-carbon technology or not. The induced innovation hypothesis holds that a policy like the EU ETS would have a disproportionate impact on low-carbon technologies, but this is an essentially empirical matter. There is a related concern, also, that the increase in low-carbon innovation will actually displace, or crowd out, development of other technologies (Popp and Newell, 2012). We can address these questions using the same matched sample and estimator described above. We estimate that the EU ETS has added on average 1 other patent $(1, 1.99)$. This translates into 305 $(305, 512.9)$ additional patents for other technologies, which represents an increase of 1.9% (1.9%, 3.2%) in their patent filings for non-low-carbon technologies, or a 0.041% (0.041%, 0.068%) increase in patenting for other technologies at the EPO. Comparing these numbers with the estimates from the previous paragraph, we see that the EU ETS has had a disproportionate impact on patenting for low-carbon technologies: 36.2% vs. 1.9% (difference is significant at 5% level). Put another way, the Scheme has nearly had a 20 times greater impact on low-carbon patenting, but it has not crowded out patenting for other technologies. If we think our estimate applies to all of the 5'568 EU ETS firms, the EU ETS would be responsible for 554 $(554, 963.86)$ additional other patents, which amounts to a 0.77% (0.77%, 1.34%) increase in their other patenting, or a 0.074% (0.074%, 0.13%) increase in the total number of other patents filed at the EPO in 2005–2009.

Table 3: Summary of results

	Matching estimates		Naive estimates
	Matched sample	Full sample	Full sample
Additional low-carbon patents	84	188	585.2
	(53, 129)	(114, 319)	
As % increase	36.2	8.1	36.5
	(20.2, 69.0)	(4.7, 14.5)	
As % increase of EPO	0.38	0.85	2.6
	(0.24, 0.58)	(0.51, 1.45)	
Additional other patents	305	554	9072.8
	(305, 512.9)	(554, 963.86)	
As % increase	1.9	0.77	16.0
	(1.9, 3.2)	(0.77, 1.34)	
As % increase of EPO	0.041	0.074	1.2
	(0.041, 0.068)	(0.074, 0.13)	

Point estimates, along with 95% confidence intervals in brackets where applicable. The matched sample estimates consider the impact only for the 3'426 matched EU ETS firms, while full sample estimates consider the impact for all 5'568 EU ETS firms in our data set. The matching estimates are calculated using our point estimates of τ obtained for the matched sample of 3'426 EU ETS firms and 4'373 non-EU ETS firms. Naive estimates are included for comparison. They have been calculated using the full set of 30 million non-EU ETS firms to construct a counterfactual, as in section 3.

Our results are summarised for convenience in table 3, along with comparable naive estimates for the full sample of EU ETS firms (calculated as in section 3). The naive estimates display the same general pattern as our matching estimates, showing increases in patenting for both low-carbon and other technologies, but with a pronounced direction. When compared to our matching estimates, however, the naive calculations are revealed to substantially overestimate the impact of the EU ETS. The matching estimates still suggest the EU ETS has had a positive and notable impact on low-carbon patenting among EU ETS firms, though relative to the overall pace of low-carbon technological development, the impact appears to have been much smaller, boosting low-carbon patenting by only a fraction of a percent. On the one hand, our findings contradict early prognostications that over-allocation of emissions permits in the EU ETS would completely undermine the incentives for low-carbon innovation. On the other hand, even a quite remarkable response among EU ETS firms—whether 36.2% among matched EU ETS firms or 8.1% among the full sample—translates into rather small impact from an economy-wide perspective, less than a 1% increase at the EPO. It is worth noting that this apparently small impact relative to the overall pace of technological change is not simply an arithmetical artifact of the small number of EU ETS firms, however, as is demonstrated by the fact that the naive estimator is more than three times higher.

Before settling on an interpretation of our estimates, however, we must ask whether they are really best explained by the EU ETS having had a very small impact? Perhaps these small numbers should instead caution us that we may have underestimated the impact? Let us therefore investigate challenges to the internal and external validity of our results.

4.3 Robustness tests

Is our conclusion driven by an omitted variable? The primary challenge for any matching study is to justify the assumption that firms that appear similar are similar in unmeasured dimensions as well—often called 'selection on observables'. In a randomized experiment one can rely on the law of large numbers to achieve similarity between a treated and control group on both observed and unobserved characteristics. Matching, on the other hand, achieves an observed similarity by construction, so similarity on matched characteristics cannot be read to as evidence that the treated and control firms are also similar on unobserved characteristics.

A simple test of whether matching has achieved balance on unobserved variables is to look at a variable that was not used to construct the matches. We have one such variable in our data set: the number of employees. As figure 5 and table 4 show, the empirical distributions of number of employees of the EU ETS and non-EU ETS firms are very similar, and we can reject the hypothesis that they are materially different.

We can therefore have some confidence that matching has indeed recovered the central identifying condition of a randomized experiment.

Figure 5: Comparison of matched EU ETS and non-EU ETS firms on 'unobserved' variable

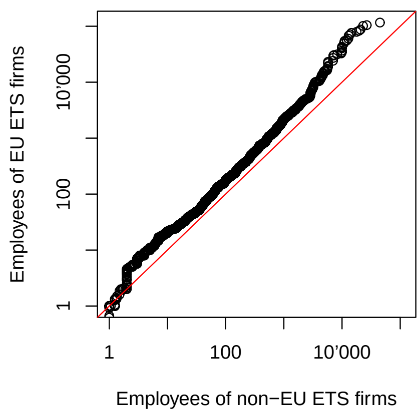


Table 4: Equivalence test for matched EU ETS and non-EU ETS firms on 'unobserved' variable

	Median difference between EU ETS and non-EU ETS firms	Equivalence range	Critical equivalence range (5% sign. lev.)
Employees	25	± 904.07	± 106.75

See caption of table 2 for details on how to read this table.

This test, though reassuring, is perhaps too simplistic. Other unobserved differences between regulated and unregulated firms might still bias our findings. What kind of an omitted variable could in principle undermine confidence in our estimate?

Imagine that we have an omitted binary variable that tells us whether a firm would be covered by a complementary carbon policy. If this variable is negatively correlated with EU ETS regulations and positively correlated with increases in low-carbon patenting (or vice versa), this omission would cause us to underestimate the impact of the EU ETS. Using the model for sensitivity analysis developed by Rosenbaum (1987) and Rosenbaum and Silber (2009), we can infer precisely how large the omitted variable bias would have to be in order to undermine confidence in our estimate relative to some larger alternative.

In order for our 3'428 matched EU ETS firms to have boosted the number of low-carbon patents filed at the EPO by 5%, say, they would have to have filed 1062 additional low-carbon patents. Since they did not file this many low-carbon patents in 2005–2009 in total, we can comfortably rule out that the EU ETS would have had such a large treatment effect even if all of the patents were additional. To have boosted low-carbon patents by just 1%, 223 of their low-carbon patents would have to have been additional. This translates back into a treatment effect of $\tau = 20.4$—more than 10 times higher than our original estimate. In order to increase our point estimate beyond this level, we would have to postulate an omitted variable that, if observed before 2005, would successfully predict more than 83 times out of a 100 (a) which firm in our matched pairs escapes EU ETS regulations *and* (b) which firm in our matched pairs would most increase their low-carbon patenting. Even if the omitted variable predicted (a) almost perfectly, it would still have to predict (b) 73 times out of 100. For the milder threshold of just being unable to reject the hypothesis that the the treatment effect is 20.4, we would still have to postulate an omitted variable that makes these prediction successfully more than 70 times out of 100.[16] We have estimated above that our sample of matched EU ETS firms account for only a 0.38% increase in low-carbon patenting at the EPO. If one finds an example of a complementary policy that was implemented in such a systematic fashion across the EU and caused such a predictable boost in the low-carbon patenting, we would have to concede that they may have boosted low-carbon patenting by as much as 1%. Even then, it is not obvious that this would seriously challenge the conclusion that the EU ETS has had but a limited direct impact on low-carbon patenting overall.

Another omitted variable candidate—whether a firm had high or low carbon emissions prior to 2005—is generally expected to be positively correlated with both a firm's chances of becoming regulated and with their chances of increasing their low-carbon patenting. The omission of a variable with these properties would imply we have overestimated the impact of the EU ETS above. To reduce our point estimate to zero, we would need to postulate an omitted variable that predicts more than 81 times out of 100 (a) which firm in our matched pairs became EU ETS regulated and (b) which firm in our matched pairs would most increase their low-carbon patenting. It would need to make these predictions successfully more than 71 times out of 100 to make us just unable to reject at the 5% level the hypothesis that the treatment effect is really zero.[17]

[16] In Rosenbaum's notation, it is just possible that the estimated treatment effect is 20.4 for a sensitivity parameter of $\Gamma = 2.65$, and we are just unable to reject this treatment effect at the 5% significance level for $\Gamma = 1.4$. This can be decomposed into the biases present in treatment assignment and outcomes using propositions in Rosenbaum and Silber (2009).

[17] In Rosenbaum's notation, it is just possible that the estimated treatment effect is 0 for a sensitivity parameter of $\Gamma = 2.34$, and we are just unable to reject this treatment effect at the 5% significance level

In sum, matching has achieved balance on at least one 'unobserved' characteristic, which might suggest it has balanced other unobserved variables as well, like a truly randomized experiment would have. Even if this is not the case, though, it appears our estimate of the low-carbon treatment effect is reasonably robust to both negative and positive omitted variable biases. If anything, the fact that the estimate is ever-so-slightly more sensitive to a positive bias would tend to reinforce our earlier conclusion that the EU ETS has had but a small direct impact on low-carbon patenting.

Are the estimates valid beyond our sample? A more serious challenge to our conclusion, perhaps, is to justify extrapolating from our sample of 3'428 EU ETS firms to all EU ETS firms. This type of calculation might lead us to underestimate the impact of the EU ETS if the firms omitted from estimation have had a systematically stronger reaction compared to those firms in our sample.

We can address this concern in three ways: (1) increasing the sample size, (2) calculating an upper bound for our estimates, and (3) calculating a lower bound for the out-of-sample response necessary to qualitatively affect our conclusions. Firstly, because turnover figures become more widely available in 2005, we are able to increase sample size if we allow ourselves to use 2005 turnover figures to construct the matches. This is not generally desirable, because the EU ETS might have affected 2005 turnover, which in turn had some effect on low-carbon patenting. If this is the case, the matching estimate using 2005 turnover would be biased because it omits this channel. However, because using 2005 turnover gives us access to a greater number of EU ETS and non-EU ETS firms, it may still provide a reasonable test of whether our findings apply to the EU ETS more broadly.

Matching using 2005 turnover figures allows us to successfully match an additional 427 EU ETS firms, producing 3'855 matched groups in total. The point estimates for this sample are 2.75 $(1, 5.99)$ for low-carbon patents and 1 $(1, 1.99)$ for other patents. The point estimate for the impact on low-carbon patents is slightly larger than before (but not significantly different), but the same for other patents. These estimates translate into 92.25 $(49, 133.89)$ additional low-carbon patents and 318 $(318, 530.85)$ additional other patents across our 3'855 EU ETS firms. In percentage terms they imply a somewhat smaller patenting response than before: increases of 18.9 (9.2, 30.0) and 2.4 (2.4, 4.2) respectively. This amounts to a 0.42% (0.22, 0.60) increase in low-carbon patenting at the EPO and a 0.042 (0.042, 0.071) increase in patent filings for other technologies, which is virtually identical to our original estimates. The typical matched firm still looks

for $\Gamma = 1.45$.

much the same, which is what one would expect if we were simply finding more firms around the same EU ETS thresholds. The EU ETS firms in our original matched sample therefore appear to be representative of a larger portion of the EU ETS. On the other hand, it also means that this re-match does not so much help address concerns that the EU ETS is affecting low-carbon patenting among the atypical companies for which suitable unregulated matches could not be found the first time around.

It is, nevertheless, possible to bound the effect that these atypical firms can have on the impact estimates. Suppose we were able to perfectly match every one of the 2'140 EU ETS firms we were forced to omit. Suppose further that the hypothetically matched non-EU ETS firms have not filed any patents since 2005, a strict lower bound. Because we observe the low-carbon patenting of the EU ETS firms, these two assumptions allow us to calculate the upper bound difference-in-differences for each of these 2'140 EU ETS firms. Pooling them with the 3'428 previously difference-in-differences, we can then estimate the upper bound of the treatment effect.[18] This procedure produces point estimates of 13 $(4, 43.99)$ for low-carbon and 6 $(4, 10.99)$ for other patents. These high point estimates are driven in large part by a small number of prolific patenters that were previously omitted, but are now matched to hypothetical non-EU ETS firms with zero patents after 2005. Subtracting a large number of patents from each firm and accounting for censoring at zero, therefore, does not add as many patents as the higher point estimates perhaps might suggest. The new estimates translate into 524 $(275, 952.9)$ additional low-carbon patents and 2093 $(1582, 3176.95)$ additional other patents, or increases of 26.7% (12.4%, 62.2%) and 3% (2.3%, 4.7%) respectively. While there is still a clear direction to induced technological change, it is less pronounced than for our original estimates. In comparison with the total numbers of patents that would otherwise have been filed at the EPO in each category in this period, the additional patents represent a 2.4% (1.2%, 4.5%) increase in low-carbon patenting and a 0.28% (0.21%, 0.42%) increase in patenting for other technologies. In economic terms, the upper bounds are perhaps slightly more noteworthy than our original estimates, though we are now very aware of the kind of extremely favourable and unrealistic assumptions needed to generate results that even begin to demand attention. And even then, the results are perhaps not so impressive as to seriously challenge the conclusion that the EU ETS has had a limited direct impact on low-carbon patenting.

Our third strategy to address concerns about external validity is to calculate what

[18] This bound is analogous to the sharp bounds derived by Manski (2007, ch. 2) for situations with missing data. The bound is sharp in the sense that it does not impose any restrictions on the process that leads to 'missingness'.

out-of-sample response would be necessary in order to qualitatively affect our conclusion. Our sample covers 9'358 out of the 12'122 installations that fell under EU ETS regulation in 2005 (see table 1). In order for the EU ETS to have boosted low-carbon patenting by 5%, say, EU ETS firms would together have to have filed 1062 additional low-carbon patents in 2005–2009. Subtracting our best estimate of 188 additional low-carbon patents for the 5'568 firms operating 9'358 EU ETS installations, this leaves the operators of the remaining 2'764 installations to have filed 874 additional low-carbon patents. To put it another way, we estimate that the average EU ETS firm in our sample filed roughly 0.03 extra low-carbon patents, but even if the remaining 2'764 were operated by as many firms (another charitable assumption), the EU ETS firms outside our sample would have to have filed 0.32 additional low-carbon patents in the same period. The out-of-sample response would have to be 10 times greater than the in-sample response. Even if we use the upper bound estimate (in-sample firms filed 524 additional low-carbon patents), the out-of-sample firms would have to have filed 538 extra low-carbon patents, or at least 0.19 per firm, which is still more than twice the upper bound for our in-sample firms (0.09). These strong responses appear especially unlikely in light of the fact that most of the out-of-sample firms operate in countries with lower patenting propensities (Cyprus, Greece, Hungary, Italy, Latvia, and Slovenia).

It seems, therefore, that none of the strategies to address concerns about external validity—increasing sample size, computing upper bounds, and calculating necessary out-of-sample responses—seriously challenge our earlier conclusion. The EU ETS appears to have had a very limited direct impact on low-carbon technological change.

Other robustness tests. Above we have tried to address the most pertinent challenges to our interpretation of the results, but one can imagine still other explanations for why the direct impact of the EU ETS appears to have been so small. We have tried to test several of these:

- Are matched non-EU ETS firms also responding to EU ETS? If so, firms less exposed to the EU ETS and to direct competition with EU ETS firms would perhaps be expected to respond less. We re-match our EU ETS firms to similar firms in Norway, Switzerland, Bulgaria, and Romania (4 countries that did not launch the EU ETS in 2005, and two of which have remained outside). We also re-matched our EU ETS firms to similar US firms. Neither comparison returns an estimate of the treatment effect significantly different from that reported above (see appendix D for further details).

- Did the main patenting response occur after the Directive was adopted in 2003, but before the EU ETS launched in 2005? Some authors have highlighted the possibility that firms patent in anticipation of new regulations (Dekker et al., 2012). To address this concern, we re-matched our EU ETS firms using 2003 as the treatment year instead of 2005. The treatment effect for the period 2003–2004 actually indicates that prospective EU ETS firms would actually have filed 1.75 additional low-carbon patents *if not* for the EU ETS (again, zero adjusted), though the number is not significantly different from zero. In other words, there is no significant difference in the patenting activities of EU ETS and non-EU ETS firms in this period.

- Is the result an artifact of how we measure low-carbon patents? To address this, we looked at using an expanded definition of low-carbon patents. This does not materially affect our conclusions, however. Moreover, it seems that our results cannot be accounted for by a failure to adjust for the quality of patents either. The number of citations for patents held by EU ETS firms do not increase more than for non-EU ETS firms (see appendix D for more details).

- Is there some other hidden bias? We look at the number of patents filed by matched EU ETS and non-EU ETS firms protecting other 'pollution control technologies', as defined by Popp (2006b). Since these technologies do not help mitigate emissions covered under the EU ETS, we would not expect the EU ETS to have had any impact. A hidden bias in our study design would manifest itself as finding a treatment effect here that is significantly different from zero. In fact, our estimated treatment effect is $\tau = 0.75$, but it is not significantly different from zero.[19]

It appears, then, that EU ETS has had a positive and notable impact on low-carbon patenting among EU ETS firms. It has spurred development of low-carbon technologies without crowding out innovation for other technologies. Since EU ETS firms account for only a small proportion of low-carbon patents, however, the impact on EU ETS regulated firms is negligible on a European scale. None of the above challenges seems to offer a compelling alternative explanation to this interpretation of the results.[20]

[19]Roughly 20% of EPO patents classified as one of Popp's pollution control technologies also fall into the low-carbon category. Excluding these, however, does not substantively affect the outcome.

[20]One must be careful also because some of the tests we have used to investigate these alternative explanations, though addressing one potential source of bias, may introduce new biases of their own (e.g. using 2005 turnover figures). The point here, however, is that to replicate our results each time, the new bias would have to be of the same sign and magnitude as the hypothesized bias in the original

If we accept, then, that the impact of the EU ETS on regulated firms does not account for the post-2005 surge in low-carbon patenting seen in figure 1, might the EU ETS still be indirectly responsible? Has it encouraged third parties to develop low-carbon technologies in the hope of selling or licensing them to newly regulated EU ETS firms? We investigate this question next.

5 The indirect impact of the EU ETS

The preceding analysis strongly suggests that the direct impact of the EU ETS has not been sufficient to account for the apparent surge in low-carbon patenting since 2005. Could the impact of the EU ETS instead have been largely indirect, spurring third parties to develop new low-carbon technologies?

There are three major reasons why we would expect the indirect impact to be comparatively small. Firstly, economic theory predicts that environmental regulations would produce greater incentives to develop new technologies for directly regulated firm than for third parties (Milliman and Prince, 1989; Fischer et al., 2003). The asymmetry arises because the latter group is not discharging costly emissions themselves and receive no additional benefit reducing its own emissions. To the extent that the EU ETS is encouraging low-carbon technological change, therefore, economic theory predicts this response to be strongest among EU ETS firms.

Secondly, EU ETS firms have filed over 120'000 patents with the EPO since 2000, circa 2.5% of which protect low-carbon technologies. These are clearly firms with above average innovation capabilities. To argue that the bulk of the response to the EU ETS comes from third-party technology providers amounts to saying that these EU ETS firms with well-developed low-carbon innovation capabilities are responding mostly by purchasing technologies from others, rather than developing the technologies in-house to suit their own specific needs.

Thirdly, the EU ETS firms in our sample are very likely technology providers themselves. As highlighted in the previous paragraph, EU ETS firms do develop new technologies themselves, including low-carbon technologies. While some firms may innovate in the hope of meeting new demand from EU ETS firms, others might expect greater opportunities to purchase the technologies developed by EU ETS firms. The indirect impact of the EU ETS is the net of these two responses.

These three reasons suggest that the indirect impact of the EU ETS would be com-

match. This explanation becomes increasingly unlikely with each new test, and the explanation that our estimate is unbiased appears more likely by comparison.

paratively small, but all claims about the indirect effect need to be met with the same level of skepticism as any other empirical hypothesis. It is a very difficult task to cleanly estimate the indirect impact of the EU ETS, not least because of the difficulty involved in identifying firms more likely to either provide new technologies to EU ETS firms or to which EU ETS firms are more likely to provide new technologies. We can, nevertheless, make a start.

Consider the set of firms that had filed at least one patent jointly with an EU ETS firm prior to 2005. A joint patent filing records a technological partnership with an EU ETS firm. One might then expect these firms to be more likely than an average non-EU ETS to either provide technologies to EU ETS firms once the regulations came into force, or to demand new technologies from EU ETS firms. They are likely to be good candidates for studying the indirect impact of the EU ETS. By comparing this set of firms with other non-EU ETS firms, therefore, we might hope to gain at least some partial insight as to the net indirect impact of the EU ETS. It is worth noting, though, that while technology provision is an asymmetric relationship, co-patenting is of course symmetric. Hence, we cannot separate co-patenters into technology providers and demanders even if each co-patenter could in principle be classified as one or the other. Nevertheless, we can provide an indicative estimate of the *net* indirect impact of the EU ETS.

From patent records we can identify 11'603 non-EU ETS firms that each filed at least one patent jointly with an EU ETS firm in 1978–2004. Many of these firms are no longer active or operate in countries not in our data set, which prevents us from matching them. Additionally, as before there are many firms for which historical data are missing, and a few for which we simply cannot find suitable comparators. Our matched sample therefore contains 2'784 co-patenters and 19'361 similar firms that had not filed a joint patent with an EU ETS firm prior to 2005.[21] Figure 6 and table 5 show the properties of our matched sample.[22]

We estimate a treatment effect of $\tau = 0.99$ additional low-carbon patents among our co-patenters, with a 95% confidence interval of $(-0.99, 1.99)$. We cannot say with confidence, therefore, that the EU ETS has had any net impact on the low-carbon patenting of co-patenters. Even taking the point estimate at face value, it translates

[21] Compared to when EU ETS firms were matched earlier, finding a single good comparator here was a good indicator that there were many good comparators available. We have kept all of these comparators in our matched sample to reduce the variance of our estimates.

[22] On average, co-patenters have historically filed more patents than EU ETS firms. It is no mystery why—to be a co-patenters a firm must have filed at least one patent prior to 2005, while EU ETS firms had no such requirement to meet.

Figure 6: Comparison of matched co-patenters and non-co-patenting firms

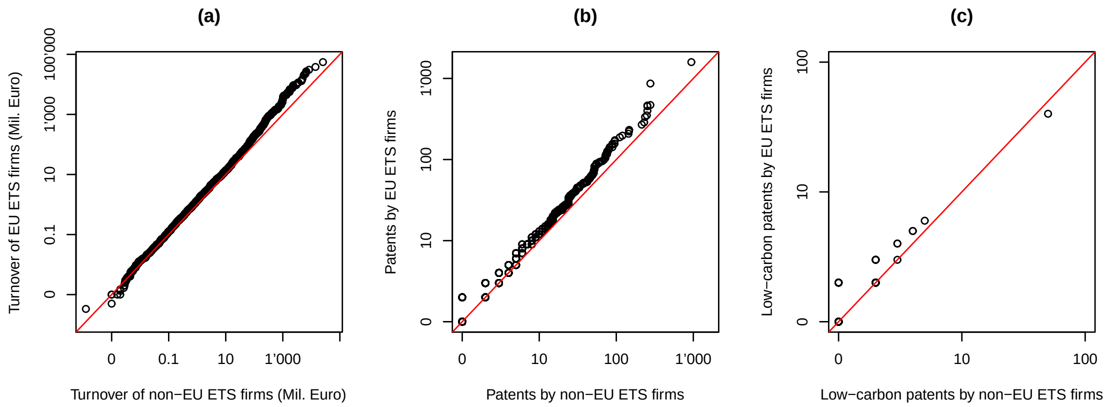


Table 5: Equivalence tests for matched co-patenters and non-co-patenting firms

	Median difference between EU ETS and non-EU ETS firms	Equivalence range	Critical equivalence range (5% sign. lev.)
Turnover (in th. Euro)	14.90	± 304'382.80	± 1'421.00
Patents	0	± 7.07	± < 0.01
Low-carbon patents	0	± 0.17	± 0.99
Year of incorporation	0	± 5.48	± 0.50
Any pre-2005 patents (binary)	Exactly matched	–	–
Economic sector	Exactly matched	–	–
Country	Exactly matched	–	–
Employees	1.66	± 1'613.82	± 20.66

See caption of table 2 for details on how to read this table. Again, the failure to reject the hypothesis of difference for low-carbon patents is a consequence of the small number of firms that filed any low-carbon patents prior to 2005. The same test also fails to reject the hypothesis that the difference is zero. Standard t-tests for differences in means reject the hypotheses of substantive differences for all variables (not reported). For completeness, the results from the robustness test of checking balance on employees is also included at the bottom of this table.

into a mere 47.52 additional low-carbon patents. Although it would represent a quite dramatic response, on the order of a 32.4% increase compared to what it would have been without the EU ETS, it would still translate into a negligible increase relative to the number of low-carbon patents filed at the EPO (0.2%). Extrapolating the number to all 11'603 co-patenters would naturally make it look as if the EU ETS has had a more impressive indirect impact, but since the estimate does not even stand up to a conventional significance test, such an exercise is not likely to be informative.

The picture is not much more encouraging for other technologies either. We estimate that the EU ETS has on average *subtracted* 0.745 other patents $(-0.99, -0.01)$ for co-patenters. We are just barely able to reject the hypothesis that the effect is actually zero, but this rejection does not withstand even the slightest challenge to robustness. Moreover, even if the point estimate were true, it would suggest that the EU ETS has crowded out patenting for non-low-carbon technologies among co-patenters.

These numbers offer no compelling evidence that the EU ETS has had an indirect impact on patenting. A patent filed jointly with an EU ETS firm is a record of a technological partnership, be it the case that the co-patenter has provided technologies to EU ETS firms or vice versa. In either case, one would expect that co-patenters are more likely than an average non-EU ETS firm to supply new technologies to EU ETS firms once the EU ETS launched, or to demand new technologies from EU ETS firms. Yet, taken together, co-patenters appear to behave no different to other non-EU ETS firms. It is of course incredibly difficult to identify potential technology providers and demanders for the purposes of estimation, so our results should not be over-interpreted. Nevertheless, our findings can perhaps be read as a reasonable indication that the EU ETS has had no net indirect impact on directed technological change. At the very least, it poses an empirical challenge for those wishing to argue otherwise.

6 Discussion

The EU ETS launched in 2005, amid both promises and pessimism. It has aimed to encourage the development of low-carbon technologies by putting a price on carbon emissions. In this paper we have investigated the Scheme's success in this regard during the 5 years subsequent to its launch.

A casual look at aggregate patenting suggests there has been an increase in low-carbon patenting since 2005, but there are several obstacles to isolating the impact of the EU ETS. Comparing patenting behaviour prior to and after 2005 risks conflating the impact of the EU ETS with other changes, like rapidly rising oil prices. Yet, looking only at the period after 2005 and comparing EU ETS regulated firms with those that escaped regulation risks conflating the impact of the EU ETS with other systematic differences in firm characteristics that might also drive patenting. Employing a matched difference-in-differences study design has permitted us to account for firm-level time-invariant heterogeneity, and to isolate that part of the change that does not depend on systematic differences in firm characteristics.

We find evidence that the EU ETS has had a strong impact on the patenting behaviour of EU ETS regulated firms. Our best estimate for a sample of 3'428 EU ETS firms implies that the Scheme has increased their low-carbon patenting by 36.2% compared to what we expect would have happened in the absence of the EU ETS. What is more, our estimates suggest that the Scheme has also encouraged EU ETS firms to increased their patent filings for non-low-carbon technologies by 1.9%. The EU ETS thus appears to have had a disproportionate impact on patenting for low-carbon technologies, but it has not crowded out patenting for other technologies.

Extrapolating our point estimates to 5'568 EU ETS firms across 18 countries (and accounting for censoring at zero), the EU ETS would account for an 8.1% increase in low-carbon patenting and a 0.77% increase in patenting for other technologies. Because of the targeted nature of EU ETS regulations, however, these responses translate into a quite unremarkable nudge on the pace and direction of technological change—a 0.38% boost to low-carbon patenting at the EPO (0.85% for the full sample), and a meagre 0.041% boost to patenting for other technologies (0.074% for the full sample).

To test whether our focus on EU ETS firms would have blinkered us to the Scheme's broader effects, we have also attempted to estimate the indirect impact of the EU ETS. To this end, we have compared non-EU ETS firms with at least one patent jointly filed with an EU ETS firm, with otherwise similar non-EU ETS firms. Although we can only provide indicative estimates, we find no compelling evidence that the EU ETS has had either a net positive or net negative impact on the patent filings of potential technology providers and demanders.

Our findings suggest a reinterpretation of the broader empirical literature on environmental policy and directed technological change. Several studies of the impacts of inclusive standards and energy or pollution taxes find evidence that the environmental policy does indeed encourage directed technological change (Lanjouw and Mody, 1996; Brunnermeier and Cohen, 2003; Popp, 2002, 2003, 2006b; Arimura et al., 2007; Lanoie et al., 2007). In contrast, studies of previous emissions trading schemes, like the US Acid Rain Program, at best unearth evidence of very small impacts on directed technological change (Popp, 2003; Lange and Bellas, 2005). Our results indicate that this discrepancy may be a consequence, not of weaker innovation incentives provided by emissions trading instruments, but of their tendency to concern a comparatively small number of firms. The impact on these firms may in fact be quite large, even in the EU ETS where permits in the initial trading phases were very likely over-allocated. When their response is compared to the overall pace of technological change, however, the effect appears negligible. Someone studying the impact of an emissions trading program by looking at patenting records at a more aggregated level is therefore likely to overlook the Scheme's strong but targeted effect. Conversely, the impact of more inclusive environmental policies, like standards, energy taxes, and pollution taxes, may be more easily detected because it is spread across so many firms, even if the change in behaviour for each firm is quite small. Debates about the relative costs and benefits of different environmental policy instruments already consider the impacts on pace and direction technological change of central importance (Kneese and Schultze, 1975; Pizer and Popp, 2008). Our results, read in combination with the findings of the broader literature, suggest that environmental policy instruments may differ also in the distribution of impacts on directed technological change. This could be potentially significant because of the positive spill-overs usually associated with innovation. It is an interesting question for future research, therefore, whether this could change the economic, or indeed the political calculus of instrument choice for environmental policy.

There are many other questions too that we have not answered in this paper. Our aim has been to establish what the overall impact of the EU ETS has been on directed technological change. Some readers, though, might be interested to know more of the impact in their own country, or perhaps in a particular economic sector. Such questions are much more difficult to answer with confidence. They involve estimating many more parameters, and there are fewer observations to estimate each one. Future research may give us a more granular picture of the impact of the EU ETS across countries and economic sectors. In focusing on the EU ETS, moreover, we also have not identified what has caused the post-2005 surge in low-carbon patenting in Europe. It would be an interesting exploratory exercise to search for the other factors contributing to this development (e.g. renewable energy policies). At present, we can establish only that the EU ETS seems to have played no more than a very limited part. A third set of questions relate to the innovation incentives attributable to specific features of the EU ETS. For instance, would we have observed a greater impact if the price of permits had been higher? Or if the permits had been auctioned instead of allocated for free? It is not feasible to test these hypotheses at present, given the lack of variation in EU ETS rules so far. Future changes to the rules may provide opportunities to study these specific questions.

Our results also have broader policy implications. The EU ETS forms an integral part of the European Union's roadmap to a low-carbon economy in 2050 (European Commission, 2011). Policy makers in New Zealand, the United States, Australia, China, Japan, South Korea, and elsewhere, can also learn from the EU ETS experience. So far, it appears that emissions reductions in the EU ETS have come largely from operational rather than technological changes, much like in past emissions trading programs. Emissions reductions have so far come largely from measures like fuel switching, but we know that such abatement strategies will not be enough to reach the EU's ambitious longer term targets. New low-carbon technologies are needed. Indeed, our results indicate that EU ETS regulated firms are cognizant of this fact, and are responding accordingly. Even so, because the impact of emissions trading appears to be concentrated to a relatively small group of firms, their response looks to nearly vanish when considered in relation to the overall pace and direction of technological change. For this reason, the Scheme in its current form might not be providing the economy-wide incentives necessary to bring about low-carbon technological change on a larger scale.

A Data

For 8 of the countries in our sample, the company registration numbers of the installation operators were obtained directly, either from national emissions trading registries or from the Community Independent Transactions Log (CITL) (the EU body to which national registries report). For the remaining 13 countries in our data set that participated in the 2005 launch of the EU ETS, a combination of exact and approximate text matching methods were used to establish a link between firm data and regulatory data. This was complemented by further manual searches, and extensive manual double-checking.

The firm data set allows us to identify majority ownership. Using this information, we excluded non-EU ETS firms that were owner, sister company, or subsidiary to an EU ETS firm. This reduces the chance of matching two potentially dependent observations.

B Matching

The matches were constructed using `GenMatch()` from the `R`-package `Matching`. It uses a genetic search algorithm to search the propensity score space for a specification that minimizes imbalances on the whole set of covariates (see Sekhon, 2007, for details). We used variable ratio matching with replacement, so that each EU ETS firm could be matched to one or more non-EU ETS firms depending on how many similar non-EU ETS firms could be found.

C Patents

We use the patent codes available at www.oecd.org/environment/innovation. For our main measure of low-carbon patents we use the EPO patent classes for low-carbon patents definition, detailed in Veefkind et al. (2012). Table 6, adapted from Veefkind et al. (2012), lists the main patent classes along with some examples of technologies for each class:

D Details of other robustness tests

Are matched non-EU ETS firms also responding to EU ETS? The matched firms that are not regulated by the EU ETS may nevertheless respond to it, either directly, or indirectly because they engage in competition with EU ETS firms. This would

Table 6: Climate change mitigation patent categories (EPO's Y02 class)

Patent code	Description	Example technologies
Y02C 10/00	CO_2 capture or storage	Chemical or biological separation, ad- or absorption, membrane technology, condensation etc.; subterranean or submarine storage
Y02C 20/00	Capture or disposal of greenhouse gases other than CO2	N2O, methane, perfluorocarbons, hydrofluorocarbons or sulfur hexafluoride
Y02E 10/00	Energy generation through renewable energy sources	Geothermal, hydro, oceanic, solar (photovoltaic and thermal), wind
Y02E 20/00	Combustion technologies with mitigation potential	Combined Heat and Power (CHP), Combined Cycle Power Plant (CCPP), Integrated Gasification Combined Cycle (IGCC), synair, oxyfuel combustion, cold flame, etc.
Y02E 30/00	Energy generation of nuclear origin	Fusion and fission
Y02E 40/00	Technologies for efficient electrical power generation, transmission or distribution	Reactive power compensation, efficient operation of power networks, etc.
Y02E 50/00	Technologies for the production of fuel of non-fossil origin	Biofuels, from waste
Y02E 60/00	Technologies with potential or indirect contribution to greenhouse gas (GHG) emissions mitigation	Energy storage (batteries, ultracapacitors, flywheels.), hydrogen technology, fuel cells, etc.
Y02E 70/00	Other energy conversion or management systems reducing GHG emissions	Synergies among renewable energies, fuel cells and energy storage

bias our estimates. If very similar unregulated firms are responding by innovating more, a comparison of EU ETS firms and matched non-EU ETS firms will under-estimate the impact of the EU ETS. If very similar unregulated firms are responding by innovating less, this comparison will over-estimate the impact of the EU ETS. To examine these possibilities we have re-matched our EU ETS firms to companies operating in European countries that did not participate in the 2005 launch of the EU ETS (Norway, Switzerland, Romania, and Bulgaria), and then separately to US companies. These comparisons are less likely to suffer from this kind of bias, because the matched non-EU ETS firms are less exposed to the market created by the EU ETS and less likely to be directly engaged in competition with EU ETS companies.[23]

Table 7 reports the estimated treatment effects for both the European and US re-matched samples, along with our original estimates for comparison. Neither of the re-matched estimates differ significantly from our original estimate. Though, if one were to interpret the point estimates, the fact that they are smaller than our original estimate would tend to indicate that very similar unregulated firms in EU ETS countries are innovating less in response to the EU ETS. Due to between-country differences,

[23]While this comparison helps address a potential bias introduced by non-EU ETS firms responding to the EU ETS, it is not able to control for between-country differences.

ht

Table 7: Treatment effect estimates using 'distant' matches

Norway, Switzerland,	1
Romania, and Bulgaria	(0, 1.99)
USA	-1
	(-1.99, 0.99)
Original estimate	2
	(1, 5)

which these re-matched estimates cannot control for, one should exercise caution in recommending such an interpretation.

Is the result an artifact of how we measure low-carbon patents? It is possible that our finding is an artifact of our particular measure of low-carbon technological change. If we compare our matched EU ETS and non-EU ETS firms using expanded definition of "low-carbon technologies", the result does not appear to change materially (see table D). Our original estimate was that the EU ETS accounts for a 36.2% increase in low-carbon patenting among matched EU ETS firms, a 8.1% increase across our full sample of EU ETS firms, and no more than a 1% increase across our study area. The new treatment effect estimates suggest the EU ETS may have increased low-carbon patenting among matched EU ETS firms by 32.4%, a 7.1% increase across our full sample, and no more than a 1% increase across our study area. The new numbers are well within our original confidence intervals, and do not appear to present a challenge for our interpretation of the results. Our findings therefore appear robust to how the outcome is defined.

Table 8: Estimates with different definitions of "low-carbon technologies"

	Additional low-carbon patents			
	Matched sample		Full sample	
	As % increase	As % increase of EPO	As % increase	As % increase of EPO
Extended definition	32.4	0.34	7.1	0.77
	(20.3, 62.5)	(0.24, 0.54)	(4.5, 12.3)	(0.50, 1.28)
Standard EPO definition	36.2	0.38	8.1	0.85
	(20.2, 69.0)	(0.24, 0.58)	(4.7, 14.5)	(0.51, 1.45)

A related concern is that patent counts would omit any EU ETS response that appears in the form of a change in the quality of patents. To address this concern, we ht

Table 9: Changes in quality of low-carbon patents

Additional citations per firm	2.25
	(-0.99, 17.99)

test whether the EU ETS has systematically changed the number of citations received by low-carbon patents held by EU ETS relative to non-EU ETS firms. Our results, reported in table 9, indicate that the EU ETS has not had a significant impact on patent quality.

References

Abadie, A. (2005). Semiparametric difference-in-differences estimators. *The Review of Economic Studies*, 72(1):1–19.

Acemoglu, D., Aghion, P., Bursztyn, L., and Hemous, D. (2012). The Environment and Directed Technical Change. *The American Economic Review*, 102(1):131–166.

Ambec, S., Cohen, M., Elgie, S., and Lanoie, P. (2010). The porter hypothesis at 20: Can environmental regulation enhance innovation and competitiveness? *CIRANO Working Papers*.

Anderson, B., Convery, F., and Maria, C. D. (2011). Technological change and the EU ETS: the case of Ireland. *IEFE Working Paper Series*, (43).

Anderson, B. and Di Maria, C. (2011). Abatement and Allocation in the Pilot Phase of the EU ETS. *Environmental and Resource Economics*, pages 1–21.

Arimura, T. H., Hibiki, A., and Johnstone, N. (2007). An empirical study of environmental R&D: what encourages facilities to be environmentally innovative? In Johnstone, N., editor, *Corporate Behaviour and environmental Policy*, chapter 4. Cheltenham, UK: Edward Elgar in association with OECD.

Brunnermeier, S. B. and Cohen, M. A. (2003). Determinants of environmental innovation in US manufacturing industries. *Journal of Environmental Economics and Management*, 45(2):278–293.

Burtraw, D. (2000). Innovation Under the Tradeable Sulphur Dioxide Emission Permits Programme in the US Electricity Sector. In *Innovation and the Environment*, pages 63–84. OECD.

Burtraw, D. and Szambelan, S. (2009). US emissions trading markets for SO2 and NOx. *Resources for the Future Discussion Paper*, (09-40).

Chay, K. Y. and Powell, J. L. (2001). Semiparametric censored regression models. *Journal of Economic Perspectives*, pages 29–42.

Cochran, W. and Rubin, D. (1973). Controlling bias in observational studies: A review. *Sankhyā: The Indian Journal of StatisticsSeries A*, 35(4):417–446. Dedicated to the Memory of P. C. Mahalanobis.

Dechezleprêtre, A., Glachant, M., Haščič, I., Johnstone, N., and Ménière, Y. (2011). Invention and transfer of climate change–mitigation technologies: a global analysis. *Review of Environmental Economics and Policy*, 5(1):109.

Dehejia, R. and Wahba, S. (1999). Causal effects in nonexperimental studies: Reevaluating the evaluation of training programs. *Journal of the American Statistical Association*, 94(448):1053–1062.

Dekker, T., Vollebergh, H. R., de Vries, F. P., and Withagen, C. A. (2012). Inciting protocols. *Journal of Environmental Economics and Management*, 64(1):45–67.

Delarue, E., Ellerman, D., and D'haeseleer, W. (2010). Short-term CO2 abatement in the European power sector: 2005-2006. *Climate Change Economics*, 1(2):113–133.

Delarue, E., Voorspools, K., and D'haeseleer, W. (2008). Fuel switching in the electricity sector under the EU ETS: review and prospective. *Journal of Energy Engineering*, 134(2):40–46.

Ellerman, A. and Buchner, B. (2008). Over-allocation or abatement? A preliminary analysis of the EU ETS based on the 2005–06 emissions data. *Environmental and Resource Economics*, 41(2):267–287.

Ellerman, A. D., Convery, F. J., and de Perthuis, C. (2010). *Pricing Carbon: The European Union Emissions Trading Scheme*. Cambridge University Press.

European Commission (2011). A Roadmap for moving to a competitive low carbon economy in 2050. Technical Report COM(2011) 112, European Union.

Fischer, C., Parry, I., and Pizer, W. (2003). Instrument choice for environmental protection when technological innovation is endogenous. *Journal of Environmental Economics and Management*, 45(3):523–545.

Gagelmann, F. and Frondel, M. (2005). The impact of emission trading on innovation-science fiction or reality? *European Environment*, 15(4):203–211.

Gerlagh, R. (2008). A climate-change policy induced shift from innovations in carbon-energy production to carbon-energy savings. *Energy Economics*, 30(2):425–448.

Goulder, L. and Schneider, S. (1999). Induced technological change and the attractiveness of CO2 abatement policies. *Resource and Energy Economics*, 21(3-4):211–253.

Greenstone, M. and Gayer, T. (2009). Quasi-experimental and experimental approaches to environmental economics. *Journal of Environmental Economics and Management*, 57(1):21–44.

Griliches, Z. (1984). *R & D, patents, and productivity.* University Of Chicago Press.

Grubb, M., Azar, C., and Persson, U. (2005). Allowance allocation in the European emissions trading system: a commentary. *Climate Policy*, 5(1):127–136.

Hall, B., Jaffe, A., and Trajtenberg, M. (2005). Market value and patent citations. *The RAND Journal of Economics*, 36(1):16–38.

Harhoff, D., Narin, F., Scherer, F., and Vopel, K. (1999). Citation frequency and the value of patented inventions. *Review of Economics and statistics*, 81(3):511–515.

Harhoff, D., Scherer, F., and Vopel, K. (2003). Citations, family size, opposition and the value of patent rights. *Research Policy*, 32(8):1343–1363.

Heckman, J., Ichimura, H., Smith, J., and Todd, P. (1998a). Characterizing Selection Bias Using Experimental Data. *Econometrica*, 66(5):1017–1098. ArticleType: research-article / Full publication date: Sep., 1998 / Copyright © 1998 The Econometric Society.

Heckman, J. J., Ichimura, H., and Todd, P. (1998b). Matching as an econometric evaluation estimator. *The Review of Economic Studies*, 65(2):261–294.

Hicks, J. R. (1932). *The Theory of Wages.* MacMillan.

Ho, D. E. and Imai, K. (2006). Randomization Inference With Natural Experiments. *Journal of the American Statistical Association*, 101:888–900.

Hoffmann, V. H. (2007). EU ETS and Investment Decisions: The Case of the German Electricity Industry. *European Management Journal*, 25(6):464–474.

Johnstone, N., Haščič, I., and Popp, D. (2010). Renewable energy policies and technological innovation: Evidence based on patent counts. *Environmental and Resource Economics*, 45(1):133–155.

Kaufer, E. (1989). *The economics of the patent system.* Routledge.

Kneese, A. V. and Schultze, C. (1975). Pollution, Prices, and Public Policy. *(Brookings Institution, Washington, DC).*

Kossoy, A. and Guigon, P. (2012). State and trends of the carbon market 2012. Annual report, World Bank.

Lange, I. and Bellas, A. (2005). Technological change for sulfur dioxide scrubbers under market-based regulation. *Land Economics*, 81(4):546–556.

Lanjouw, J. and Mody, A. (1996). Innovation and the international diffusion of environmentally responsive technology. *Research Policy*, 25(4):549–571.

Lanoie, P., Laurent-Lucchetti, J., Johnstone, N., and Ambec, S. (2007). Environmental policy, innovation and performance: new insights on the Porter hypothesis. *CIRANO Working Papers*.

List, J. A., Millimet, D. L., Fredriksson, P. G., and McHone, W. W. (2003). Effects of Environmental Regulations on Manufacturing Plant Births: Evidence from a Propensity Score Matching Estimator. *Review of Economics and Statistics*, 85(4):944–952.

Manski, C. F. (2007). *Identification for Prediction and Decision*. Harvard University Press.

Martin, R., Muuls, M., and Wagner, U. (2011). Climate change, investment and carbon markets and prices – evidence from manager interviews. *Climate Strategies, Carbon Pricing for Low-Carbon Investment Project*.

Milliman, S. and Prince, R. (1989). Firm incentives to promote technological change in pollution control. *Journal of Environmental Economics and Management*, 17(3):247–265.

Newell, R., Jaffe, A., and Stavins, R. (1999). The induced innovation hypothesis and energy-saving technological change*. *Quarterly Journal of Economics*, 114(3):941–975.

OECD (2009). OECD Patent Statistics Manual. Technical report, OECD.

Petsonk, A. and Cozijnsen, J. (2007). Harvesting the Low-Carbon Cornucopia: How the European Union Emissions Trading System (EU-ETS) is spurring innovation and scoring results. *Environmental Defense*, pages 1–23.

Pizer, W. A. and Popp, D. (2008). Endogenizing technological change: Matching empirical evidence to modeling needs. *Energy Economics*, 30(6):2754–2770.

Popp, D. (2002). Induced innovation and energy prices. *The American Economic Review*, 92(1):160–180.

Popp, D. (2003). Pollution control innovations and the Clean Air Act of 1990. *Journal of Policy Analysis and Management*, 22(4):641–660.

Popp, D. (2004). ENTICE: Endogenouse Technological Change in the DICE Model of Global Warming. *Journal of Environmental Economics and Management*, 24(1):742–768.

Popp, D. (2006a). Innovation in climate policy models: Implementing lessons from the economics of R&D. *Energy Economics*, 28(5-6):596–609.

Popp, D. (2006b). International innovation and diffusion of air pollution control technologies: the effects of NOX and SO2 regulation in the US, Japan, and Germany. *Journal of Environmental Economics and Management*, 51(1):46–71.

Popp, D. (2010). Innovation and climate policy. *NBER Working Paper*.

Popp, D. and Newell, R. (2012). Where does energy R&D come from? Examining crowding out from energy R&D. *Energy Economics*, 34(4):980–991.

Popp, D., Newell, R., and Jaffe, A. (2009). Energy, the environment, and technological change. *NBER Working Paper*.

Porter, M. E. (1991). Essay: America's green strategy. *Scientific American*, 264(3).

Rosenbaum, P. (1987). Sensitivity analysis for certain permutation inferences in matched observational studies. *Biometrika*, 74(1):13–26.

Rosenbaum, P. and Silber, J. (2009). Amplification of sensitivity analysis in matched observational studies. *Journal of the American Statistical Association*, 104(488):1398–1405.

Rosenbaum, P. R. (2009). Design of observational studies. page 384.

Schleich, J. and Betz, R. (2005). Incentives for energy efficiency and innovation in the European Emission Trading System. *In Proceedings of the 2005 ECEEE Summer Study—What Works and Who Delivers? Mandelie*, pages 1495–1506.

Schmalensee, R., Joskow, P., Ellerman, A., Montero, J., and Bailey, E. (1998). An interim evaluation of sulfur dioxide emissions trading. *The Journal of Economic Perspectives*, 12(3):53–68.

Sekhon, J. (2007). Multivariate and propensity score matching software with automated balance optimization: The matching package for r. *Journal of Statistical Software*, 10(2):1–51.

Smith, J. and Todd, P. (2005). Does matching overcome LaLonde's critique of nonexperimental estimators? *Journal of econometrics*, 125(1):305–353.

Tomás, R., Ribeiro, F. R., Santos, V., Gomes, J., and Bordado, J. (2010). Assessment of the impact of the European CO2 emissions trading scheme on the Portuguese chemical industry. *Energy Policy*, 38(1):626–632.

Trajtenberg, M. (1990). A penny for your quotes: patent citations and the value of innovations. *The Rand Journal of Economics*, pages 172–187.

van der Zwaan, B., Gerlagh, R., Schrattenholzer, L., et al. (2002). Endogenous technological change in climate change modelling. *Energy economics*, 24(1):1–19.

van Zeebroeck, N. (2011). The puzzle of patent value indicators. *Economics of Innovation and New Technology*, 20(1):33–62.

Veefkind, V., Hurtado-Albir, J., Angelucci, S., Karachalios, K., and Thumm, N. (2012). A new EPO classification scheme for climate change mitigation technologies. *World Patent Information*, 34(2):106–111.