THE LONDON SCHOOL
OF ECONOMICS AND
POLITICAL SCIENCE

EMISSIONS TRADING AND TECHNOLOGICAL CHANGE

Raphael Calel

A thesis submitted to the Department of Geography & Environment of the
London School of Economics for the degree of Doctor of Philosophy,
London, June 2013

Declaration

I certify that the thesis I have presented for examination for the PhD degree of the London School of Economics and Political Science is solely my own work other than where I have clearly indicated that it is the work of others (in which case the extent of any work carried out jointly by me and any other person is clearly identified in it).

The copyright of this thesis rests with the author. Quotation from it is permitted, provided that full acknowledgement is made. This thesis may not be reproduced without the prior written consent of the author.

I warrant that this authorisation does not, to the best of my belief, infringe the rights of any third party.
I declare that my thesis consists of 48,627 words.

Statement of conjoint work

I confirm that Chapter 5 was jointly co-authored with Dr. Antoine Dechezleprêtre and I contributed 75% of this work. In order to make the published version of Chapter 5 self-contained, it incorporates sections that appear in Chapter 4 in this thesis. Chapter 4 is single authored by the candidate.

Statement of prior publication

A version of Chapter 2 has been published in Wiley's Interdisciplinary Reviews: Climate Change (Calel, 2013). Earlier versions of Chapters 3 and 5 have appeared as working papers, as Calel (2011) and Calel & Dechezleprêtre (2012) respectively.

Statement of use of third party for editorial help

I confirm that my thesis was copy edited for conventions of language, spelling and grammar by Jeremy Grove of Grove Proofreading & Editorial Services.

Disclaimers

Chapter 4 contains statistical data from the Office of National Statistics which is Crown copyright and reproduced with the permission of the Controller of HMSO and the Queen's Printer for Scotland. The UK Data Service agrees that the attached outputs are non-disclosive, and cannot be used to identify a person or organisation. The original data creators, depositors or copyright holders, the funders of the Data Collections (if different) and the UK Data Service at the UK Data Archive bear no responsibility for the further analysis or interpretation of the data. This work uses research datasets which may not exactly reproduce National Statistics aggregates.

Chapter 5 uses statistical data from Bureau van Dijk, obtained under a license held by the London School of Economics and Political Science.

Abstract

Emissions trading programmes have grown in number and scope over the last forty years, and in the last decade they have become a centerpiece of global climate change policy. Emissions trading can in principle offer policy makers a flexible mechanism to reduce harmful emissions—polluters can choose their own emissions abatement strategy, and the trading mechanism can reduce the overall abatement cost by flexibly redistributing emissions permits to those polluters that find abatement costliest. In the context of climate policy, though, it is the potential to stimulate innovation and technological change that is most alluring. Without transforming production, the quantity of emissions abatement will be insufficient; without technological change, the cost will be prohibitive. Emissions trading programmes are clearly not the only policy that affect technological change, but the extent to which these programmes encourage low-carbon technological change is perhaps still the most important criterion on which to judge their success or failure.

Advances in monitoring, greater data availability, and improvements in statistical and computational techniques have only recently made it possible to systematically study the impacts of emissions trading programmes on a large scale. In recent years, researchers have studied the impact of emissions trading programmes on company profitability, on employment, and on capital investment. This thesis aims to advance this research programme by contributing a systematic analysis of how emissions trading affects technological change.

This thesis comprises four essays. The first essay examines past emissions trading programmes and the extent to which these experiences provide guidance on the ability of emissions trading programmes to affect low-carbon technological change in the future. The second essay investigates the degree to which economic theory can help constrain the range of expected impacts in a world of at least moderate complexity. The third and fourth essays present the first comprehensive empirical assessment of how the world's largest emissions trading programme, the EU Emissions Trading Scheme, has affected technological change, measured in terms of carbon dioxide intensity of output, research and development, and patenting.

Acknowledgements

The thanking of friends and colleagues and co-conspirators is the most enjoyable part of the completion of any work. To give proper due to all whom I owe, however, would be quite impossible. I must therefore preemptively extend my thanks to all of you whom I have neglected to mention here, and beg your forgiveness.

I am grateful for the time and counsel of my supervisors Sam Fankhauser and Carmen Marchiori. I would also like to give special thanks to Antoine Dechezleprêtre and Antony Millner, two collaborators from whom I have learnt a great deal. Conversations with Devin Caughey, Denny Ellerman, Christian Johansson, George MacKerron, Ralf Martin, Blas Pérez Henríques, James Rydge, and Luca Tascini have also provided ideas and inspiration, and I am fortunate to have had the opportunity to draw upon their knowledge and experience. Haydn Jones of the Environment Agency has generously shared his unparalleled knowledge of the many intricacies of UK climate change policy. Richard Welpton and his dedicated colleagues at the UK Data Service have provided invaluable data access and assistance. They provide a genuine public service.

I owe great thanks to the Grantham Foundation, the Economic and Social Sciences Research Council, and the Jan Wallander and Tom Hedelius Foundation, whose generous financial support has allowed me to devote my full energies to research. I am also grateful for further financial support from the London School of Economics and Political Science, which has allowed me to attend additional conferences. The Grantham Research Institute on Climate Change and the Environment has offered an edifying environment in which to work, and I am grateful to the staff whose dedication has made it possible for me to conduct my research without distraction.

I would be remiss not to thank Phil Faulkner, Sriya Iyer, Melvyn Weeks, and Malcolm Pemberton. While their influence on this thesis may be more remote, their past mentoring has been no less instrumental in turning me into the researcher I am today. I also owe an intellectual debt to Paul Rosenbaum, whose writings have been especially influential in shaping my thinking as an empirical researcher. I can only hope that this work is a credit to all of their names.

My PhD thesis would not have been possible without two pieces of open-source software—LaTeX and R. I would like to acknowledge the thousands of people who have given their time and effort to make these available to the public free of charge.

Then—not lastly, but at long last—I arrive at my chance to express my inexpressible gratitude to family and friends. Your support has been a source of renewed motivation when my own waned, and you have offered sense when I took leave of mine. Though it may be a cliché, it is certainly no exaggeration to say neither I nor this thesis would have made it this far without your help. Thank you.

Contents

Appendices

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Emissions trading and technological change

> *Over the long haul, perhaps the most important single criterion on which to judge environmental policies is the extent to which they spur new technology toward the efficient conservation of the environment.*
>
> —Kneese & Schultze (1975, p. 38)

> *Technological change is at once the most important and least understood feature driving the future cost of climate change mitigation… Yet, in many ways, we are no closer to understanding the answer of how policies will affect the overall rate and direction of technological change.*
>
> —Pizer & Popp (2008, p. 2768)

Emissions trading programmes have assumed an increasingly prominent role in environmental policy over the last few decades. In the US, the Acid Rain Program, the Regional Greenhouse Gas Initiative (RGGI), and California's cap-and-trade programme are all examples of this trend. The EU Emissions Trading Scheme (EU ETS) has been the centerpiece of European climate change policy for the last decade. Australia, New Zealand, and the Canadian province of Quebec have all recently created their own emissions trading programmes to regulate greenhouse gas emissions. China, Japan, South Korea, and several others are individually making moves toward launching their own programmes as well. In terms of its traded value the international carbon trade is today worth over $175 billion a year (Kossoy & Guigon, 2012), and with so many new initiatives in the pipeline, this number is expected to grow much larger in years to come.

The principal objective of emissions trading programmes is to reduce harmful emissions. This can in principle be achieved by reducing output among heavily polluting firms and industries, but in practice the aim is to encourage these firms to produce their output with less emissions. In comparison with more conventional regulatory approaches such as technology-based standards, emissions trading programmes give firms much greater flexibility to choose their compliance strategy. It is this flexibility that has made emissions trading attractive to economists, policy makers, and industry alike. In the short term, the cost of abatement is lower because the price mechanism reallocates emissions permits to the firms that find abatement costliest. In the longer term, one hopes that this flexibility will encourage firms to undertake innovation that reduces the cost of emissions abatement.

In the context of climate change, the hope that emissions trading programmes will encourage technological change reigns supreme (Stavins, 2007).[1] Without transforming existing capital stocks, abatement strategies such as fuel switching in the power sector will likely achieve no more than 3% of the emissions reductions needed by 2050 (International Energy Agency, 2012). In Europe, fuel switching has the potential to reduce carbon dioxide emission by only about 300 million tonnes per year (Delarue et al., 2008), less than 10% of what is needed to meet the EU target to cut emissions by 80% by 2050 against 1990-levels.[2]

If expense was no object, it might be feasible to meet the world's needs in the next half-century while simultaneously avoiding potentially dangerous increases of atmospheric carbon dioxide

---

[1] From page 32: "Given the long-term nature of climate change, it is exceptionally important that the cap-and-trade approach provide incentives for long-term technological change. Technologies yet to be developed may significantly reduce the long-run cost of achieving climate policy objectives. It is critical that climate policies encourage innovations in technologies and in how fossil fuels are used. By rewarding emissions reductions, however they are accomplished, the cap-and-trade system provides broad incentives for innovations that lower the cost of achieving emissions targets."

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

concentrations using only existing technologies (Pacala & Socolow, 2004). In practice, though, cost is perhaps the chief obstacle to major mitigation action, and technological change may be the single most important determinant of the future cost of emissions abatement (Pizer & Popp, 2008, quoted above). Without transforming production, the quantity of abatement will be insufficient; without technological change, the cost will be prohibitive. In this sense, technological innovation is a necessary precursor to achieving longer term emissions abatement targets at a manageable cost. Consequently, the ability of new emissions trading programmes to influence the rate and direction of technological change is a key criterion on which to judge their success or failure.

The often articulated hope that emissions trading will stimulate low-carbon innovation (see, for instance, European Commission, 2005) springs in large part from an application of the "induced innovation" hypothesis (Hicks, 1932; Porter, 1991). It posits that when regulated firms come to face (or expect to face) a higher price on emissions relative to other costs of production, they innovate to reduce the emissions intensity of their output.[3] This would in principle apply to any regulatory regime that makes emissions costlier, but one hopes that by giving firms the flexibility to choose their own compliance strategy, a market-based instrument like emissions trading affords polluters greater opportunities and incentives to innovate and develop new cheaper ways to reduce emissions.

It is important to note that, although low-carbon innovation is under-provided, the under-pricing of carbon emissions may not be the only cause. A number of other market failures in early research, in demonstration and in commercialisation would similarly contribute to under-investment (Garnaut, 2011). The inability of investors to write long-term contracts with consumers (Neuhoff & De Vries, 2004), and the failure of the market to adequately price external knowledge economies also contribute to the problem (Jaffe et al., 2005). When these market failures are taken into account, a picture emerges in which emissions trading is considered only one element of the set of policies needed to induce low-carbon innovation (Fischer & Newell, 2008; Hanemann, 2009, 2010; Newell, 2010; Acemoglu et al., 2012). Even with this more modest view as to what level of low-carbon innovation an emissions trading programme

---

[3] It follows from this hypothesis that if carbon emissions are under-priced, low-carbon innovation is under-provided.

might accomplish, however, it remains a hypothesis with empirical content. The purpose of this thesis is to investigate how emissions trading affects technological change.

Before outlining the structure of the thesis, it is perhaps worth to try disposing of a common source of terminological confusion. Terms like *innovation* and *technological change* have already cropped up in the opening paragraphs, and will be used throughout this thesis, but how does one define them? A literature spanning the works of Joseph Schumpeter and W. Brian Arthur has not yet agreed upon an unambiguous definition, and I would not presume here to have a good answer to this question either. Firms make operational improvements, acquire more fuel-efficient equipment and machinery, develop entirely new technologies, etc.. These strategies differ in many dimensions; they are associated with different costs, different potential emissions reductions, different probabilities that future emissions reductions will be realised, different time-scales on which such emissions reductions might be realised, and with different opportunities to monetize and appropriate the return on investment. While acknowledging these differences, the term *innovation* is perhaps most useful as a shorthand for this collection of strategies. A term like *technological change* places greater emphasis on a subset of these strategies, namely those with a greater emphasis on enlarging the set of technologically feasible abatement opportunities. This does not resolve all of the terminological ambiguities, of course, but it will be mostly safe to set them aside for present purposes. It will be enough to acknowledge that these terms evoke useful sets of ideas that facilitate discussion.

When in later chapters I study particular variables—like the number of patents, R&D expenditures, and carbon intensity of output—the intention is first and foremost to describe the behaviour of quantities that decision makers are likely to find of interest, or quantities that are at least thought to be closely related to some set of strategies of interest (e.g. patents are believed to be closely related to the creation of technological knowledge and products). They are inevitably imperfect measures of innovation, and I shall always discuss the advantages and limitations of any indicator before it is used. While recognising the limitations, I will nevertheless often use terms like *innovation* and *technological change* when discussing the behaviour of these quantities. When employed in this context, these terms serve chiefly as devices for avoiding cumbersome sentences that make for tiresome reading.

1.2 Thesis outline

The remainder of the thesis comprises four essays, each addressing questions about the impact of emissions trading on technological change. Chapter 2 undertakes the first crucial task of trying to acquire an understanding of the historical context in which emissions trading programmes, and carbon markets in particular, have developed. This provides essential background for questions about the purpose and likely success of emissions trading programmes for greenhouse gases. It is also a starting point for interpreting the limited evidence we already have on the real-world consequences of emissions trading programmes. To this end, Chapter 2 presents a historical overview of the rise of emissions trading as an instrument of climate change policy, and an assessment of the early empirical evidence on the impacts of carbon markets. This historical perspective highlights that emissions trading programmes have often been adopted because of it offers an attractive compromise in many different political contexts. The ultimate success of these programmes, however, has been determined by other factors, such as the technological opportunities for pollution control. Although the political process of conflict and compromise that has given rise to carbon markets is familiar from historical experience, this process has not guaranteed the same preconditions that have allowed some earlier programmes to succeed. In particular, the technological opportunities for controlling carbon emissions today are very different from the technological capacity to produce unleaded petrol in the late 1970s, to substitute for chlorofluorocarbons in the late 1980s, and to desulphurize coal-fired power plants in the 1990s. This limits our ability to extrapolate the likely impact of carbon markets on technological change from past emissions trading programmes, and highlights the value of gathering new evidence.[4]

Stepping back from the historical overview of Chapter 2, Chapter 3 asks what economic theory would lead us to believe about the relationship between carbon markets and innovation. In this chapter I propose a simple but general algebraic model of a firm's innovation decision, which incorporates many strands of the theoretical literature on induced innovation in environmentally sound technologies. The objective is to integrate into one analytical framework the large

---

[4] An abridged version of Chapter 2 has already been published in *Wiley Interdisciplinary Reviews: Climate Change* (Calel, 2013).

number of potential settings in which an emissions trading might be introduced—with market power, with firm heterogeneity, with dynamic inconsistency, etc.—and to try to discover the extent to which economic theory can help delineate the relationship between emissions trading and innovation in a way that may be of use for empirical study. Economic theory, it turns out, accommodates a great many possibilities, including the possibility that a higher price on emissions reduces the incentive to innovate. A general economic framework can serve to highlight some surprising, and potentially perverse, impacts of emissions trading programmes, and to help explain why one might observe such effects, but it provides few predictions about the impacts of emissions trading on innovation that can be easily tested in practice.

To learn about how emissions trading actually impact upon technological change, then, it is necessary to systematically probe incoming observations. This is what I do in Chapters 4 and 5, which investigate the effects of the European Union Emissions Trading Scheme (EU ETS) on technological change. The EU ETS is the largest carbon market anywhere in the world, accounting for over 85% of the international carbon trade (Kossoy & Guigon, 2012). It would be very difficult to detect the effect of the EU ETS on the pattern of innovation without first linking that innovation data to other company data and to regulatory data. When this research was started, then, the lack of such data sets posed a special challenge. The analyses presented in Chapters 4 and 5 were only made possible by considerable efforts to collect and link together information from a large number of data sources.

Another challenge was to develop empirical strategies fit for the purpose of identifying the causal impact of the EU ETS on innovation. The growing empirical literature employs a variety of strategies, often based on expert or manager interviews, but few studies make adequate attempts to link descriptive statements to causal ones. I use regulatory variation arising from installation-level inclusion criteria—thresholds used by regulators to determine which installations are big enough to regulate—to hone in on sets of firms for which the introduction of the EU ETS parallels the conditions of a randomised trial. With a combination of matching and nonparametric estimators modified to take account of the special properties of innovation data (e.g. patenting is censored from below at zero), I estimate the impact of the EU ETS on innovation.

Chapter 4 presents a detailed study of the impact of the EU ETS on the innovation activities of UK firms. I exploit installations-level inclusion criteria to estimate the impact of the EU ETS on carbon intensity of output at the firm-level, on low-carbon patenting, and on low-carbon research and development (R&D) expenditure. These measures respectively serve as indicators of changes in efficiency, of the development and marketing of new low-carbon technologies, and of future technological advances. Together, these three indices also speak more broadly to the question of whether the EU ETS has substantively altered the incentives for low-carbon innovation. The evidence suggests that the principal impact of the EU ETS has been an increase in low-carbon R&D and patenting. Sizeable responses among firms indirectly covered by the EU ETS, however, translate into increases in low-carbon R&D and patenting roughly in the order of 2% in the context of the wider UK economy. There are, though, also indications that these gains in low-carbon innovation may have crowded out other innovative activities. An important finding in its own right, though, is that there are important data restrictions that limit our ability to draw confident conclusions about the EU ETS's impact on innovation. In practice, sample size becomes an important limiting factor when studying firms in a single country, comparing within that country only subsets of similar firms, and being concerned with activities like patenting and R&D that are observed for relatively small samples and that, in any case, many firms do not take part in. The empirical estimates therefore provide an informed sketch of the EU ETS's impact on innovation, which can serve as a basis for further investigation. Additional evidence must be brought to bear on individual elements of this story in order that we may either revise or reinforce our preliminary conclusions.

With this objective in mind, Chapter 5 presents the first comprehensive EU-wide empirical assessment of the impact of the EU ETS on technological change. Exploiting the programme's installations-level inclusion criteria once again, we estimate the impact of the EU ETS on patenting for low-carbon technologies. Studying the EU ETS as a whole overcomes the sample size concerns of Chapter 4 and allows us to estimate the impact with greater precision. We find that the EU ETS has increased low-carbon patenting among regulated firms by as much as 10%, while not crowding out patenting for other technologies. We also find evidence to suggest that the EU ETS has not had an impact on patenting beyond the set of regulated companies. These results imply that the EU ETS accounts for nearly a 1% increase in European low-carbon patenting compared to a counterfactual scenario without the EU ETS. The results speak to the impact of emissions trading on the rate, the direction, as well as the distribution, of technological change. The estimates reflect a roughly comparable effect, although somewhat more modest, on low-carbon patenting to that observed in Chapter 4, but reverses the conclusion that the EU ETS has crowded out patenting for other technologies. On the central question, the results in Chapter 5 broadly reinforce the conclusion that the EU ETS has had an impact on the rate and direction of technological change in a way that favours low-carbon technologies, but also emphasise the limited reach of this effect.

The essays can, in principle, be read independently—each reviews relevant background literature, discusses methods and data, and draws conclusions from the analysis in that essay—though there are recurring questions and themes throughout (and, unavoidably, some repetition, which I hope the reader will forgive). Chapter 6 concludes the thesis by pulling together the key findings from the four essays. I consider whether any overarching conclusions can be drawn, and try to identify potentially fruitful avenues for future research.

Chapter 2

Carbon Markets: A historical overview

2.1 Introduction

One of the core recommendations from environmental economics is that when the market fails to exact an adequate price for environmental damages, governments must instead demand that this price is paid. As the *Stern Review* famously put it, climate change "must be regarded as market failure on the greatest scale the world has seen" (Stern, 2007, p. 25), and the carbon market is one of the chief instruments with which governments all over the globe have chosen to redress this failure.

International carbon markets have a traded value of over $175 billion a year (Kossoy & Guigon, 2012), and affect businesses in all sectors of the economy. Despite uncertainty surrounding what kind of an international framework might succeed the Kyoto Protocol, carbon markets remain a central component of world climate policy. Carbon market programmes have already been implemented in the European Union, New Zealand, the US (at state level), Canada (province level), and Kazakhstan, and further initiatives are underway in US (also state level), Australia (currently a fixed price scheme), Canada (again at province level), China (province level), Japan, and South Korea.

The history of carbon markets is, on the one hand, a great political success story. Where disagreements between businesses and environmentalists, the US and the EU, developing and developed countries, had previously stymied efforts to tackle rising emissions, emissions trading proposals ultimately gained support from both sides. On the other hand, the more recent history of carbon markets is characterised by criticism: criticism for not delivering real emissions reductions, for providing financial windfalls to emitters, and for failing to provide incentives for private sector investment in low-carbon technologies.

This chapter reviews this history of conflict, compromise, and criticism, from the 1960s onwards, as a prism through which we can better understand what is happening now. Viewing these markets in a historical light teaches us both about bad habits we must work harder to break (e.g. over-allocating permits), and about good fortunes that we perhaps cannot take for granted (e.g. technological change). Many of the current problems have precedent, and we are perhaps not learning enough from past experiences. If carbon market policies were more geared toward systematic evaluation, and more open to incorporating past lessons into new policy, carbon markets may stand a greater chance of helping achieve the transition to a low-carbon economy.

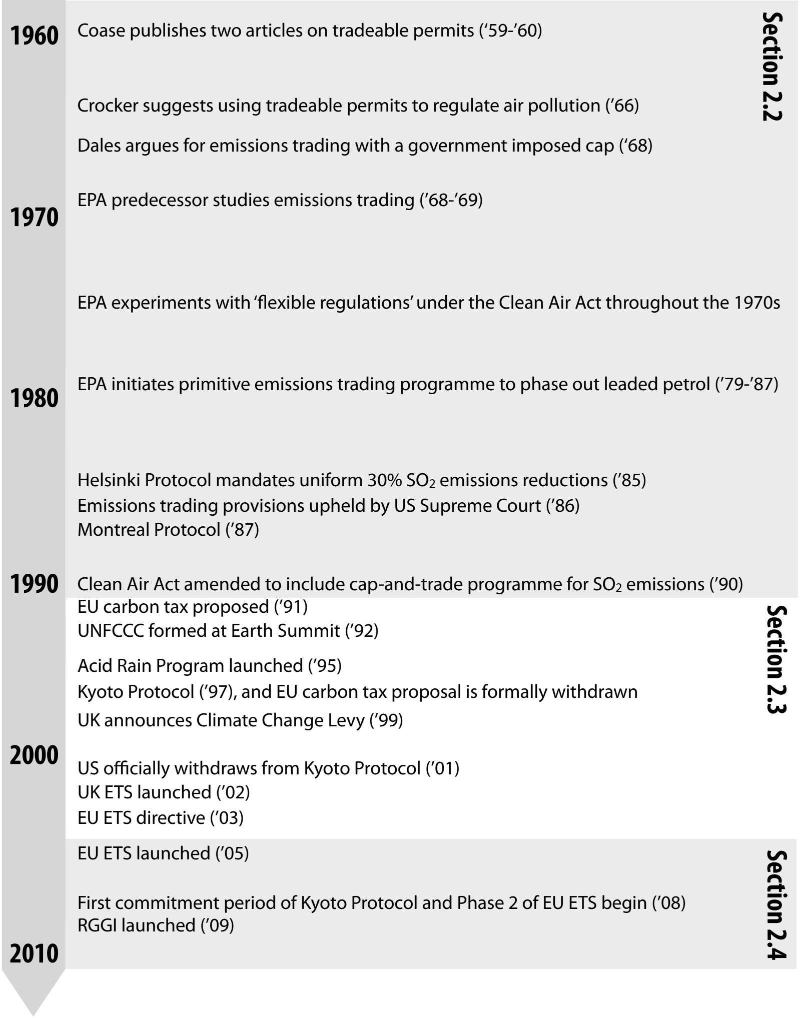
Section 2.2 recounts the early history of emissions trading, before it was considered a way to control greenhouse gas (GHG) emissions. Section 2.3 then reviews the events of the 1990s and 2000s that gave rise to carbon markets. Section 2.4 surveys the most recent history of carbon markets, since their implementation. Figure 2.1 provides a timeline of significant events, and indicates the section in which each event is discussed. Section 2.5 tries to understand the recent performance of carbon markets in light of the political processes that created them, and what lessons we might learn. Section 2.6 offers a few concluding observations.

2.2 The early history of emissions trading

Before the 1960s, the discipline of economics could mainly offer Pigou's suggested method of controlling excessive pollution to policy makers: levy a tax on polluters for each unit of emissions. Then Coase (1959, 1960) proposed a new form of intervention. First establish the property rights of the parties, he argued, and then "it can be left to market transactions to bring an optimum utilization of rights" (Coase, 1960, p. 27).

Coase, at least at that time, did not think such a scheme would work for pollution control (see

Figure 2.1: A timeline of significant events



Coase, 1959, p. 29), but Crocker (1966) argued that a system of tradeable pollution permits offered important advantages. Chiefly, it allowed the regulator to learn from the price signal whether or not the regulations were effective. Dales (1968a,b), writing independently, argued that although pollution taxes could in principle achieve the same outcome, it would be incredibly difficult to set and continually adjust the tax to achieve the desired environmental quality. A better alternative was to:

> *Let [the government]…issue* x *pollution rights and put them up for sale, simultaneously passing a law that everyone who discharges one equivalent ton of waste…during a year must hold one pollution right throughout the year…The virtues of the market mechanism*

> *are that no person, or agency, has to* set *the price—it is set by the competition among buyers and sellers of rights…*
>
> —Dales (1968a, p. 801)

Meanwhile, the growing modern environmental movement in the US was demanding stronger environmental protections. The business community pushed back, arguing that environmental regulations would inhibit economic growth (Voß, 2007). The work of Coase, Crocker, and Dales could potentially offer an innovative solution that might appease both environmentalists and businesses: caps on pollution would satisfy environmentalists, but trading provisions would give industry flexibility to determine how to achieve the targets. This influence was apparent when the US National Air Pollution Control Administration began studying emissions trading in the late 1960s (Burton & Sanjour, 1968, 1969a,b).

When the Clean Air Act was adopted in 1970, the National Air Pollution Control Administration, along with its curiosity about emissions trading, was absorbed into the new Environmental Protection Agency (EPA), which was charged with monitoring and enforcing the new National Ambient Air Quality Standards established by the Act. To enable construction of new industrial facilities in areas where emissions were already high, the EPA created a new rule that the firm would have to 'offset' the additional emissions with an even greater emissions reduction elsewhere within the airshed (Gorman & Solomon, 2002). Offsetting was eventually codified in the 1977 amendments to the Clean Air Act. Of course, proving that you are reducing emissions compared to what would have happened otherwise is not always an easy task, as we will see again in later offsetting schemes, so in practice firms would generally close down an old plant in order to build a new one.

The EPA continued to experiment with, and expand the use of, market-like pollution control mechanisms under the Carter administration (Cook, 1988). Hoping to secure business support for emissions trading, new mechanisms were added to increase flexibility, assure market liquidity, and reduce price volatility (Voß, 2007). These mechanisms saved some businesses millions of dollars, and many of these mechanisms were used again when the EPA helped phase-in new refining equipment and phase-out leaded petrol in the late 1970s and early 1980s (Gorman & Solomon, 2002).

Environmental groups were not always pleased with the new flexible mechanisms, however. The EPA trading provisions faced repeated legal challenges from environmental interest groups (Voß, 2007), but were ultimately upheld by the US Supreme Court in 1986 (Gorman & Solomon, 2002).

With pollution regulation receiving more attention from policy makers, academic study of market-based instruments intensified in the 1970s. Important contributions from Baumol & Oates (1971, 1979), Montgomery (1972), Weitzman (1974), Roberts & Spence (1976), Adar & Griffin (1976), and Yohe (1977) built up the theoretical foundations of emissions trading. When Tietenberg (1985) later published a study evaluating the EPA's *de facto* emissions trading system, he helped highlight it as "a first instance of a new policy instrument in practice, a proof of the principle that emission reduction obligations could be traded" (Voß, 2007, p. 334).

Tietenberg's study was of further significance because it advanced the argument that emissions trading provided efficient incentives for innovation and investment in new pollution control technologies. This was quickly adopted as an argument in favour of emissions trading (Downing & White, 1986), and within a few years it was considered one of the three key strengths of emissions trading, alongside minimising short-term abatement costs and placing a relatively low informational burden on the regulator (Malueg, 1989).

The EPA released a report in 1986 consolidating their new practices, already reviewed by Tietenberg, and support for emissions trading soon spread beyond the EPA to groups like the Environmental Defense Fund, an environmental advocacy group, and Project 88, a nonpartisan initiative convened by US Senators Timothy Wirth and John Heinz to explore new environmental policy solutions. The shift in attitude in the 1980s towards more flexible environmental regulations was also greatly facilitated by the broader push for pro-market economic policies under the Reagan administration (Bernstein, 2001). The EPA's new emissions trading mechanisms were estimated to have saved a few big companies (Armco, DuPont, USX, and 3M) between \$5 billion and \$12 billion (Stavins, 2003), but most businesses never took active part and did not experience any notable cost reductions. At the time, this later failure was excused by the fact the theoretical recommendations had not yet been systematically implemented (Voß, 2007).

Throughout the 1970s and 1980s, evidence was accumulating that (1) sulphur dioxide emissions from the burning of coal and oil was causing water and soil acidification, and (2) emissions of chlorofluorocarbons (CFCs) were depleting the ozone layer (Bolin, 2007). The international community made "desulphurization of fossil fuels" one of the chief objectives of future co-operation (see the Final Act of the Conference on Security and Co-operation of 1975), and negotiated a voluntary international agreement in 1978 to reduce CFC emissions, followed by the Vienna Convention in 1985 and the 1987 Montreal Protocol. The Montreal Protocol established legally-binding CFC quotas, and a mechanism that permitted international trade of these quotas.

European countries and the US responded very differently to these events. Though CFC emissions quotas were very occasionally traded in Europe (Stavins, 2003), European nations mostly directly regulated what technologies could and could not be used. Most of the trading under the Montreal Protocol was carried out between US and Canadian plants of two major US companies, DuPont and Dow Chemicals (Gorman & Solomon, 2002). Moreover, the Protocol motivated the EPA to create a programme for the Protection of Stratospheric Ozone in 1988, capping CFC emissions through a tradeable permit system (Tripp & Dudek, 1989).

The same pattern was visible in Europe's and the US' handling of sulphur emissions. European nations agreed to uniformly reduce sulphur emissions by 30%. This was a prime opportunity for letting countries trade their emissions quotas (Mäler, 1991), but such provisions were conspicuously absent from the European approach. In the US, however, emissions trading had gained steam throughout the 1970s and 1980s. California passed their own emissions trading legislation for nitrogen and sulphur dioxides in 1983, and various state level trading programmes were operating in Colorado, Georgia, Illinois, Louisiana, and New York (Stavins, 2003). This gradual change, combined with the apparent success of the ozone protection scheme, allowed President George H.W. Bush to amend the Clean Air Act in 1990, creating the Acid Rain Program—a national permit market for sulphur dioxide emissions.

2.3 The rise of carbon markets

2.3.1 The road to Kyoto

Throughout the 1970s and 1980s scientists repeatedly warned about global warming induced by anthropogenic GHG emissions, and economists began warning of the potential economic consequences (Nordhaus, 1974, 1977a,b, 1979). In 1988, a hot summer and crop failure in the US sparked a wider political discussions about global warming. NASA scientist James Hansen's testimony before the US Congress echoed around the world: "Global warming has begun" (Fleming, 1998; Bolin, 2007). The World Conference on the Changing Atmosphere held that same year called for a 20% reduction in carbon dioxide emissions by 2005. The Intergovernmental Panel on Climate Change (IPCC) was created and charged with conducting a comprehensive scientific assessment of the causes and consequences of global warming.

Putting the problem of climate change together with the theory of emissions trading, Stavins (1988), writing for Project 88, recommended creating a global carbon market to manage GHG emissions. An increasing number of economists now favoured a global carbon market (Swisher & Masters, 1989; Dudek & LeBanc, 1990), saying that it was actually feasible to implement (Victor, 1991), and moreover, that it was the only proposal that could realistically bring the international community together to successfully curb GHG emissions (Grubb, 1989).

The 1992 UN Earth Summit in Rio de Janeiro resulted in the Framework Convention on Climate Change (UNFCCC). It declared a "concern that human activities have been substantially increasing the atmospheric concentrations of greenhouse gases…and may adversely affect natural ecosystems and humankind", but strong US fossil fuel interests persuaded the US to oppose mandatory abatement targets (Meckling, 2011). No binding targets made it into the agreement. Still, the Convention demanded that "policies and measures to deal with climate change should be cost-effective so as to ensure global benefits at the lowest possible cost". This was a clarion call for economists.

Many economists turned their attention to the questions of formulating an international treaty and designing an international carbon market.[1] The IPCC concluded that "for a global treaty,

---

[1] The bibliography of Chapter 11 of the Contribution of Working Group III to the Second Assessment Report

a tradeable quota system is the only potentially cost-effective arrangement where an agreed level of emissions is attained with certainty" (IPCC, 1996, p. 401).

The US had pioneered emissions trading, but US industry now stood united in opposition to any form of carbon controls. However, at the first Conference of the Parties (COP 1) to the UNFCCC in Berlin in 1995, the two European oil giants BP and Shell began to soften their stance for fear of damaging their public image (Meckling, 2011). Perhaps because of this, COP 1 managed to set a two-year deadline before countries had to agree on mandatory GHG emissions targets, something industry had prevented at the Earth Summit. A pilot programme was also launched—Activities Implemented Jointly (AIJ)—to learn more about how an international carbon offset market might work in practice. Unfortunately, it seems the AIJ did not result in any emissions reductions that would not have happened anyway, and moreover, the verification process was prohibitively difficult (Schwarze, 2000).

But the US Acid Rain Program, signed into law in 1990, came at a pivotal time. It was launched in 1995, and its widely publicised success overshadowed the smaller AIJ. Sulphur emissions were substantially reduced (Schmalensee et al., 1998), and these emissions reductions were estimated to have cost businesses $1 billion less per year than they would have under command-and-control regulations (Stavins, 2003). The benefits of the Program appeared to have far outweighed the costs (Burtraw et al., 1998).

The Acid Rain Program launched to great acclaim, and a few major US companies now defected from the anti-regulation camp to join the cause of the pro-market Environmental Defense Fund. These businesses wanted to ensure that emissions trading would be the policy of choice, should governments ultimately agree to binding carbon reduction commitments. Their message fell on receptive ears in the Clinton administration, and the new business-NGO coalition sidelined both the old opposition to carbon controls from business and the opposition to emissions trading from environmental groups (Meckling, 2011). At COP 2 in 1996, the US announced it now favoured binding commitments as long as a new international agreement included provisions for global carbon trading.

The US was one of the few countries with practical experience of emissions trading, and led

---

of the Intergovernmental Panel on Climate Change (IPCC, 1996) provides a comprehensive list of references to relevant literature from this period.

an alliance of nations supporting the proposal for an international carbon market (Stowell, 2005). The EU favoured uniform binding commitments of 15% emissions reductions but opposed a market, a position reminiscent of the European sulphur emissions treaty. The new business-NGO coalition lobbied for carbon trading, with BP even announcing in May of 1997 a partnership with the Environmental Defense Fund to set up its own internal carbon trading scheme. In June 1997 the EU conceded that its opposition to a carbon market should not be allowed to undermine the objective of achieving binding emissions targets, and at COP 3 held in Kyoto in that December, BP and the Environmental Defense Fund lobbied the European delegates to accept the US proposal. The US and EU eventually reached an agreement in the form of the Kyoto Protocol, which included both binding commitments and a carbon market, though the details of the market would be left for COP 4 to determine. The US also demanded targets for developing countries, but the G-77 and China opposed this proposal. A compromise was finally reached in the form of the Clean Development Mechanism (CDM), a carbon crediting mechanism similar to the AIJ (Meckling, 2011). The carbon market provisions in the Kyoto Protocol would go into effect in 2008.

2.3.2 Emissions Trading in Europe

In Europe, the years leading up to the Kyoto Protocol had seen the failure of a proposal to establish an EU-wide carbon tax. The European Commission had proposed such a tax in the early 1990s, but was forced to withdraw the proposal in the face of overwhelming opposition from business and from several member states. The EU had also failed to keep emissions trading out of the Kyoto Protocol.

COP 4 did not finalise rules for the international carbon market after all, but instead agreed that this should be accomplished by the year 2000. The carbon market lobby took this opportunity to coalesce and intensify their efforts. BP launched its internal trading scheme in September 1998, with the self-imposed target of reducing its GHG emissions by 10% by 2010 (a target they expected to achieve by reducing waste, at virtually no cost). A trade association for the carbon industry, the International Emissions Trading Association (IETA), was formed in November 1998, and a series of high-profile workshops were held to bring together academics, practitioners, and policy makers to discuss carbon markets (Ellerman et al., 2010). Shell launched its own trading scheme in January 2000, and Alcoa, Motorola, and Waste Management followed suit (Hoffman, 2005).

When the UK government announced its Climate Change Levy in March 1999, a group of thirty organisations (mostly large businesses) formed the UK Emissions Trading Group. Their immediate objective was to persuade the government to adopt an emissions trading scheme instead of the new tax, and their broader aim was to influence future EU regulations in favour of carbon trading. The message was well-received by the new Labour government, which wanted to make London the financial hub of the new market should the EU be swayed toward emissions trading (Meckling, 2011). The UK Emissions Trading Scheme was finally launched in 2002 as a supplementary policy to the Levy, but few firms participated, most easily met or even overshot their emissions abatement targets, and ultimately the scheme appears rather to have subsidised a handful of firms to undertake voluntary emissions reductions (Smith & Swierzbinski, 2007). By way of contrast, the Climate Change Levy does appear to have induced firms paying the full rate to reduce energy use by 10% and increase patenting for low-carbon technologies without compromising firms' economic performance (Martin et al., 2009; Martin & Wagner, 2009), while simultaneously raising more than £800 million of revenue a year for the British government (Cambridge Econometrics et al., 2005). Yet somehow seeing a real-life carbon market in the UK seems to have had a greater impact on the rest of Europe than seeing the market's actual performance. The apparent success of the US Acid Rain Program, moreover, seemed to offer compelling evidence that emissions trading could work in practice, even if the small-scale carbon market experiments so far had had less success.

No agreement was reached on the rules for the international carbon market until COP 7 in 2001. The Japanese delegation in particular opposed giving the UN the power to take action against a country that did not meet its emissions targets (Convery, 2009). It was becoming clear that, since the EU wanted strong enforcement, they would need to create a European scheme with the European Court of Justice as its enforcer. An EU carbon market might also have helped convince the US to ratify the Protocol. The US officially abandoned the Kyoto Protocol in 2001, however, and it seemed now that only strong EU leadership might save it

(Meckling, 2011).

The EU had been dealt one blow after another: the failure of an EU carbon tax, the failure to first keep emissions trading out of the Kyoto Protocol, the failure to underpin the international carbon market with credible enforcement mechanisms, and finally the US withdrawal from the Kyoto Protocol. The European Commission had first announced its support for emissions trading in 1998, but only after this series of events, played out against a backdrop of sustained lobbying, could the most ardent opponents of a European carbon market finally be persuaded. Germany only declared its support for emissions trading in December 2002 (Meckling, 2011).

The directive to establish the EU Emissions Trading Scheme (EU ETS) was adopted in July 2003, and the new European carbon market launched in January 2005. Early movers like BP and Shell had acquired substantial experience of carbon trading, and they had considerable influence on the design of the EU ETS (Hoffman, 2005).

2.3.3 Carbon markets around the world

Ever since the US withdrawal from the Kyoto Protocol in 2001, US companies and states have been working to get emissions trading back on the agenda. The Chicago Climate Exchange (CCX) ran from 2003 to 2010, a trading platform that encouraged businesses to voluntarily make legally binding commitments to cut their emissions. The Regional Greenhouse Gas Initiative (RGGI) launched in 2009, capping electricity sector emissions in 10 Northeastern US states.[2] California launched its long anticipated carbon market in 2013. Elsewhere in North America, the Canadian province of Quebec has recently launched a new cap-and-trade scheme as well.

In 2008 New Zealand launched its own emissions trading scheme (NZ ETS). The programme expanded in 2010 to cover additional economic sectors, and is scheduled to expand further to become a nearly economy-wide programme by 2015.

There are several more carbon markets just coming over the horizon. The initial voluntary phase of the Swiss programme has recently ended, and as of January 2013 it has been manda-

---

[2] The RGGI presently includes 9 states, owing to New Jersey's recent withdrawal.

tory for Swiss energy-intensive industries to participate in the country's carbon market. Australia's Carbon Pricing Mechanism, currently operating with a fixed price, is due to become a fully flexible emissions trading programme in 2015. In January 2013 Kazakhstan officially initiated a one-year pilot phase of its new national carbon market. Japan, South Korea, Brazil, Mexico, and Turkey have all adopted legislation laying the foundation for their own carbon markets as well, and efforts to develop emissions trading schemes are under way in most of these countries. Perhaps most significantly, two of China's seven planned provincial carbon markets are due to launch later in 2013. The planned market will be the world's second largest after the EU ETS, and is expected to expand into a national programme by 2015-2016 (Scotney et al., 2012).

The future of a strong international environmental agreement may look bleak at present—COP 17 in December 2011 resulted in an agreement to renew the Kyoto Protocol for a second commitment period, but there remains a substantial gap between pledged emissions reductions and how much is needed to avoid temperature increases in excess of 2°C. It is still possible that a global carbon market will emerge by joining together national and regional markets. Quebec and California have announced their intentions to link their markets. The EU and Australia have also announced plans to establish a link between their carbon markets from 2015. Though the economic and legal issues involved in linking markets are complex (Jaffe et al., 2009), pro-market lobbying efforts now appear to see this as a more credible route to a global market (Meckling, 2011).

2.4 Carbon markets in action

International carbon markets have been operating in earnest since 2005, when the EU ETS launched and the CDM rules came into force. There are a growing number of carbon market initiatives around the globe, but only EU ETS and the Kyoto mechanisms have been subjected to systematic scrutiny so far (see, for instance, Hepburn, 2007, for an early review). This section considers these experiences, and in particular I try (both in this section and the next) to relate the performance of carbon markets to what we now know of their history. I also briefly discuss preliminary assessments of RGGI and NZ ETS.

2.4.1 The EU Emissions Trading Scheme

The EU ETS covers roughly 12,000 industrial and power installations and nearly half of the EU's GHG emissions. It launched in 2005 and now accounts for nearly 85% of world carbon trading (Kossoy & Guigon, 2012).

Nearly 6.5 billion tonnes-worth of allowances were allocated in Phase 1 (2005–2007). In 2006 it became apparent that there was a surplus of allowances, however, and their price collapsed. It seems the emissions cap was too generous, and the price collapse has consequently been widely interpreted as evidence that no emissions reductions took place. However, the €10–€30 allowance price through 2006 and the continued positive price of 2008 futures could have induced firms to cut emissions. Indeed, official numbers show that EU ETS installations in aggregate have cut emissions by roughly 8% in absolute terms between 2005–2010 (European Commission, 2011), though this does not account for factors like rising fuel prices and the recession. When these things are accounted for, Phase 1 emissions are estimated to have been only about 3% lower than they would have been without the EU ETS (Ellerman & Buchner, 2008; Ellerman et al., 2010; Anderson & Di Maria, 2011). Nevertheless, it is a real challenge to predict what EU ETS installations would have done in the absence of the EU ETS so there is considerable uncertainty around these estimates, and they should be interpreted knowing that total emissions often jumped ±5% year-on-year in 1990–2004. When EU ETS installations are instead compared directly to similar installations that were not covered by the EU ETS, although this has so far only been done for a very limited number of installations, even the modest 3% reduction vanishes (Jaraite & Maria, 2011). Most of the 8% reduction identified by the European Commission came during Phase 2 rather than Phase 1, but perhaps as much as a third of these reductions appear to be due to the 2008 recession (New Energy Finance, 2009). Estimates that account for macroeconomic conditions in Phase 2 attribute emissions reductions of about 3% to the EU ETS (Zachmann et al., 2011; Egenhofer et al., 2011), though alternative estimates suggest this number may be on the high side (Cooper, 2010; Kettner et al., 2011; Lewis & Curien, 2010). The evidence, though still thin, suggests on balance that EU ETS installations have cut emissions, perhaps even in part because of the EU ETS.

A key objective in Phase 1 was to "establish the infrastructure and institutions and to gain the experience to make the subsequent, 'real', period a success" (Ellerman et al., 2010, p. 36). Indeed, there are some signs of institutional learning. For instance, the historical emissions data needed to set caps for each installation often was not available before the start of Phase 1, and regulators were forced to rely on largely unverified voluntary submissions from installation owners (Ellerman, 2007). Naturally, firms had an incentive to exaggerate their historical emissions in order to receive more generous allocations. Moreover, disagreements between the European Commission and member states meant that the total number of allowances was not finalised until well into Phase 1. In contrast, the data collection and the process for allocating Phase 2 and 3 allowances was much more orderly (Ellerman et al., 2010). Having said that, since Phase 2 and 3 have now been found to be over-allocated as well, European policy makers are trying to intervene and modify the emissions cap. At the time of writing, a contentious plan to temporarily withhold some of the previously authorised allowances for Phase 3 has just been rejected, and the price of allowances has crashed to historic lows.

Practically all of the allowances so far have been given to companies for free in accordance with historical emissions ('grandfathering'), rather than sold at auction. Consultations with business had convinced the European Commission that grandfathering was necessary to gain industry support (Skjaerseth & Wettestad, 2008), despite some arguing that this would adversely affect private-sector investment (Neuhoff et al., 2006a,c) and though economic analyses of the EU ETS have shown that greater auctioning need not have had the harmful competitive effects feared by industry (Hepburn et al., 2006). Although firms have been given allowances for free, they have raised their prices (and profits) in some countries. It was estimated that UK power companies would earn an additional £800 million (€930 billion) per year in Phase 1 (IPA Energy Consulting, 2005), and power companies in Belgium, France, Germany, and the Netherlands earned between €4.5 billion and €13.5 billion in windfall profits in a 'representative' year (Sijm et al., 2006). Several studies also show that even industrial sectors of the economy are marking up their prices and earning windfall profits (Bruyn et al., 2010; Oberndorfer et al., 2010; Alexeeva-Talebi, 2010), and estimates suggest that the 10 largest beneficiaries (iron, steel, and cement companies) are making €4.1 billion in profits from the EU ETS in Phase 2 (Sandbag, 2011). It is worth noting that this effect of grandfathering was understood before the EU ETS directive was adopted (Burtraw et al., 2002), and was expected (Martinez & Neuhoff, 2005; Smale et al., 2006). It is by no means unprecedented, however, that a few big firms make profits from emissions trading schemes (as with the EPA's early trading provisions and the UK ETS). Not only is it questionable whether the free allocation of permits conforms to the EU's commitment that polluters should bear the cost of their emissions, as well as EU and international rules about state aid, but to the extent that shareholders are wealthier than the average citizen, windfall profits may also have a regressive redistributive impact. A greater share of allowances will be auctioned in Phase 3—perhaps a sign of learning among policy makers—though compelling evidence suggests that a far greater share still could be auctioned without adversely affecting competitiveness (Martin et al., 2012a).

Industry is learning as well. The institutional awareness of firms is growing, especially among large polluters (Hervé-Mignucci, 2011), and allowances have tended to flow from installations with surplus to those with deficits (Ellerman et al., 2010). There are clear limits nevertheless. Despite a surplus of 267 million allowances and a near-zero allowance price at the end of Phase 1 (Ellerman et al., 2010), a number of installations still operated without sufficient allowances, resulting in over €3 million in fines (over 75,000 tonnes of emissions at €40 per tonne) (European Environment Agency, 2008). It also appears that, as with preceding emissions trading schemes, most regulated firms are passive participants (Martin et al., 2011).

The EU ETS has also aimed to encourage low-carbon innovation and investment. Many have expressed scepticism (Schleich & Betz, 2005; Grubb et al., 2005; Schleich et al., 2009), and the price collapse in Phase 1, as well as the low current price, could very well have undermined the signal to investors. Claims in the literature range from the EU ETS having a strong impact on innovation (Petsonk & Cozijnsen, 2007) to it having no impact at all (Aghion et al., 2009). More systematic studies detect a small positive impact of the EU ETS on innovation (Martin et al., 2011; Anderson & Di Maria, 2011), primarily operational and process innovations. When it comes to investment, anecdotal evidence suggests that the EU ETS is having a small positive effect as well (Ellerman et al., 2010; Hervé-Mignucci, 2011), though some more recent evidence that takes greater pains to establish a credible counterfactual throws some doubt on these conclusions (Löfgren et al., 2013). One should also consider the fact that a large part of abatement thus far appears to have come from switching between coal and gas in the power sector (Ellerman & Buchner, 2008; Delarue et al., 2008, 2010), a cheap way to reduce emissions that requires neither innovation nor investment.

In sum, the evidence suggests the EU ETS is responsible for a small reduction in emissions. The evidence is weaker on its impact on investment and innovation, but provides reasons to be conservative. On the basic question of whether the EU ETS has managed to "establish the infrastructure" and "gain the experience" to make carbon trading a success, one can point to such things as the gradual movement toward more auctioning of allowances. On the other hand, revelations of crime, regulatory incompetence, and outright corruption in the EU ETS do call into question whether to this day such an infrastructure exists (Transparency International, 2011). It is perhaps safest to conclude that, while European policy makers are slowly learning about the potential and pitfalls of emissions trading, the lessons of the EU ETS are hard won.

2.4.2 The Kyoto mechanisms

The first commitment period of the Kyoto Protocol coincided with Phase 2 of the EU ETS (2008–2012). The Kyoto mechanisms include Emissions Trading (ET), a government-to-government cap-and-trade mechanism based on the same ideas as the quota trading provisions of the Montreal Protocol, as well as Joint Implementation (JI) and the Clean Development Mechanism (CDM), two offset mechanisms that allows emissions reductions from projects in uncapped counties to be converted into new allowances that can be sold to help to capped countries achieve their targets. The lion's share of activity under the Protocol comes from the CDM, and for the most part the new carbon credits are sold to help European firms comply with the EU ETS.

As with the AIJ before it, it has been difficult and costly to verify that individual projects actually lead to emissions reductions compared to what would have happened otherwise. Many have questioned whether the CDM actually reduces emissions (Michaelowa & Purohit, 2007), and there is now convincing evidence that the CDM has actually *increased* emissions from some activities (Schneider, 2011). In some instances, the CDM has furnished emitters with large financial windfalls (Wara, 2007a,b; Elsworth & Worthington, 2010; Sandbag, 2011). These concerns are compounded by reports showing undeclared conflicts of interest among members of the Executive Board (Transparency International, 2011), and revelations that project developers routinely prepare a separate balance sheet showing the non-viability of a project without CDM benefits to obtain credits, despite having already submitted a balance sheet showing the viability of the project without CDM credits when securing funding from the bank (Consulate Mumbai, 2008).

The CDM was also meant to encourage development of low-carbon technology and infrastructure in developing countries, but most of the credits issued historically are actually for the destruction of industrial gases (chiefly HFC-23), which have high global warming potential (so they are worth a lot of credits) but are cheap and easy to destroy with existing technologies. The CDM's contribution to sustainable development appears to have been modest at best (Olsen, 2007).

Like in the EU ETS and earlier programmes, emissions reductions in the CDM are largely coming from cheap and easy fixes that require neither innovation nor much investment, but ultimately have very limited potential for greater emissions reductions in the longer term. Since the specific problem concerning HFC-23 came to light, no new projects of this kind have been approved, and other abatement projects now form a growing part of the CDM portfolio.

2.4.3 Preliminary assessment of New Zealand Emissions Trading Scheme and RGGI

The NZ ETS was launched in 2008. Though it is still in its transitional phase, an independent review published in September 2011 noted that the programme so far "had not had a significant impact on investment decisions and competitiveness... had not yet incentivised behavioural changes nor had it resulted in significant reductions in domestic emissions... [and] is unlikely to have had such a marked effect on costs that [businesses] have had to reduce their energy consumption or emissions" (Emissions Trading Scheme Review Panel, 2011, pp. 17–18).

RGGI launched in 2009. One important feature of RGGI is that all allowances are sold at auction, and therefore generate revenue for state governments. State governments have been eager to highlight that over $600 million of the revenues raised (roughly 75%) have been invested in improving energy efficiency, deploying renewable energy technologies, and assisting low-income households with paying high energy bills (RGGI Inc., 2011). RGGI does appear to have had, on balance, a positive economic impact so far (Hibbard et al., 2011), but it is still unclear whether or not it has reduced GHG emissions. The statutory programme review recently confirmed initial suspicions (Daley, 2008) that there has been "a significant excess supply of allowances relative to actual emission levels" (RGGI Inc., 2013a), which was soon followed by a proposal to slash the emissions cap by 45% (RGGI Inc., 2013b).

2.5 Lessons

The history of carbon markets is a great political success story. Early emissions trading schemes in the US provided compromise solutions that created internal divisions within interest groups, and thereby helped pacify opposition from both business and environmental groups. Emissions trading fractured business opposition to an international climate change treaty with binding emissions targets, helping to bridge the gap between European and US demands at the negotiations in Kyoto, as well as between developed and developing countries. Emissions trading allowed the EU to forge a unified climate policy after attempts to implement a carbon tax had failed. However, the same history also reveals precedents for many of the current problems with carbon markets. Let us consider here a few of the key lessons one might learn from piecing together this history.

2.5.1 Participation

Early evaluations of the US emissions trading provisions noted that the benefits from trading were heavily concentrated among a few large companies (Stavins, 2003). In the case of the UK ETS, similarly, only about a quarter of eligible firms even participated in the trading, and the scheme ended up subidising the emissions reductions of a small number of firms (Smith & Swierzbinski, 2007). The discovery now that a majority of EU ETS regulated companies do not take part (Martin et al., 2011) while a few companies are making large windfall profits, therefore, should not come as a total surprise. Lack of participation is not *necessarily* problematic, because the "price [of allowances] can equal marginal abatement cost even if many firms fail to participate in the market", as Burtraw (2000, p. 12) explains. In this case, however, "even if [the] allowance price were equal to marginal abatement cost [as] in the least-cost solution, it would not follow that all trading gains were realized" (Burtraw, 2000, p. 12). Low levels of participation, therefore, makes it difficult to label any emissions trading programme fully efficient.

In the case of the EPA's early trading programmes, this pattern was attributed to easily fixable design flaws, but its recurrence perhaps indicates that something more fundamental is at issue. One clue lies in the political struggles over emissions trading—the EPA's emissions trading provisions were a compromise to get the business lobby on-side, the UK Emissions Trading Group pushed for the UK ETS, BP and Shell broke with the rest of the business community and made possible an emissions trading compromise in the Kyoto Protocol, IETA pushed for the EU ETS. In each case, a rather select group of large businesses have been instrumental in advocating for emissions trading, ultimately influencing the programme design (Meckling, 2011). It is perhaps only to be expected then that these policies, as implemented, would most benefit this type of actor. This is also consistent with the suggestion that the pattern of benefits follows companies' differential capacities to engage with emissions trading as a market opportunity, as opposed to simply a matter of compliance (Burtraw, 2000). In the EU ETS, as well, it is the power sector, which perhaps has most institutional capacity to manage an allowance portfolio, that has been most engaged in emissions trading. Perhaps this historical experience offers some clue as to the appropriate scope for emissions trading policies, and the need for alternative or complementary policies to speed the transition of more compliance-oriented segments of the economy.

2.5.2 Over-allocation

Precedent can also be found for over-allocation of emissions allowances, as well as the inability to redress the problem once it becomes apparent. The US Acid Rain Program set a target of 8.95 million tonnes of annual emissions, roughly half 1980 levels. At the time or writing the allowance price has collapsed and a number of studies have concluded that the efficient cap is much lower than the Congressionally-mandated cap, somewhere between 1 and 3 million tonnes (Banzhaf et al., 2004; Muller & Mendelsohn, 2009). When the US Congress failed to pass legislation to adjust the cap, the EPA tried to introduce a rule that required firms to surrender more than one allowance for each tonne of emissions, effectively tightening the cap. The new rule was struck down by the courts in 2008, though, and Congress still has not adjusted the cap.

In the case of the Kyoto Protocol, emissions allocations were calculated against 1990 levels. This was very generous to former Soviet countries that had experienced large emissions reductions since the Soviet collapse (it is noteworthy that Russia was the 55th country to sign onto the Kyoto Protocol, crossing the threshold needed for the Protocol to enter into force). Consequently, there was a lot of surplus allowances in the system, which have become known as 'hot air'. Efforts to remove 'hot air' from the system have not been entirely successful, having produced a few relatively small non-governmental schemes that try to pressure governments to channel the proceeds from selling surplus allowances into green investments (Blyth & Baron, 2003).

In the UK ETS, with a fixed budget of £215 million the government managed to purchase 4 million tonnes-worth of abatement commitments from those demanding least subsidy per tonne. Subsequent events suggest they overpaid. Firstly, while the closing price at the auction was nearly £18 per annual tonne, the trading price never exceeded £13 and spent more time hovering between £2 and £4. Secondly, half of the 4 million tonnes in abatement originated with 4 companies whose emissions were already below the baseline before the compliance period had started, by virtue of having sharply-declining emissions trajectories even before the auction took place. An analysis of the UK ETS concludes that there was an excess supply of roughly £3.5 million tonnes (Smith & Swierzbinski, 2007), corresponding to 75% of the commitments the government had paid for dearly at auction.

The difficulty of verifying 'additionality' has also created another form of over-allocation in the context of offset markets. In the EPA's early programmes, in the AIJ, and now in the CDM, it is costly and difficult to establish with confidence that projects result in emissions reductions beyond what would have happened otherwise. When the evidentiary threshold was high, as in the EPA's programme, this resulted in very few offsets ever being issued, and then a firm would practically have to shut down one of their older plants to build a new one. The desire to open up and streamline the verification process in the CDM has resulted in a large number of offsets being issued, but many of questionable 'additionality'.

There appears to be a persistent tendency toward over-allocation in emissions trading programmes. While the amendments to the Montreal Protocol that further limit ozone-depleting substances offer an exception to the rule, the over-allocation of allowances in the EU ETS can hardly be considered surprising. Even without analyses showing that the proposed EU ETS allocations ran a substantial risk of being excessive (Neuhoff et al., 2006b), historical experience alone should moderate our surprise. The frustrated efforts to slow the release of Phase 3 allowances are not without precedent either. Advocates of this approach have made little progress so far, but it will be interesting to see if the EU ETS eventually manages to defy precedent.

The North-American and Australian programmes display some signs of having learnt from this history. RGGI has introduced a reserve price in the permit auctions, to guard against releasing too many permits into the system. With the economic recession and the natural gas boom, however, the permits already in the system have been plentiful enough to crash the price. The Australian programme is trying a different solution: it has an initial phase where permits are traded at a fixed price (effectively a carbon tax), which will help the regulator establish the appropriate level of the cap for the second trading phase. It remains to be seen whether this model works better than the reserve price auction in the US.

2.5.3 Investment and innovation

When it comes to innovation and investment, a closer inspection of emissions trading successes—the leaded petrol phase-down, the Montreal Protocol, the Acid Rain Program—raises doubts about whether a similar technological transition can be repeated with a carbon market. When the lead phase-down began in 1979, the EPA was only trying to encourage efficient adoption of an existing refining technology. The cost of this technology did not come down markedly, nor were any new technologies introduced (Kerr & Newell, 2003). When CFC markets were set up in the late 1980s, an economically-competitive replacement (HCFC) already existed (Gorman & Solomon, 2002). When the Acid Rain Program was launched in 1995 the technology to scrub sulphur from exhausts was already available (Schmalensee et al., 1998), and in fact, all coal-fired power plants built since 1978 were already legally required to use scrubbers (Burtraw, 2000). Still, Phase 1 of the Program resulted in installation of fewer scrubbers than the EPA had anticipated (Burtraw, 2000; Hanemann, 2009). Even though the cost of operating scrubbers per unit of avoided emissions did come down (in part because of increased utilisation of the plants with scrubbers) (Burtraw, 2000), and though there was in fact an increase in patents protecting efficiency improvements for scrubbers (Popp, 2003), 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, so it is not entirely clear how much of this was the market's doing. For one thing, it appears that scrubbers would have been uneconomic without the bonus allowances (Carlson et al., 2000), which is consistent with findings that the use of scrubber technology as an abatement strategy has actually declined over time (Burtraw & Szambelan, 2009). Moreover, as Hanemann (2010) points out, there was no obvious boost to other low-emission technologies for coal combustion (e.g. integrated gasification combined cycle), which one might have expected if the emissions price was the key driver of innovation. The lion's share of emissions reductions have come from power plants switching to low-sulphur coal.

The pattern of undertaking primarily cheap and technologically easy abatement in earlier emissions trading schemes has been repeated in the EU ETS (fuel-switching) and the CDM (destruction of industrial gases). Unlike these historical cases, however, fuel-switching will not be sufficient to achieve major reductions in carbon emissions (Delarue et al., 2008), and CDM credits are no longer issued for these industrial gas projects. Experience suggests that the real strength of emissions trading lies in its ability to harness existing technological trends, leading to the efficient introduction of operational improvements and known near-market abatement technologies. Carbon markets can be valuable in this regard, but we must recognise that the technological opportunities for controlling carbon emissions today are more limited than the capacity to un-lead petrol in the late 1970s, to replace CFCs in the late 1980s, and to desulphurize coal plants in the 1990s. History does not justify placing too great an onus on them to deliver low-carbon investment and innovation on a large scale in the future, but then again, emissions trading has never really been used for this purpose before. It is perhaps understandable, then, that several observers are now emphasising the need to complement carbon markets with public R&D and other forms of technology support (Newell, 2010; Söderholm, 2010). Although the political process of conflict and compromise that has given rise to carbon markets is familiar from historical experience, this process has not guaranteed the same preconditions for success. On the issue of technological change, at least, past experiences underline the special need to gather more direct empirical evidence on the impacts of new carbon markets.

2.6 Conclusion

A historical perspective sheds new light on many of the current problems with carbon markets, and can help us learn from both past successes and failures. Apart from the specific problems with carbon markets, however, a historical perspective also helps us identify two key problems with the carbon market debate itself. First, policy makers and commentators often begin with some *a priori* definition of 'success' that is based more in the theory of emissions trading than in practical experience. Experience teaches us that there are certain things that carbon markets can potentially do very well, but it is unreasonable to expect them to cut global carbon emissions, to minimise the short-run cost of abatement, to bring about a low-carbon technological revolution, and be a tool for achieving a more equitable global income distribution, all at once. In fact, these objectives often conflict, so we must leverage our historical experience to better understand what kind of success it is reasonable to expect. The political economy of carbon markets appears to offer a very real obstacle to achieving efficient cuts to emissions, and in light of this, the ability to minimise the short-run cost of 'abatement' (e.g. by utilising fuel switching, HFC-23 projects, etc.) may be a Pyrrhic victory. What is more, minimising the short-run abatement cost may be at odds with spurring low-carbon innovation and minimising the long-run abatement cost (Vogt-Schilb & Hallegatte, 2011).

The second problem is that many continue to argue, as Tietenberg did in 1985, that the problems with carbon markets can be avoided by fully implementing the theoretical recommendations. Phase 1 of the EU ETS was, after all, primarily a learning phase. The CDM is still being modified, and the NZ ETS is in its transitional period. We are still at a steeply rising part of the learning curve, one hears. But in light of historical experiences one must ask whether the problems run deeper.

It is partly hindsight that now permits us to notice the warning signs, but it does seem that we are not learning enough from past experiences. There are some encouraging signs in RGGI and the Australian programme, but one would hope that we had learnt more of the lessons from earlier emissions trading programmes. Carbon markets form a large and integral part of climate policy, and although they may still be in their infancy, the learning curve is not steep enough. A historical perspective teaches us both about bad habits we must work harder to break (e.g. over-allocating permits), and about good fortunes that we perhaps cannot take for granted (e.g. technological change). If the design of these policies were more geared toward systematic evaluation, we might stand a better chance of finding opportunities to intervene to break bad habits, and to quickly evaluate performance and respond if need be. A greater openness to incorporating these elements into programme designs may help us design more effective carbon markets, and to better complement them with a portfolio of policies that will facilitate our transition to a low-carbon economy.

Chapter 3

Do market-based instruments encourage 'green' innovation? A theoretical synthesis

3.1 Introduction

Market-based instruments—emissions taxes and tradeable emissions permits—are widely used to regulate a range of air- and water-borne pollutants. In 2009 alone, environmental taxes raised over \$1.1 trillion in revenue for governments across the world.[1] In the same year, the value traded on international carbon markets was over \$140 billion (Linacre et al., 2011). Market-based instruments are clearly already playing a prominent role in environmental and climate policy, and they are expected to play an even bigger role in the future (see, for instance, European Commission, 2011).

There are several economic arguments favouring market-based instruments over more traditional command and control regulations. One of the main motivations for market-based instruments is the claim that they encourage innovation and investment in 'green' technologies.

---

[1] The OECD maintains a comprehensive database of environmentally related taxes and tradeable permit systems, as well as deposit-refund systems, environmentally motivated subsidies, and more. This figure is based on numbers reported therein.

Emissions reductions that arise from changes in technology are more likely to be real and permanent, in contrast with emissions reductions achieved through other means, like outsourcing and offshoring (which merely makes emissions invisible to the regulator) or fuel switching (which can quickly be reversed in response to price fluctuations). What is more, in contrast to other paths to cutting emissions, technological change can also dramatically alter the cost of abatement itself. Consequently, the ability of market-based instruments to encourage innovation and investment in abatement technologies is perhaps the single most important measure of their success or failure (Kneese & Schultze, 1975), and at the very least a good near-term indicator of whether market-based instruments can be expected to achieve more ambitious long-term emissions reductions.

So what is the relationship between market-based instruments and firms' technology choices? Underpinning the now growing empirical literature on this question (see Popp et al., 2009, Popp, 2010, and Ambec et al., 2013, for recent surveys) is an extensive theoretical literature that compares the incentives for innovation under permits and taxes (Malueg, 1989; Fischer et al., 2003; Weber & Neuhoff, 2010), tries to model the properties of different technologies (Bauman et al., 2008), asks what effect market power (Montero, 2002a,b) or the credibility of the regulator (Kennedy & Laplante, 1995, 1999; Mash et al., 2003; Requate, 2005) might have on these incentives, and much more. Existing contributions, though, often rely on different assumptions or model different settings, making it difficult to compare their conclusions. This chapter presents a simple analytical framework that brings this literature together.

Apart from surveying a large part of the theoretical literature, a coherent treatment also provides an opportunity to explore the relationship between market-based instruments and technology choices more systematically. This methodical search highlights some interesting properties of the relationship between market-based instruments and firms' technology choices. For instance, I identify plausible circumstances in which a higher price of emissions actually reduces the incentive for investment in abatement technologies. This occurs for sufficiently high emissions prices when the abatement technology reduces emissions per unit of output without affecting the optimal level of output. I consider the implications of this observation for policy and research. More broadly, bringing the firm's technology choices into a single conceptual framework makes clear that a price on emissions invariably affects the type of abatement technologies firms invest in—not even a single price on emissions is 'technology neutral'. The technological aspects of emissions abatement must therefore be considered in tandem with the design of the market-based instrument.

It is also worth noting what this chapter does *not* do. The word 'synthesis' in the title is used in the literal sense of combining different ideas within a single theoretical framework. The insights gained from this exercise are not of the 'grand unifying'-kind, but instead shed light on the relationships between the many disparate special cases studied in the sprawling theoretical literature. While this may be a less climactic conclusion to a 'synthesis', it does reveal something fundamental about the subject matter. Ultimately, designing market-based instruments is not about finding a general rule that applies everywhere, but rather about understanding and thinking through the particular economic and technological circumstances in which a policy will be implemented. By bringing these scenarios into a coherent conceptual framework, a synthesis better equips us for this task.

Section 3.2 introduces a simple model of technology choice in both algebraic and graphical forms. I shall refer back to the mathematical model throughout, but since many of the formal results can be found in one form or another elsewhere in the literature, I rely mainly on graphs to communicate the conclusions of the analysis. Section 3.3 extends the technology choice problem to situations when a firm's expectations about competitor and regulatory responses are more complex, such as when firms have market power, when they can affect the diffusion of their innovations, and when the regulator cannot commit to a future policy. Section 3.4 offers concluding observations relevant to both the design of market-based instruments and the empirical study of their impacts on innovation.

3.2 Market-based instruments and technology choices

3.2.1 The model

Let us first set out a simple model of the firm's technology choice. The model is a more general version of that presented by Bauman et al. (2008), and further modifies their model in two important respects. Firstly, it includes a price on emissions, and secondly, it makes the firm's technology choice explicit.

Consider a firm producing a final good, Q, and in doing so generating emissions e. The firm's production function $Q = Q(x, \gamma)$ exhibits diminishing marginal returns to the input x. Both the level of output and the marginal product of x are increasing in the productivity parameter γ.[2] The input x can be purchased at a per unit price of z, and the output can be sold at a per unit price p.

The firm faces a price on emissions, t. This price can be either a tax per unit of emissions or the equilibrium price in a competitive market for tradeable permits. At price t the firm must pay $t(e - \bar{e})$ to obtain the necessary emission rights, where e is final emissions and $\bar{e}$ is the initial allocation of rights. Let us also define gross emissions, G, to be what the firm would emit in the absence of end-of-pipe abatement. G is increasing in input use and decreasing in the emissions efficiency parameter β, $G = G(x, \beta)$.

End-of-pipe abatement is the difference between G and final emissions e. The firm's total end-of-pipe abatement cost is given by $F = F(G - e, \alpha)$, which is increasing in end-of-pipe abatement ($G - e$), and decreasing in the effectiveness of the end-of-pipe technology α, whenever $G > e$. $F(0, \alpha) = 0$.

The parameters α_i (end-of-pipe effectiveness), β_i (emissions efficiency), and γ_i (productivity) then describe technology i. In addition, the (certainty equivalent) fixed cost of adopting/developing technology i is c_i.[3]

With a price of emissions t, a firm using technology i can earn a maximum profit of:

$$\pi_i = \max_{x,e} [pQ(x, \gamma_i) - zx - t(e - \bar{e}) - F(G(x, \beta_i) - e, \alpha_i)] \tag{3.1}$$

Let x_i denote the profit-maximising input choice with technology i, and e_i the profit-maximising level of emissions. The incentive to invest in a new technology i can then be written as the dif-

---

[2] Table 3.1 summarises notation, and also restates the functional restrictions described in the text in algebraic terms.

[3] In this chapter I make no substantive distinction between innovation and investment. As most of the literature reviewed here, I am interested in a firm's incentive to change the technologies used in production, whether that occurs through adoption of existing technologies or development of new ones. The distinction between innovation and investment occasionally become important in Section 3.3, and is then highlighted, but otherwise the terms are used interchangeably.

ference between profits earned with the new technology and the profits earned with the initial technology (for convenience, let us denote the initial technology by subscript 0). Formally, we write:

$$\begin{aligned}\phi_i &= \pi_i - \pi_0 \\ &= p[Q(x_i, \gamma_i) - Q(x_0, \gamma_0)] - z(x_i - x_0) \qquad (3.2) \\ &\quad -[F(G(x_i, \beta_i) - e_i, \alpha_i) - F(G(x_0, \beta_0) - e_0, \alpha_0)] - t(e_i - e_0)\end{aligned}$$

The first two terms on the right-hand-side give us the changes in profit resulting from changes in revenue and input costs. It is the last two terms that represent the incentive for investment into technology i provided by the market-based instrument. They both drop out when the price of emissions is zero.[4] Let $x_{i,\max}$ and $e_{i,\max}$ respectively denote the optimal input choice and emissions with technology i when $t = 0$.

Since we are especially interested in the incentive for innovation and investment provided specifically by the market-based instrument, let us define this concept separately as

$$\Phi_i = F(G(x_0, \beta_0) - e_0, \alpha_0) - F(G(x_i, \beta_i) - e_i, \alpha_i) + t(e_i - e_0) \qquad (3.3)$$

The first term on the right-hand-side gives us the change in profit resulting from a change in abatement costs and the second term gives us the change in profit resulting from a change in payments for emission rights. Notice that when the firm faces a given price t, as would be the case under an emissions tax or in a competitive permit market, the initial allocation of emission rights $\bar{e}$ does not affect a profit-maximising firm's incentive to invest in new technologies (Requate, 2005).[5] There are many reasons why we would not expect this standard result to hold in practice (see, for instance, Hepburn et al., 2006), and we will see some of the caveats accompanying this result more clearly in Section 3.3.

Φ_i can also be represented graphically. The function $F(G(x_i, \beta_i) - e_i, \alpha_i)$ gives the total cost of emissions abatement at the optimal emissions level with technology i. We write the corresponding marginal abatement cost as $f(G(x_i, \beta_i) - e_i, \alpha_i)$. Now imagine deviating from the

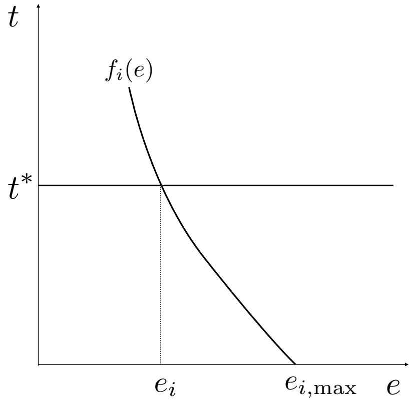
---

[4] The first term drops out since the firm would never optimally incur any end-of-pipe abatement (i.e. it would set $G = e$ with any technology, so $F = 0$), and the second term drops out trivially.

[5] The same conclusion can also be deduced from Hahn (1984), who shows that the level of emissions of a price-taking firm is independent of its initial allocation of emissions rights.

optimal level of emissions for a given technology i. $f(\cdot)$ then gives us the marginal abatement cost curve. Since i fixes G and α_i, we can simplify our notation and let $f_i(e)$ denote the marginal abatement cost curve for technology i. $f_i(e)$ is a decreasing function of emissions e. This curve is illustrated in Figure 3.1. Φ_i is the difference between the areas under two such curves, with the addition of any revenues generated from a change in the cost of complying with the emissions price.

Figure 3.1: 'Demand for emissions' with technology i



With technology i, the firm's demand for emissions is $f_i(e)$. At a given emissions price, t^*, the firm would optimally emit $f_i^{-1}(t^*) = e_i$. The firm would optimally emit $e_{i,\max}$ if the emissions price were zero.

This point can be seen even more clearly if we harmonise the algebraic and graphical representations. We can rewrite Equation 3.3 using the notation for marginal abatement costs:

$$\Phi_i = \int_{e_0}^{e_{0,\max}} f_0(e)de - \int_{e_i}^{e_{i,\max}} f_i(e)de + t(e_i - e_0) \tag{3.4}$$

The net gain from adopting technology i is obtained by subtracting the cost of adoption, c_i, from the total gain, ϕ_i. Formally, a profit-maximising firm will only invest in technology i if

$$\phi_i - c_i \geq \max(\phi_1 - c_1, \ldots, \phi_{i-1} - c_{i-1}, \phi_{i+1} - c_{i+1}, \ldots, \phi_I - c_I, \bar{r}) \tag{3.5}$$

where $\bar{r}$ is a reservation return. Equation 3.5 is an investment condition, and defines the firm's technology choice problem.

Table 3.1 on the following page summarises all of the notation in this section for easy reference.

One salient feature of our setup is the four-parameter family of technologies, $(\alpha, \beta, \gamma, c)$. We can choose these parameters to describe any physical technology of interest (or any combination of

Table 3.1: Summary of notation

Notation	Description
i	Subscript i denotes a technology. Technology i is fully characterised by the four parameters $(\alpha_i, \beta_i, \gamma_i, c_i)$. The technology also determines the firm's optimal level of input x_i and emissions e_i, as seen in Equation 3.1. Subscript 0 is used to denote the firm's starting technology.
α_i	The end-of-pipe effectiveness parameter. A higher α indicates that the technology is associated with a lower total cost of a given level of end-of-pipe abatement.
β_i	The emissions efficiency parameter. A higher β indicates that the technology produces more units of gross emissions per unit of input.
γ_i	The productivity parameter. A higher γ indicates that a technology produces more output per unit of input.
c_i	The technology-specific fixed cost of adoption.
x	The firm's input. We use x_i to denote the firm's optimal input choice for technology i.
z	The price per unit of input.
p	The price per unit of output.
t	The price per unit of emissions.
e	The firm's level of emissions. We use e_i to denote the firm's optimal level of emissions for technology i.
$\bar{e}$	The initial allocation of emissions rights to the firm. This is zero under an emissions tax, but may be positive under an emissions trading scheme.
$e_{i,\max}$	The technology-specific level of emissions when the price of emissions is zero, $t = 0$.
$Q = Q(x, \gamma)$	Q is the firm's total output, and $Q(\cdot)$ is the firm's production function, with $Q_x > 0$, $Q_{xx} < 0$, $Q_\gamma > 0$, and $Q_{x\gamma} > 0$.
$G = G(x, \beta)$	G is the firm's gross emissions (i.e. prior to end-of-pipe abatement), and $G(\cdot)$ is the gross emissions function, with $G_x > 0$ and $G_\beta < 0$.
$F = F(G - e, \alpha)$	F is the firm's total cost of end-of-pipe abatement, and $F(\cdot)$ is the total end-of-pipe abatement cost function, with $F_{G-e} > 0$ and $F_\alpha < 0$, whenever $G > e$. $F(0, \alpha) = 0$. Note that the firm's end-of-pipe abatement is equal to gross emissions less final emissions $(G - e)$.
$f_i(e)$	The marginal abatement cost for technology i is a function of the level of emissions, e.
ϕ_i	The change in the firm's maximum profit resulting from a switch from technology 0 to technology i.
Φ_i	That part of ϕ_i due to a market-based instrument.
$\bar{r}$	A reservation return on investment.

physical technologies), and any level of investment in this physical technology. Therefore, this analytical framework can simultaneously address questions about *what* technologies to invest in, and *how much* to invest.

Another feature of our model is the simplicity of the firm's expectations about the gains from innovation and investment in new technologies. In this model of an emissions price the firm's decision is based entirely on how much it *expects* to gain from changing technology, so real variables are important only in so far as they shape expectations. Here the firm considers only its own choice, taking prices and other firms' decisions as given. In Section3.3 we consider what happens when the circumstances warrant more complicated expectations. But first let us see what we can already glean about how the price of emissions affects the firm's technology choices.

3.2.2 Incentives to invest in 'green' technologies

Now that we have set out our basic model both algebraically and graphically, the first task is to examine the firm's incentives to invest in different types of technologies.[6] To do this we compare the maximum profits the firm can earn by adopting one of a number of 'pure innovations' that differs from the initial technology in only one of the parameters $(\alpha, \beta, \gamma, c)$.

End-of-pipe innovations (increases in α)

Let us begin by considering the emitter's incentive to develop and adopt an end-of-pipe technology (*EOP*). The original argument that market-based instruments encourage innovation considered just such a technology (see, for instance, Tietenberg, 1985; Downing & White, 1986; Malueg, 1989; and Milliman & Prince, 1989), and it remains the most commonly discussed technology in the literature (see, for instance, Fischer et al., 2003 and Weber & Neuhoff, 2010). End-of-pipe technologies filter the exhaust of a production process, but do not actually affect production itself. This means that $x_0 = x_{EOP}$, so that in this case $\phi_i = \Phi_i$. In other words,

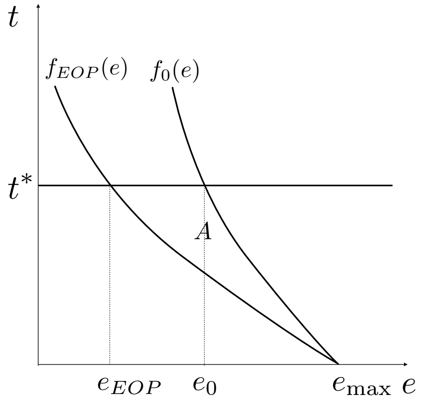
---

[6] This section borrows from and significantly extends the discussion of different technologies in Bauman et al. (2008).

end-of-pipe abatement has no impact on sales revenues and input costs. The end-of-pipe innovation does, however, increase α from α_0 to α_{EOP}. As a consequence, the firm faces a lower marginal abatement cost for every positive level of emissions ($f_{EOP}(e) < f_0(e)$ for all $e > 0$).

Graphically, the result is a downward pivot of the marginal abatement cost curve around the point $e_{\max}$ (see Figure 3.2). Φ_i is given by the area A in Figure 3.2. As Figure 3.2 also illustrates, the optimal amount of emissions will always be lower with the end-of-pipe technology installed. The incentive to adopt a given end-of-pipe technology is therefore increasing in the price of emissions, t.

Figure 3.2: End-of-pipe innovations



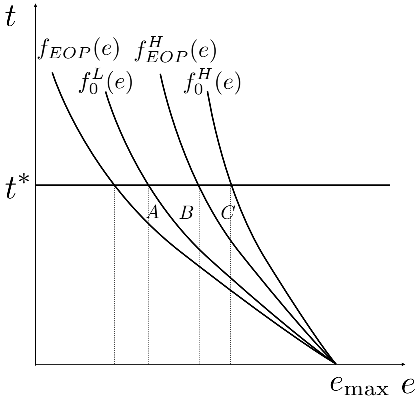
The inverse demand curve pivots downward as a result of adopting an end-of-pipe technology.

Traditionally, end-of-pipe innovations have been modelled as a lumpy investment in a ‘discrete’ technology. Whatever the firm’s starting technology, adopting the end-of-pipe innovation results in the same marginal abatement cost curve. This means that a firm with an initially steeper marginal abatement cost curve would stand to gain more from the end-of-pipe innovation. Weber & Neuhoff (2010), however, consider what we may term ‘proportional’ end-of-pipe innovations, so that investing in innovation pivots the marginal abatement cost curve downward from its original position in proportion to the level of investment.[7] A given investment in a ‘proportional’ end-of-pipe innovation is then more attractive to a firm with initially shallower marginal abatement cost curve (Weber & Neuhoff, 2010, Equation 5), the exact opposite of the ‘discrete’ technology. Figure 3.3 illustrates this point.

---

[7] Although innovation and emissions have stochastic components in their model, their comparative statics are conducted in terms of expected returns on investment, and so are fully comparable with the present analysis.

Figure 3.3: 'Discrete' and 'proportional' end-of-pipe innovations



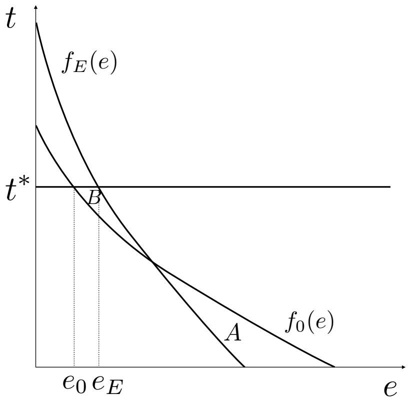
With a 'discrete' end-of-pipe innovation, the firm's marginal abatement cost curve becomes $f_{EOP}(e)$ if it adopts the new technology, whether they start out with a shallow curve $f^{L}_{0}(e)$ or a steep curve $f^{H}_{0}(e)$. The incentive to adopt the 'discrete' end-of-pipe technology is given by the area A in the former case, and $A+B+C$ in the latter. With 'proportional' end-of-pipe innovations, however, firms do not end up with the same marginal abatement cost curve after equivalent investments. Rather, this results in equivalent pivots of their marginal abatement cost curves—from $f^{L}_{0}(e)$ to $f_{EOP}(e)$ and from $f^{H}_{0}(e)$ to $f^{H}_{EOP}(e)$. In this case, the incentive to innovate is A when starting with a shallow curve, and C when starting with a steeper curve, where $A > C$.

Irrespective of whether end-of-pipe innovations are 'discrete' or 'proportional', the incentive to adopt a given end-of-pipe technology Φ_i is increasing in the price of emissions t. This is one of the classic arguments for pollution pricing (Tietenberg, 1985; Downing & White, 1986), although it must be noted that it was originally used in reference to sulphur-scrubbers in the US Acid Rain Program. If we look instead at carbon pricing initiatives like the EU Emissions Trading Scheme, however, this particular argument based on end-of-pipe technologies is less persuasive. With the possible exception of Carbon Capture and Storage, which in any case few believe will be delivered in response to low or moderate carbon prices, there do not appear to be sufficient technological opportunities for end-of-pipe abatement to offer a compelling case for carbon prices. It would be valuable instead to consider the incentives market-based instruments provide for investment in other types of abatement technologies.

Efficiency-enhancing innovations (increases in β)

Consider the incentive to adopt an efficiency-enhancing technology, E, which increases β from β_0 to β_E. The output produced with one unit of input is unchanged, but the emissions per unit of input is reduced. Put another way, the technology increases efficiency with respect to emissions only, not with respect to any of the other inputs. Consequently, a more drastic reduction of output would now be needed to abate one unit of emissions. In other words, the marginal abatement cost rises more steeply ($f'_E(e) < f'_0(e)$ for all e). Moreover, as long as the end-of-pipe technology is the same, the emitter's profits whenever he is emitting nothing remains the same, regardless of whether he adopts the efficiency-enhancing innovation or not ($F_0(0) = F_E(0)$). Seen graphically, the marginal abatement cost curve is steeper, but the area beneath the curve is the same. The incentive to invest provided by the market-based instrument, Φ_i, is given by the area $A - B$ in Figure 3.4.

Figure 3.4: Efficiency-enhancing innovations



The marginal abatement cost curve becomes steeper when adopting efficiency-enhancing technologies, but the area beneath the curve remains constant.

The first thing to note is that the optimal amount of emissions may either increase or decrease as a result of an efficiency-enhancing innovation. Somewhat counterintuitively, efficiency-enhancing innovations are likely to increase emissions at a higher emissions price t, and the incentive for adoption of the technology is therefore weaker for a higher emissions price. The reasoning goes as follows: while it had previously been optimal to draw down production at a high price of emissions, a more efficient technology increases the benefit of emitting an extra unit. The higher the price, the less you were already emitting under the old technology, and the more you now gain at the margin from increasing emissions. When the price of emissions is high, increasing emissions would be more expensive, so the firm would have a weaker incentive to adopt the efficiency-enhancing technology in the first place.

The converse line of reasoning suggests that efficiency-enhancing innovations are likely to reduce emissions at a low emissions price, and that the incentive to adopt the technology is stronger at a lower price. The incentive for technology adoption reaches a maximum when $t = f_E(e) = f_0(e)$ in Figure 3.4, and thereafter declines as the emissions price increases further. Thus, contrary to the traditional arguments that refer to end-of-pipe technologies, a lower price of emissions (to a point) may actually give stronger incentives for investment for efficiency-enhancing technologies. This may be a lesson worth bearing in mind for sectors of the economy where the bulk of innovations are expected to be of the efficiency-enhancing sort. We discuss some of the policy implications of this observation below.

Process innovations (increases in γ)

Next, consider the incentive to adopt a process innovation, P, causing an increase in γ from γ_0 to γ_P. Process innovations increase the amount of output per unit of input, but does not affect emissions per unit of input. A process innovations might affect the optimal scale of production and emissions, and a price on emissions may therefore provide an incentive or disincentive to adopt such technologies.

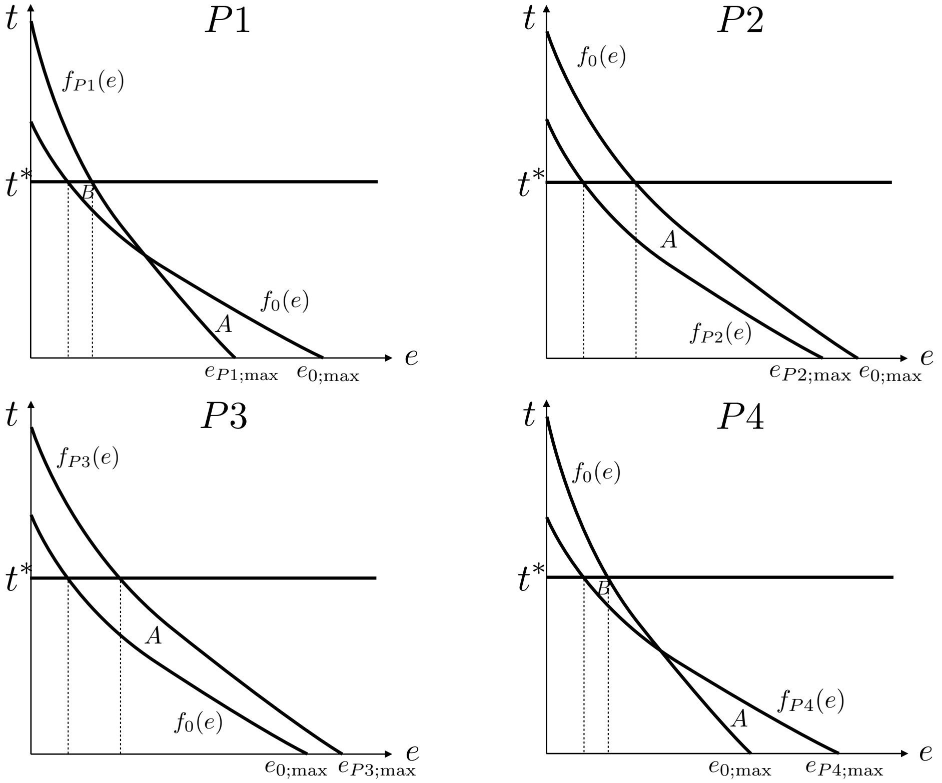
Even when the price of emissions is zero, a process innovation may increase the optimal scale of production and hence emissions ($e_{P,\max} > e_{0,\max}$), or it may reduce it ($e_{P,\max} < e_{0,\max}$).[8] A process innovation, moreover, may in principle be associated with either a decrease or an increase in the cost of abating all the way to zero emissions ($F_0(0) - F_P(0) \lesseqgtr 0$). There are then four interesting cases of process innovations (see Figure 3.5):

P1 'Clockwise pivot' $\{e_{P1,\max} < e_{0,\max},\ F_0(0) - F_{P1}(0) < \epsilon\}$: With a reduction in optimal level of unconstrained emissions and an increase or small reduction in the cost of full abatement (here represented as being less than some positive quantity ϵ), the horizontal intercept of the marginal abatement cost curve decreases (i.e. $e_{P1,\max} > e_{0,\max}$), but the vertical intercept increases (i.e. $f_{P1}(0) > f_0(0)$). As panel $P1$ of Figure 3.5 illustrates, this looks similar to adoption of an efficiency-enhancing innovation. The incentive to invest is given by the area $A - B$, and is increasing in the price of emissions up to the point

---

[8] One economic rationale for this is market power. If demand for the firm's output is very elastic, the firm would increase production when the marginal costs of production falls. If demand is inelastic, the firm may optimally restrict its production.

Figure 3.5: Process innovations



Depending on the optimal scale of production at a zero emissions price and the change in the cost of full abatement, process innovations can cause a variety of shifts of the marginal abatement cost curve.

where $p = f_0(e) = f_{P1}(e)$ in the first panel of Figure 3.5, and thereafter decreasing in the price of emissions.

P2 'Shift down' $\{e_{P2,\max} < e_{0,\max}, F_0(0) - F_{P2}(0) > \epsilon\}$: With a reduction in optimal level of unconstrained emissions and a large reduction in the cost of full abatement, the marginal abatement cost curve shifts inward so that the whole curve lies beneath the old curve (i.e. $f_{P2}(e) < f_0(e)$ for all e), as illustrated in panel $P2$ in Figure 3.5. The incentive to invest is given by area A, and is increasing in the price of emissions.

P3 'Shift up' $\{e_{P3,\max} > e_{0,\max}, F_0(0) - F_{P3}(0) < \epsilon\}$: With an increase in optimal level of unconstrained emissions and an increase or small reduction in the cost of full abatement, the marginal abatement cost curve shifts outward so that the whole curve lies above the old curve (i.e. $f_{P3}(e) > f(e)$ for all e), as seen in panel $P3$ of Figure 3.5. The disincentive to invest is given by A, and is increasing in the price of emissions.

P4 'Anti-clockwise pivot' $\{e_{P4,\max} > e_{0,\max}, F_0(0) - F_{P4}(0) > \epsilon\}$: With an increase in the optimal level of unconstrained emissions and a large reduction in the cost of full abatement, the horizontal intercept of the marginal abatement cost curve increases, but the vertical intercept decreases, as illustrated in panel $P4$ of Figure 3.5. The incentive to invest provided by the emissions price, Φ_{P4}, is given by $B - A$. This type of process innovation increases the optimal level of emissions at a low price, but reduces emissions at a high price. A low price therefore discourages this type of innovation, and the disincentive initially becomes stronger as the price of emissions increases. The incentive reaches a minimum when $t = f_{P4}(e) = f(e)$, and thereafter increases with the emissions price.

Note that the impact of a market-based instrument on the firm's incentive to adopt process innovations depends on how the innovation would affect the firm's optimal scale of production. Hence, the market conditions in the output markets in which the emitters operate may influence the firm's incentives to invest in different process innovations.

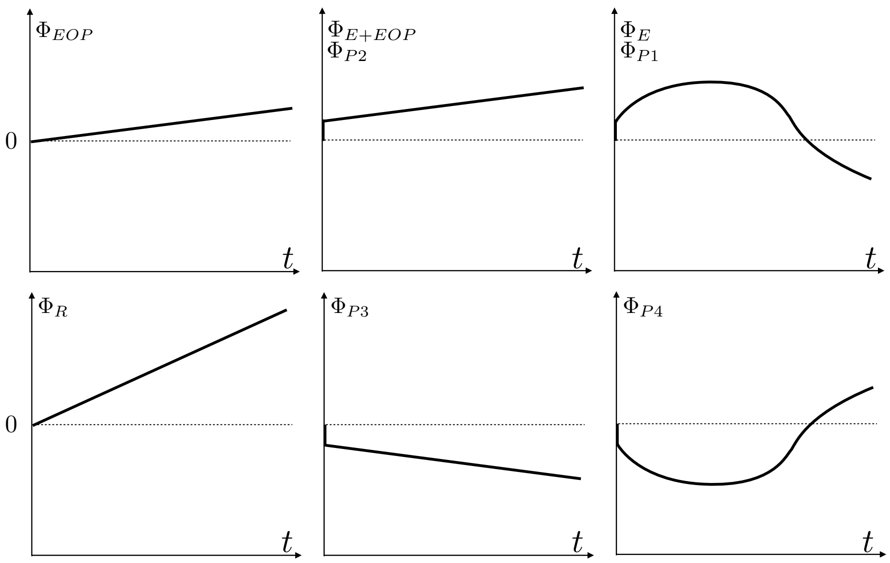
Replacement innovations (very large increases in α or γ)

Until now we have looked at innovation and investment in abatement technologies. Yet another type can be described as *replacement* technologies, R (Laffont & Tirole, 1996a,b; Scotchmer, 2011). Replacement technologies, such as a fully efficient end-of-pipe technology or a pollution-free perfect substitute for the polluting good, eliminate the need for abatement as such. In our model, these would respectively be represented as a very large increase in α or γ. With such technologies, the optimal amount of emissions is always zero, so $e_{R,\max} = 0$. Graphically, the incentive to invest in replacement technologies is the whole area beneath the marginal abatement cost curve which falls below the price of emissions, t. The incentive to innovate and invest in replacement technologies is always increasing in the price of emissions.

3.2.3 Market-based instruments and technology choices

We can now compare the incentives to invest in different technologies. For convenience, Figure 3.6 summarises how the gains from innovation and investment provided by the market-based instrument, Φ_i, depends on the price of emissions.

Figure 3.6: Incentives for investment



The six stylized panels illustrate how the incentives for adopting technologies of different types depend on the price of emissions, t. To facilitate comparisons, the cost of adopting each technology, c_i, is assumed to be zero for all technologies. A positive c_i would simply shift the curves vertically down.

Firgure 3.6 emphasizes the importance of opportunity cost in technology choice. A higher emissions price not only affects overall incentive for innovation and investment in clean technologies against the alternate use of those resources, but also the relative appeal of alternative technologies. For instance, in Figure 3.6, the efficiency-enhancing innovation (E) looks relatively more attractive at lower emissions prices, while the replacement technology (R) becomes much more attractive at higher prices. Incorporating many different types of innovations into a coherent analytical framework emphasises that the firm's problem is not just how much to invest, but one of *technology choice*. We have illustrated the technology choice problem by looking at 'pure innovations'—technologies that alter just one of the parameters $(\alpha, \beta, \gamma, c)$—but our framework can be applied without modification to analyse the firm's optimal choice from the whole set of feasible physical technologies (and combinations of physical technologies) defined in $(\alpha, \beta, \gamma, c)$-space.

Moreover, this perspective highlights that a price on emissions invariably affects the type of abatement technologies firms will invest in. Even a single economy-wide emissions price will almost inevitably shift investments between economic sectors and between different technologies—not necessarily in accordance with cost-efficiency or abatement potential, but sometimes depending on market structure and other factors. A single economy-wide emissions price is often advocated on the grounds that it leaves technology choices to the market (Metcalf, 2009), but our analysis casts doubt on whether a comprehensive emissions tax or cap-and-trade programme can be said to be technology-neutral in any meaningful sense. Even with these policies a government cannot realistically avoid "picking winners" among new 'green' technologies. Since these policies are not really technology-neutral, it would seem justified to explicitly and seriously consider the technological aspects of emissions abatement in tandem with the design of the market-based instrument.

One of the more surprising features of Figure 3.6 is that the incentive for investment in abatement technologies is not always an increasing function of the emissions price. For some technologies, a lower price of emissions (to a point) may actually provide greater incentives for innovation and technology adoption. This finding derives from very conventional producer theory, yet sharply contrasts with the conventional wisdom. The negative relationship between the price on emissions and incentives for innovation and investment arises from the fact that what we normally would think of as 'green' technologies are, for certain pollution prices, in actual fact emissions-increasing technologies.[9]

Three points are worth highlighting about this finding. Firstly, this result is conceptually distinct from the better-known rebound effect. The rebound effect states that increases in demand for output partly or wholly erode the emissions reductions from introducing a more efficient technology (i.e. one with a lower per unit price of emissions). Meanwhile, the relationship

---

[9] Versions of this result have been independently produced by Bréchet & Meunier (2012) and Perino & Requate (2012), who discuss it at greater length and provide formal proofs. The essential features are easy enough to see in a graph, so we dispense with an algebraic demonstration of the result here.

illustrated in Figure 3.6 arises out of the optimal decisions of a competitive firm without reference to changes in demand. The former also usually makes a claim about the response of demand to improvements in efficiency over time, while the latter describes a result that follows immediately from the firm's optimal decisions. There is perhaps no obvious theoretical reason why sectors of the economy for which the technological opportunities are considered chiefly of the efficiency-enhancing kind should also be the sectors in which the rebound effect is generally considered important (lighting, automobiles, etc.). Yet, to the extent that these coincide in practice, one may worry that emissions reductions might be doubly eroded when policy makers pursue energy efficiency via an emissions price.

Secondly, the non-monotonic relationship between the emissions price and innovation potentially characterises a large and important class of 'green' technologies. In sectors of the economy where investments in these technologies are thought an important objective of policy, for instance in reducing the carbon-footprint of buildings, introducing an emissions price may not yield the anticipated outcome. The Carbon Reduction Commitment Energy Efficiency Scheme in the UK is one prominent example of such a policy. If the pollution price is too high, the program might actually discourage investments in efficiency-enhancing technologies. Alternatively, if the Scheme starts with a low pollution price that is gradually raised, which is how programmes are often intended to develop, this might result in early investments in efficiency-enhancing technologies that end up optimally producing greater-than-"business-as-usual" emissions when the strictness of the policy is eventually adjusted. With transparent advance planning by regulators, though, forward-looking firms would avoid this.

Thirdly, although a higher price on emissions may in some cases discourage investment in 'green' technologies, this is not necessarily an undesirable outcome. As our analysis indicates, the high price will discourage investment in efficiency-enhancing technologies that actually do not result in any emissions reductions at that price. In a broader context, a very high emissions price might be read as the mark of a society that wishes to aggressively pursue emissions reductions, and in this setting, the types of abatement technologies concerned (e.g. efficiency-enhancing technologies) may not represent welfare-improving investments in any case. Less innovation and investment in these technologies may then reflect an efficient outcome.

3.3 Extensions of the model

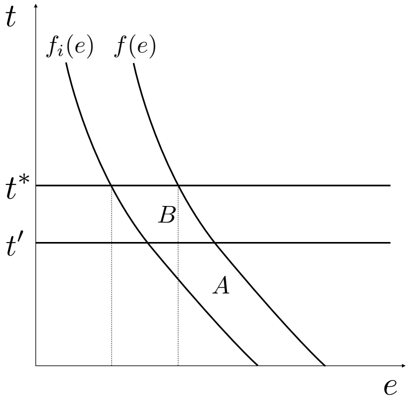
The simple model in Section 3.2 yields several insights into the effect that market-based instruments have on the firm's technology choices. Yet, the analysis made a central simplifying assumption—an exogenously given emissions price. Although it would be rational for the firm to act as a price-taker with respect to the emissions price in this setting, there is no general justification for assuming that the price of emissions does not also respond to technology choices. This section looks at how optimal technology choices change when the price of emissions is endogenous.

3.3.1 Innovation and investment in equilibrium

In some settings, firms' technology choices may affect the emissions price they face. For instance, the price set in a permit market responds to changes in demand for permits, which in turn depends on technology choices. In order to characterise the relationship between the equilibrium permit price, t^*, and the number of firms that adopt new technologies, n, we need to know whether adopting the technology increases or decreases the firm's optimal level of emissions. Based on our previous analysis, we know that adopting one of the technologies EOP, $P2$, or R, unambiguously reduces the optimal amount of emissions. Adopting E or $P1$ reduces emissions if the emissions price is sufficiently low, and $P4$ reduces emissions if the price is sufficiently high. We shall refer to these situations collectively as *emissions-reducing innovations*. For $P3$, emissions unambiguously increase. Emissions also increase when the price of emissions is sufficiently high with E and $P1$, as well as for $P4$ when the price is sufficiently low. We shall refer to these situations as *emissions-increasing innovations*. Note that for some technologies, the price of emissions determines whether they are emissions-reducing or emissions-increasing.

Requate & Unold (2003) consider adoption of emissions-reducing innovations. With such technologies, adoption reduces demand for permits, so the equilibrium price falls ($t^{*'}(n) < 0$) and the gains from innovation and investment therefore also decrease ($\Phi_i'(n) < 0$, since Φ_i is an increasing function of the emissions price for emissions-reducing innovations). Noninnovating firms share in the reduced abatement costs that come from a lower emissions price despite not investing themselves. They are free-riding on the innovators (Requate & Unold, 2003). This is illustrated in Figure 3.7. If only one firm were to adopt an emissions-reducing innovation, it would stand to gain profits equal to the area $A + B$. More widespread technology adoption, however, reduces aggregate demand for permits. Since the supply of permits is fixed, their price falls. If the firm expects the price to fall to t' as the technology spreads, the expected gain from adopting the technology would equal only area A.

Figure 3.7: Incentives in equilibrium



The incentive to adopt an emissions-reducing innovation i is given by area $A + B$ when the equilibrium price is $t*$. The incentive for adoption is smaller, area A, when the price has fallen from t^* to t'. The change in the price can be brought about if a sufficient number of emitters adopt the emissions-reducing innovation. This figure is adapted from Requate & Unold (2003).

The converse reasoning applies to emissions-increasing innovations. The permit price increases as the innovation spreads ($t^{*\prime}(n) > 0$), since firms demand more permits. Since the incentive for investment is decreasing in the emissions price for emissions-increasing innovations, prior adoption again reduces the gains for further adoption ($\Phi_i'(n) < 0$). Thus, when the price of emissions is set in a permit market, more widespread technology adoption always reduces the gains from adopting any given type of innovation.

Three important clarifications are in order here. Firstly, a forward-looking firm would only consider the gain in equilibrium, i.e. $\Phi_i(t')$ calculated at the emissions price that obtains when the equilibrium number of firms have adopted the technology, t'. This is given by area A in Figure 3.7. The incentive to invest in technology i is then independent of the number of firms that have adopted the technology so far. However, for a firm that acts on the basis of the currently prevailing equilibrium emissions price t^*, whether because they are myopic or because they do not have good enough information about future equilibrium prices, the incentive to adopt a new technology depends on the number of prior adopters at any given point. In this situation, the incentive for investment is greater for early adopters ($A + B$ in Figure 3.7) than for late adopters (A).

Secondly, for a constant cost of adoption c_i, we may have partial technology diffusion in equilibrium with an emissions trading programme, but not with an emissions tax. The price of emissions in a tradeable permit scheme responds to technology adoption, and firms would stop adopting when the benefit no longer exceeds the cost. Partial adoption would not be possible with an emissions tax, since the emissions price faced by firms (and hence the benefit of technology adoption) is constant and independent of prior technology adoption.

Thirdly, it is important to note that prior adoption reduces the gains from further adoption only for the *same* type of innovation (i.e. emissions-reducing or emissions-increasing). Adopting emissions-reducing innovations puts downward pressure on the permit price, and hence on the incentive for further adoption of emissions-reducing innovations. However, a lower price *increases* the incentive to adopt emissions-increasing innovations. Conversely, adopting emissions-increasing innovations puts upward pressure on the price, and hence increases the incentive to adopt emissions-reducing innovations. On route to a stable emissions price, adoption of an emissions-reducing innovation by one firm may induce another to adopt an emissions-increasing innovation, and so on. An equilibrium involves a stable portfolio of technologies across firms, but a simple static model does not provide much information about what the final portfolio of technologies will look like.[10] I return to this issue in Section3.3.4 below.

3.3.2 Market power

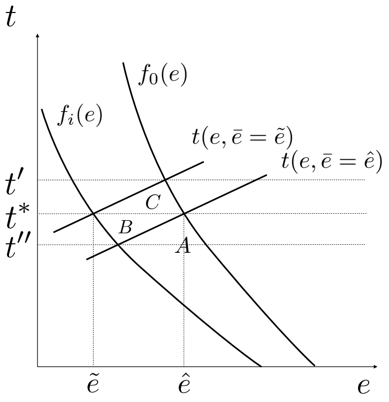
Let us continue with an emissions price set in a permit market. In a competitive market, as above, diffusion of an emissions-reducing innovation reduces the permit price, but the

---

[10] See Moreno-Bromberg & Taschini (2011) for dynamic simulations of this problem, which do provide more information about what technologies firms adopt in equilibrium.

technology choice of each firm has no noticeable impact. This is a world of small emitters. However, as Oates & Strassman (1984) noted years ago, a large proportion of emissions are often, unsurprisingly, accounted for by large emitters. When the innovating firm is a large enough emitter, it might conceivably sell enough permits to cause a noticeable drop in the price. Conversely, buying permits may cause a noticeable increase in the price. The price of emissions t is then an increasing function of the level of emissions e, and a decreasing function of the initial allocation of emissions rights $\bar{e}$ ($t_e > 0$ and $t_{\bar{e}} < 0$).[11] For a large enough emitter, therefore, the price of emissions would be plotted as an upward sloping curve in 'price-emissions'-space. The curve shifts downward for more generous initial allocations of emissions rights, $\bar{e}$. Figure 3.8 illustrates.

Figure 3.8: Market power and initial emissions allocation



A generous initial allocation of allowances, $\hat{e}$, means that the firm would be faced with selling excess allowances until the price falls to t'', should it adopt technology i. The gain is given by area A. A stringent initial allocation, $\tilde{e}$, on the other hand, means the firm would have to purchase allowance up to the price t' if it did not adopt technology i. The gain from investment is therefore given by area $A + B + C$. The converse argument yields *losses* $A + B + C$ and A, respectively, for an emissions-increasing innovation.

Suppose the emitter is initially allocated the right to emit up to the point $\tilde{e}$ and the initial equilibrium price is t^*. With the firm's initial technology it would like to emit $\hat{e}$ at this price, but taking account of how its own purchasing decisions affects the emissions price, the firm would stop short of purchasing $\hat{e} - \tilde{e}$ permits when the price had reached t'. Because adopting technology i allows the firm to avoid these permit purchases, which push up the price for each additional permit, the gain from adopting technology i is given by area $A + B + C$ in Figure

---

[11] See Kennedy & Laplante (1999) for a more general argument that the emissions price t is an increasing function of e.

3.8. By contrast, if the initial allocation is such that the firm is allowed to emit up to $\hat{e}$ and the equilibrium price is t^*, the firm would optimally sell $\hat{e} - \tilde{e}$ permits if it adopted technology i. Taking into account the fact that the firm fetches a lower price for each additional permit it tries to sell, the gain from technology adoption is now equal only to area A. Had the firm been a price-taker with respect to the emissions price, the gain from adopting technology i would have been equal to area $A + B$ regardless of the initial allocation of emissions rights.

It is straightforward to modify the model from Section3.2 to take account of market power. We simply need to make the price of emissions an increasing function of e and a decreasing function of $\bar{e}$, rather than a constant. Instead of Equation 3.4, the gain from adopting technology i is now

$$\Phi_i = \int_{e_0}^{e_{0,\max}} f_0(e)de - \int_{e_i}^{e_{i,\max}} f_i(e)de + \int_{e_i}^{e_0} t(e,\bar{e})de \tag{3.6}$$

As Equation 3.6 shows, the incentive to invest now depends on the initial allocation of emissions rights. In a competitive permit market with only small emitters the firm's incentive to invest is not affected by its initial endowment of emissions rights (see Section3.2 and Requate, 2005). The same would be true of an emissions tax, where the price on emissions is simply constant. However, in a permit market a more stringent initial allocation of permits furnishes large emitters with greater incentives to invest in abatement technologies.

3.3.3 Imperfect competition

Let us now combine the two extensions from above: incentives in equilibrium and market power. Now each firm has market power in either the output or permit market, or both, and it considers the change in equilibrium (i.e. including the equilibrium responses of its competitors that also have market power) in both markets resulting from its technology choices.

In the case with an imperfectly competitive permit market, $t'(e) > 0$, but perfectly competitive output market, the earlier conclusions are still valid. The incentive to invest in emissions-reducing innovations is decreasing in the investments made by competitors in the permit market, as well as being muted by the firm's own market power (Storrøsten, 2010). Net permit buyers will have greater incentives to adopt innovations since they benefit from a lower permit price, while net sellers have diminished incentives. This implies that a firm is likely to under-invest when allowances are freely allocated, while full auctioning encourages over-investment in new technologies (Montero, 2002b).

Consider now the reverse: a situation with a perfectly competitive permit market (i.e. $t(e) = t^*$ for all e), but Cournot competition in the output market (so that, given the competitor's equilibrium response, the output price p is a decreasing function of the firm's output Q). In this scenario, innovation that reduces the marginal cost of abatement puts downward pressure on the permit price for a given level of emissions, and the innovating firm actually increases output to exactly offset this effect (Montero, 2002b). The price of emissions is therefore unchanged, and the incentive to invest is the same as in the previous section.

When we combine imperfect competition in the allowance market with Cournot competition in the output market, the analysis becomes slightly more intricate. Imperfect competition in the allowance market still means that net permit buyers have greater incentives for innovation than do net sellers. However, innovation now has an additional effect. Although the reduced marginal cost of abatement encourages the innovator to increase output, this does not completely offset the downward pressure on the permit price. The lower price reduces the marginal abatement costs of competitors, who consequently increase their output. In essence, when there is imperfect competition in both the permit and output markets, innovation has a spillover-effect through the permit market, which is then fed back to the innovating firm in the form of stiffer competition. The incentives for innovation and investment are dampened because of this spillover-effect (Montero, 2002b). In equilibrium, the permit and output prices are lower, and total output is higher. Montero (2002a) examines the case where emitters compete à la Bertrand with differentiated products. Although the reasoning is slightly different, the results are qualitatively similar for an emissions price set in a permit market.

3.3.4 Heterogeneous firms

One of the problems mentioned in Section3.3.1 is that, although there might be an equilibrium corresponding to some set of technologies being adopted, a simple static model does not tell us how that equilibrium would actually come about in practice. Apart from the corner solutions, in which the number of technology adopters M is equal to zero or to the number of firms N, identical firms would all have exactly the same incentive *ex ante* to adopt a given technology, though only some would adopt it. Put another way, although the equilibrium number of technology adopters may be uniquely defined, it may correspond to a large number of Nash equilibria. For instance, if we were to represent the problem as a game of 'chicken' between N identical firms, with firms choosing to adopt a technology i or not, there are $\binom{N}{M}$ Nash equilibria. The simple model provides no justification for preferring any one of them.[12]

One suggested solution is to set the investment decision within an extensive form game, in which case there is a unique sub-game perfect Nash equilibrium (Storrøsten, 2010). In essence, this is an attempt to introduce firm heterogeneity through the order of movers. The problem is now instead how to determine the order. When the order of movers can be related to an observed market structure or some such, this may be an informative modelling approach. Without such a link, however, there would be $N!$ equally plausible extensive form games, which once again yield a total of $\binom{N}{M}$ possible equilibria. We have only shifted the problem one step.

Even when the order of movers does not offer an informative approach, heterogeneity can be incorporated in a number of other ways. Firms might, for instance, have different initial technologies, in which case they would face different marginal abatement cost curves. Weber & Neuhoff (2010) introduce firm heterogeneity in this way, without greatly increasing the complexity of the analysis.

Differences between firms could also be introduced through the cost of technology adoption, c_i. Firms may differ, for instance, in their abilities to raise internal and external funds (Cramton & Kerr, 2002).

The cost of technology adoption may also vary as a result of the processes at work as innovations are adopted. For instance, the originator of a technology may incur greater costs than subsequent firms adopting the same technology. Differences in the cost of adoption may still be present between the n^{th} and the $(n+1)^{th}$ firm to adopt a technology, due to 'learning-by-doing', network externalities, or other types of economies of scale. The cost of technology

---

[12] Barrett (2005, Ch. 4) discusses parallel concerns in the context of analysing country participation in international environmental agreements.

adoption will then be a decreasing function of the number of prior adopters.[13] This might also mean that although early adoption reduces the potential gain from later adoption, the cost c_i may fall more than enough to compensate. If this effect is sufficiently strong, economies of scale may dominate until a certain threshold has been reached, and we would observe the familiar S-shaped pattern for the diffusion of technology.

The cost of adoption could, of course, instead be an increasing function of the number of previous adopters. This might be the case if, say, a large cost component of the new technology is the cost of some finite resource (e.g. precious metals in catalysts and solar panels). The cost of the technology may then rise as the resource is depleted. In this case, the gains from later technology adoption may be doubly undermined by early adoption—both through the drop in the permit price (in permit markets) and through the rising cost of technology adoption.

Firm heterogeneity opens up a further possibility. With identical firms, an emissions tax would result in either zero or complete technology adoption. Only a market for tradeable permits provides a mechanism by which partial technology adoption can be achieved. Firm heterogeneity, however, opens the possibility of partial adoption even under a tax.

3.3.5 Patents

The preceding discussion has considered the direct gains of innovation—the gains arising to the innovating firm through changes to its own production and emissions. We now extend this analysis to look at how the incentives are altered when firms consider their ability to appropriate some of the social gains of their innovations.

Milliman & Prince (1989) were early to note the difference between patented and unpatented innovations in this context. They model patents in a very simple way: if there are N identical firms in the industry that are subject to a price on emissions, the innovating firm simply gets a share $s \in [0, 1]$ of industry-wide non-innovator gains. Thus, the incentive to develop and adopt technology i provided by the price on emissions is just

$$\Phi_i + s\Phi_i(N-1) \tag{3.7}$$

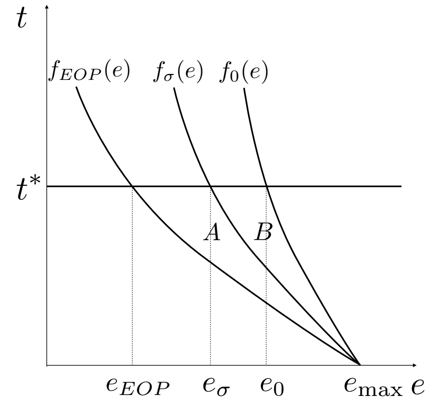
---

[13] This possibility is cursorily considered by Requate (2005).

Notice that, with patents, the overall incentive to innovate is increasing in the size of the market for the innovation, N. Even if the innovating firm is not itself an emitter and does not have to pay for its own emissions, the emissions price nevertheless does affect its incentive to develop abatement technologies. Instead of Equation 3.7 we would simply have $s\Phi_i N$, which is strictly less than $\Phi_i + s\Phi_i(N-1)$ as long as $s < 1$.

Fischer et al. (2003) give more structure to the benefits from patents. They consider an end-of-pipe innovation that increases α from α_0 to α_{EOP}, though the analysis that follows can equally be applied to any other type of innovation. The innovating firm gets a patent for this end-of-pipe innovation. Other firms can adopt this new innovation, but would need to pay a licence fee to the innovator. If all other firms adopt the new innovation, we get Equation 3.7. However, the other firms also have the option to adopt an imitation technology σ with effectiveness $\alpha_\sigma = \sigma\alpha_{EOP} + (1-\sigma)\alpha_0$, with $\sigma \in [0,1]$. When $\sigma = 1$ the innovation is a pure public good, and any firm can copy the inventor at no cost. When $\sigma = 0$, on the other hand, the innovation is a pure private good, and no imitation is possible. Figure 3.9 illustrates the marginal abatement cost curves $f_0(e)$ and $f_{EOP}(e)$, as well as $f_\sigma(e)$ for some intermediate value of σ.

Figure 3.9: Incentives with patents



The area $A + B$ is the value of adopting the new technology EOP, while the smaller area B is the value of adopting the imitation technology σ. The difference, area A, is the additional benefit of adopting the new technology over and above the imitation.

As long as the innovating firm charges a licence fee that is no larger than the area A in Figure 3.9, other firms would prefer to licence rather than imitate. The optimal licence fee at a given emissions price is therefore a share of the gain from adoption, $s\Phi_i$, where s is optimally set to $s = \frac{\text{area } A}{\text{area } A+B}$, so that other firms are just indifferent between licensing and imitating. This provides an economic rationale for the parameter s in Equation 3.7; it can now be interpreted as the licence fee charged by the innovator. In this view, s is a decreasing function of the appropriability of the gains from adoption, σ.

When the price on emissions is set with a tax, diffusion of the technology always increases the gains to the innovator. As we saw in Section3.3.1, however, when the price is determined in a permit market, adoption of an emissions-reducing innovation causes the price of emissions to fall (Fischer et al., 2003; Scotchmer, 2011). In this case the potential gains from adoption are smaller, which means that the licence fees that the innovating firm can extract are smaller. The innovator is thus a classic monopolist, choosing between technology diffusion and extracting higher licence fees. The implication is that the innovator may prefer to limit diffusion of the new technology, especially if there is no good imitation technology (σ close to one), and especially if the innovation causes a substantial reduction in the optimal emissions level (the technology represents a large increase in α here). Notice that these are precisely the circumstances in which the social cost of limiting the diffusion would be particularly large.

Scotchmer (2011) further notes that when the permit price falls, the optimal level of output will increase for non-adopters (and it will not decrease for the adopters). If demand for the output is inelastic (another situation where the social cost of limiting diffusion is high), this expansion of output will reduce the innovating firm's profits. In addition to a decline in the licence fees the innovating firm can charge, therefore, technology diffusion causes a drop in sales revenues, providing a double-disincentive for technology diffusion.

These concerns do not arise with an emissions tax, but with permit markets the innovating firm has excessive incentives to limit the diffusion of abatement technologies. Regrettably, these incentives are strongest when the social costs of limiting diffusion are greatest.

3.3.6 Optimal policy adjustment

As our final extension consider the possibility that the regulator sets a price on emissions with some expectation of firms' technology choices, and may in some cases wish to revise the price once it can observe actual technology choices. This provides firms with yet another opportunity to make strategic technology choices in order to affect the price on emissions.

The most frequently discussed version of this problem was first considered by Milliman & Prince (1989).[14] Once firms adopt new technologies and shift the marginal abatement cost curve, the price on emissions may no longer be equal to the marginal damage from emissions. If the emissions price or permit quota had initially been set to equate marginal damages and marginal abatement costs, a welfare-maximising regulator would now have an incentive to adjust the emissions tax or permit quota in order to realign marginal damages and the emissions price.

For convenience, let us assume that marginal damages are increasing in emissions. Additionally, purely so that we can draw the firm's marginal abatement cost curves and the marginal damage curve in the same graph (see Figure 3.10) we assume that there is only a single emitter.[15] Alternatively, we can interpret the curves in Figure 3.10 as representing aggregate marginal abatement costs of many emitters, with a single firm considering adopting a new technology and taking the technology choices of all other firms as given. Now, once the emitter adopts an emissions-reducing innovation, causing a shift in the (aggregate) marginal abatement cost curve, the marginal damages from emissions will no longer equal the price on emissions, whether that price is set by a tax or permit quota. To see this, consider Figure 3.10. The marginal abatement cost curve with the initial technology is $f_0(e)$, and the regulator has set an optimal emissions tax t^* that induces a level of emissions $\bar{e}$. Adopting technology i shifts the marginal abatement cost curve to $f_i(e)$, and the firm would now choose to emit e'. The gain from innovation, as we have seen before, would be $A + \ldots + G$. Note, however, that the emissions price t^* exceeds the marginal damages at this level of emissions. With the new technology, the optimal emissions tax is t'' and optimal emissions are $\bar{e}''$. For a permit market, the initially optimal emissions cap is $\bar{e}$, resulting in an equilibrium permit price t^*. Technology adoption causes a drop in the permit price to t', which is below the new optimal permit price

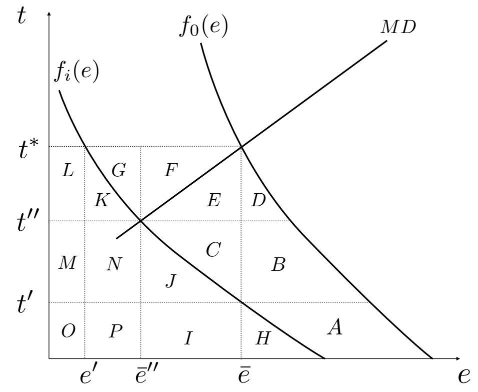
---

[14] More recent discussions include Kennedy & Laplante (1995, 1999), Mash et al. (2003), and Requate (2005).

[15] In order not to overcomplicate matters, this emitter is still assumed to act as a price-taker in a permit market. This allows us to isolate the effects arising from the optimal policy adjustment. All of the analysis in this section can be performed with a monopolist or under imperfect competition, but the effect of optimal policy adjustment will become confounded with other effects.

t''. By the same argument as in Section3.3.1, for a firm that expects the permit price to drop to t' the incentive to innovate is A. The new optimal permit quota is $\bar{e}''$.

Figure 3.10: Incentives for innovation for 'regulation-takers' and 'regulation-setters'



Hence, technology adoption would cause a welfare-maximising regulator to want to lower the emissions tax, something emitters are likely to welcome. With a permit market, however, technology adoption would cause the regulator to restrict the permit quota, most likely opposed by emitters. Milliman & Prince (1989) further speculate that firms would anticipate the regulator's optimal reduction of the emissions tax, or tightening of the permit quota, which would modify their incentives to invest in the first place.

To see what happens to the firm's incentives, imagine first that the firm correctly anticipates the new regulations but does not believe it has any power to influence the regulator—the firm is a 'regulation-taker'. The firm knows that the regulator will adjust the emissions tax from t^* to t'' in Figure 3.10. In the absence of regulatory adjustment, the gain from technology adoption is $A + \ldots + G$, while it is only $A + B + C$ with optimal adjustment (by the same argument as in Section3.3.1). Hence, optimal adjustment of an emissions tax reduces the incentives to invest. The opposite is true of a permit market. The regulator would optimally adjust the emissions cap from $\bar{e}$ to $\bar{e}''$, resulting in a permit price of t''. Without intervention to restrict the emissions cap, however, the price would have fallen to t'. The gain from switching technology is therefore $A + B + C$ with optimal policy adjustment, as opposed to just A. Thus, contrary to an emissions tax, optimal policy adjustment increases the incentives to invest under a permit market where participants are 'regulation-takers'. Notably, with optimal policy adjustment the incentives for innovation are the same under both an emissions tax and permit market.

Imagine now that the firm is not a 'regulation-taker'. In fact, let us suppose the firm knows that the regulator's decision is entirely contingent on the firm's technology choice—the firm is effectively a 'regulation-setter'.[16] Under an emissions tax with no adjustment, the incentive to innovate is $A + \ldots + G$, as before. A regulation-setting firm will realise, however, that if it adopts technology i the regulator would lower the tax rate to t''. As a consequence, the firm would optimally increase emissions to $\bar{e}''$, which reduces their abatement costs by $K + N + P$ but increases their tax receipts by $N + P - L$ at the new tax rate. Thus, in addition to the area $A + \ldots + G$, the 'regulation-setter' also expects a gain of $K + L$. Optimal tax adjustment therefore increases the incentives for innovation for a 'regulation-setter', opposite to its effect on the incentives of the 'regulation-taker'. In a permit market, the cost-savings to the firm would be equal to the area A without adjustment. However, the regulator would optimally cancel some of the firm's allowances, forcing it to reduce emissions to $\bar{e}''$ at a cost $I + J$. The resulting incentive to innovate is only $A - I - J$. Optimal adjustment thus reduces the incentive to invest in a permit market when the firm is a 'regulation-setter', the opposite of the effect on the incentives of a 'regulation-taker'. Table 3.2 summarises these observations.

To these observations we must then add any compensation that the firm may obtain for the permits it has lost, an exercise that would require additional modelling beyond the scope of this chapter. One may note, nevertheless, that the issue of compensation opens up additional dimensions of the policy design, most prominently the rules for allocating permits in a market. When there is optimal policy adjustment, the standard result that innovation decisions are independent of initial allocations of emissions rights (see Section3.2) does not hold in general.

Table 3.2: The effect of optimal policy adjustment on the incentives of 'regulation-takers' and 'regulation-setters'

	Regulation-taker	Regulation-setter
Emissions tax	Decrease	Increase
Permit market	Increase	Decrease

We have considered two extreme situations—one where the firm is a 'regulation-taker' and one where the firm is a 'regulation-setter'. For the many intermediary cases, the effect of optimal adjustment on the incentives to innovate is not clearly signed. However, one would

---

[16] The analysis of this scenario extends a discussion in Kennedy & Laplante (1999).

expect that the more influence a firm's technology choices has on the regulator's decisions, the greater is the additional incentive to innovate under a tax, and the smaller is the incentive in a permit market.[17] This suggests that the choice of instrument will affect *who* innovates. When emitters expect this kind of optimal policy adjustment, an emissions tax will provide stronger incentives for investment for powerful firms that believe they can influence policy, but provide weaker incentives for less influential emitters. A permit market reverses this relationship, providing relatively stronger incentives to the less influential firms. Thus, we would expect optimal adjustment of an emissions tax to strengthen incentives for innovation when emissions are concentrated among a few large firms, while optimal adjustment of a permit quota would strengthen incentives when emissions are distributed among a large number of small firms. This provides us with some guidance on the question of choosing an emissions tax or a permit market when the regulator cannot credibly commit to a future policy. In the absence of credible commitment, the temptation to adjust the policy might also be better resisted if the policy covers multiple sectors, so that the impact on emissions relative to their optimal level is smaller for any individual innovation, and also because the initial cap might more reasonably incorporate some expectation of successful innovation across at least some of the sectors.

Speaking more generally, the regulator may well have other objectives in mind than to equate marginal abatement costs and marginal damages. For instance, Helm et al. (2003) describe a scenario where the regulator has an incentive to weaken the emissions cap (or lower the tax rate) once investments have taken place in order to improve the international competitiveness of exporting sectors. Abrego & Perroni (2002) examine a situation where the regulator has distributional objectives. Taxes, as well as grandfathered permits, are likely to be regressive with regards to income. Once income becomes more unevenly distributed, the regulator will have a greater incentive to lower the tax rate or weaken the emissions cap in order to reduce the adverse distributional impact. Marsiliani & Renstrom (2000) consider a regulator that uses environmental taxes primarily to raise revenues. In this situation, if investments by firms reduce the elasticity of the tax base, the optimal tax rate for revenue-raising (i.e. the Ramsey tax) increases. The regulator will then have an incentive to raise the tax once firms have

---

[17] For a more extensive treatment of the impact of this type of optimal policy adjustment on incentives for innovation and investment, see Requate & Unold (2003) and Requate (2005).

invested in a new abatement technology. In terms of our typology of innovations, it is easy to see that, for instance, $P1$-innovations reduce the emissions price elasticity of emissions, and would cause the regulator to increase a revenue raising emissions tax. The same argument can be made for a permit market, where, if permits are auctioned to raise revenue, the regulator would have an incentive to tighten the cap once firms have invested in abatement technologies.

It is easy to get lost in the intricacies of optimal policy adjustment, but the central point is that the regulator's objective function matters. Optimal adjustment of an environmental policy can take different forms, which have correspondingly different impacts on the incentives for innovation and investment.

3.4 Conclusion

Market-based instruments are widely employed to regulate emissions, and it is often argued that one of their chief benefits is their ability to encourage 'green' innovation. This paper has offered a detailed analysis of the link between market-based instruments and firms' optimal technology choices. The simple model presented in Section3.2 showed how the gains from different types of innovations depend on the price of emissions. One of the more surprising findings here was that, for some types of innovations, the incentive for investment in abatement technologies may actually be decreasing in the price of emissions. This suggests that the conventional wisdom that 'higher emissions prices induce more innovation in clean technologies' deserves at the very least some qualification. This conventional wisdom is valid for some types of technologies, and under some market conditions, but the existence of counter-examples has several important implications.

Firstly, it could make the policy maker's problem more difficult. To the extent that one hopes to encourage 'green' innovation, one must carefully consider the technological opportunities available in the sectors to become regulated. For some sectors and some emissions price trajectories, market-based instruments may have the unanticipated effect of discouraging innovation. As we have noted, though, less innovation may in some settings be more efficient, so this is not necessarily an undesirable outcome.

Secondly, these cases can potentially change the policy maker's economic calculus more broadly. Since a price on emissions effectively raises the marginal cost of production, it will typically induce the firm to restrict output, which may entail a loss of social welfare. The social welfare gains from a higher price on emissions (reduced emissions and potentially more innovation) are therefore traded-off with the losses from restricted output (Oates & Strassman, 1984). Interestingly, in circumstances where reducing the price of emissions increase the incentive for innovation, a lower emissions price provides the dual benefits of increased incentives for innovation and reduced welfare losses associated with output restrictions.

Thirdly, this finding presents the empirical researcher with an ultimatum of sorts. The incentive to invest in 'green' technologies is a complicated function of the emissions price—economic theory predicts it to be sometimes an increasing and at other times a decreasing function, to assume both positive and negative values, and favouring one technology or another depending on the emissions price. The information necessary to constrain the shape of this function provides a minimum requirement of what is needed to restrict the functional form used to estimate the relationship between an emissions price and the incentive to innovate. If economic theory predicts that a price on emissions can either increase or decrease the incentives for innovation, theory alone clearly cannot justify assuming that the relationship is monotonic. More demanding parametric restrictions—that the relationship is linear, quadratic, or some such—would, of course, demand that the researcher is able to characterise the set of potential technologies both in terms of their cost and impact on the firm's marginal abatement cost curve. While this kind of exercise may be possible, it is certainly outside the scope of most empirical studies, especially when a large set of sectors (and therefore technologies) are concerned. In the absence of this kind of detailed information, economic theory does not provide justification for many of the conventional statistical restrictions that researchers rely on to identify the causal impact of a policy. Fewer such restrictions mean the researcher may be limited to estimating average or aggregate impacts, and may be unable to leverage the data to make reliable statements about the separate impacts of different design features of the policy, of the stringency of the policy, or how responses differ across subgroups, etc.

It is also important to acknowledge that although our discussion assumed a profit-maximising firm, incentives for minimising costs are present in a number of different managerial models, including Williamson's model of utility-maximising managers (Williamson, 1963) and Niskanen's model of bureaucracies (Niskanen, 1977).[18] Therefore, even if our algebraic expressions do not reflect all of the forces at work, they are still likely to capture some of the key determinants of the incentives to innovate and invest.

Another important feature of our analysis was to represent the firm's problem as one of technology choice. Most of the literature cited in this paper considers the firm's problem as one of deciding whether, or how much, to invest in a given technology—a single alternative technology or a one-dimensional continuum of technologies. Our framework allows us to consider the choice between technologies that can vary along several dimensions. This allows a much more faithful representation of the portfolio of alternative technologies and the firm's actual decision problem, and emphasizes that a changing price of emissions alters the *relative* incentives for adopting different types of abatement technologies. This point should be considered carefully when designing emissions regulations, since there are different technological opportunities for abatement in different sectors of the economy.

From the policy maker's perspective, this means that any price on emissions invariably favours some abatement technologies over others, or some firms over others, however the price is set. There is no such thing as setting the price and leaving market forces completely at liberty to choose the 'best' abatement technologies. All emissions regulations affect the direction of technological progress, and market-based instruments do not allow the regulator to relinquish the responsibility of 'picking winners' among new technologies. This should not discourage policy makers, but instead emphasises that the technological aspects of emissions abatement must always be considered in tandem with the design of the market-based instrument itself.

---

[18] See Oates & Strassman (1984) for a discussion.

Chapter 4

Emissions Trading and Innovation: A study of UK firms

4.1 Introduction

Emissions trading programmes have assumed an ever more prominent role in environmental policy over the last several decades. In the US, the Acid Rain Program, the Regional Greenhouse Gas Initiative (RGGI), and California's cap-and-trade programmeare all examples of this trend. Australia, New Zealand, and the Canadian province of Quebec have all recently created their own cap-and-trade programmes to regulate greenhouse gas emissions, and China, Japan, and South Korea are all individually making moves toward launching their own. International carbon markets are today worth over $175 billion a year (Kossoy & Guigon, 2012), and with so many new initiatives 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 tradeable emissions permits to over 10,000 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 cap-and-trade programme. Like all of the new emissions trading initiatives around the globe, the primary aim of the EU ETS

---

[1] 24 countries were included from the beginning. 7 countries have joined since then, now putting the total closer to 12,000 installations.

is to reduce carbon emissions, but to do so through innovation rather than output reduction. Indeed, policy makers hope that the EU ETS will be "the engine to drive low-carbon growth in Europe" (European Commission, 2012, p. 1). More sceptical observers, however, have from the very outset questioned whether the EU ETS would induce innovation on the scale needed to achieve such ambitious goals (Schleich & Betz, 2005; Gagelmann & Frondel, 2005; Grubb et al., 2005). Yet, with the number of carbon trading initiatives now growing across the world, it remains an important and unanswered question whether these programmes actually bring about this low-carbon innovation.

This chapter conducts the first systematic investigation of how UK firms have responded to the EU ETS. The EU ETS would be an interesting case study simply by virtue of being the largest environmental policy initiative of its kind anywhere in the world. It is only made more interesting by the fact that, in order to control administrative costs, the Scheme 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 and as innovative as those affected by the regulations.[2] Because innovation takes place at the level of the firm, we can exploit these installation-level inclusion criteria to compare firms with similar resources available for research and similar patenting histories, but which have fallen under different regulatory regimes. 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 & Gayer, 2009). Studies employing these methods have found that environmental regulations inhibit new plant formation (List et al., 2003), but stimulate capital investment in existing plants (Fowlie, 2010). This chapter leverages these tools to study the impact of emissions trading on innovation.[3]

The UK is among the largest emitters in Europe and houses roughly 1,200 of the 12,000 EU ETS installations. To gauge the impact of the EU ETS on innovation, I have collected and linked data from a large number of sources. To start with, I have collected information about basic firm characteristics from the UK Business Structure Database, the coverage of the UK's main

---

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

[3] See Appendix A for a more detailed account of the quasi-experimental techniques used here, and their relationship to randomised experiments.

national climate change policy initiatives from the Department of Energy & Climate Change, and the coverage of the EU ETS from the Environment Agency and from the Community Independent Transaction Log. To measure innovation, these data sets have been linked to the Quarterly Fuels Inquiry (a quarterly survey of fuel and electricity purchases for a representative cohort of UK firms), PATSTAT (the worldwide patent database), the Business Enterprise Research and Development survey (an annual survey of R&D expenditures), the UK Innovation Survey (a biannual survey of R&D expenditures for a different sample of firms), and the DECC Low Emissions R&D Survey (a one-off survey of low-carbon R&D expenditures in 2008). The full data set includes over 5 million firms active between 2002 and 2009, of which 431 have operated at least one of the 1,200 EU ETS regulated installation at some point since the Scheme launched in 2005. Using this newly constructed data set, I attempt to estimate the impact of the EU ETS on CO_2 intensity, patenting for low-carbon technologies, and low-carbon R&D expenditures. This is the first time anyone has been able to analyse and compare these three innovation measures in one study.

I employ a risk-set matched difference-in-differences study design, which takes account of both cross-sectional and time-varying confounding factors (Heckman et al., 1998a,b; Smith & Todd, 2005; Abadie, 2005). By exploiting variation in EU ETS participation arising both from installation-level inclusion criteria in the EU ETS and variation in other regulatory obligations arising from serendipitous features of the UK's national climate change policies, it is possible to construct matches where both firms were subject to the same UK regulations prior to one of the firms entering the EU ETS. This allows us to isolate the impact of the EU ETS. The results provide the first systematic empirical assessment of the impact of the emissions trading on innovation.

Our best estimates indicate that the EU ETS has had no substantive impact on the CO_2 intensity, yet show a positive effect of the EU ETS on the low-carbon R&D spending and patenting of UK firms. There are also some indications, though, that the increases in low-carbon R&D and patenting may have crowded out other innovating activities.

These estimates should be interpreted with caution, however. Despite painstaking efforts to obtain the best and most comprehensive data base available, the evidence is insufficient to reach firm conclusions about the impact of the EU ETS on innovation. This is an important finding in its own right. Exploiting the installation-level inclusion thresholds to obtain quasi-random variation in EU ETS regulation at the firm level will necessarily restrict our sample to the types of firms operating around those thresholds. Combining this factor with our focus on a single country, even a large EU ETS country like the UK, ultimately whittles down the set of comparable EU ETS and non-EU ETS firms too far for us to precisely estimate small but economically interesting effects with precision. Though one may be forced to sacrifice the ability to observe the full range of innovation indicators, future research should try to estimate the impact of the EU ETS on innovation at a European level.

The remainder of this chapter is structured as follows. Section 4.2 surveys the empirical evidence on the link between emissions trading and innovation. Section 4.3 introduces the data set and considers in greater detail our three measures of innovation. Section 4.4 describes the introduction of the EU ETS in the UK and the matching strategy that will be employed to estimate the Scheme's impact on innovation. Section 4.5 presents the estimation results, and Section 4.6 offers some concluding observations.

4.2 Emissions trading and innovation

4.2.1 Empirical background

Several studies have found evidence that environmental policy does have an impact on innovation (Lanjouw & Mody, 1996; Brunnermeier & Cohen, 2003; Popp, 2002, 2003, 2006; Arimura et al., 2007; Lanoie et al., 2007). Popp (2006) 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 innovation, a more careful reading of the literature yields reveals a different pattern that seems particularly relevant for the EU ETS.

Firstly, when examining the impact of emissions trading programmes specifically, rather than environmental policies more broadly construed, the conclusions about its impacts are more modest. Most earlier studies consider 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 & Bellas, 2005). This squares with findings that the use of scrubber technology as an emissions abatement strategy has actually declined over time (Burtraw & Szambelan, 2009). To put it simply, past programmes like the Acid Rain Program primarily impact operational innovation and technology adoption, but perhaps do not provide a precedent for the kind of induced technological change EU policy makers are hoping the EU ETS will provide.[5]

Secondly, 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 give us a very rough idea 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 therefore expect the innovation 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). Nevertheless, it can help aid our expectations about the likely

---

[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'.

[5] Chapter 2 contains a more extensive discussion of this point.

impact of the EU ETS.

So while policy makers envisage the EU ETS as a driving force behind low-carbon innovation, and though there is empirical evidence that supports a positive link between environmental policy and innovation generally, the observations above—the weak patenting response in previous emissions trading programmes, and the meager patenting response to be expected from the diluted price signal—invite a degree of scepticism about strong claims for the ability of the EU ETS to promote innovation. These observations motivate a special interest in providing policy makers with direct empirical evidence on whether or not the EU ETS is encouraging firms to develop new low-carbon technologies. Historical experience would lead us to expect a stronger impact on the adoption of existing technologies that were not previously competitive. So is the EU ETS following this historical pattern, or is it breaking the mould?

4.2.2 The EU ETS and innovation

In 2005, the EU ETS launched initially 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) allowed firms to bank unused permits for later use in Phase 3 (2012–2020), as well as a limited form of borrowing against future emissions reductions. For each year in Phase 1, over 2 billion tonnes-worth of tradeable 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).[6] The price of emitting one tonne 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. Installations (or rather the firms that operate them) can then make abatement and investment decisions according to the price of carbon revealed in the market.

Since it launched in 2005, there has been vigorous debate about whether the EU ETS would induce firms to innovate, many arguing that an overly generous allocation of emissions permits (Schleich & Betz, 2005; Gagelmann & Frondel, 2005; Grubb et al., 2005) or an ill-advised allocation methodology (Neuhoff et al., 2006c) would undermine firms' incentives to innovate and to reduce their carbon intensity. It has also been argued that, in any case, a carbon price addresses only one of several market failures that cause under-provision of low-carbon innovation (Jaffe et al., 2005; Fischer & Newell, 2008; Newell, 2010). Let us attempt to piece together the incoming evidence on the Scheme's impacts.

Firstly, 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 operational innovation. Macroeconomic estimates suggest that the EU ETS reduced total emissions by roughly 50–100 million tonnes of $\mathrm{CO_2}$ annually in Phase 1, or roughly 3–6%, compared with a "business-as-usual" scenario (Ellerman & Buchner, 2008; Ellerman et al., 2010; Anderson & Di Maria, 2011). Meanwhile, model-based estimates of power sector emissions abatement from fuel switching alone range from 26–88 million tonnes per year (Delarue et al., 2008, 2010). These estimates suggest that fuel switching very likely accounts for the lion's share of emissions reductions in the EU ETS so far. This is not a problem in and of itself, of course. As mentioned earlier, the US Acid Rain Program 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

---

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

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 tonnes 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.[7]

Secondly, a growing literature of case-studies and expert interviews suggests there may have been some efforts to improve energy efficiency among EU ETS firms, but that no resources have been made available for technological development.[8] Yet none of these studies offer a group of non-EU ETS firms for comparison, so it is difficult to assess how much of their findings can be attributed to the Scheme. Indeed, more systematic attempts to learn about the Scheme's impact on innovation hint that the reality might be exactly opposite to what the case-study literature portrays. Using a data set of 700 Swedish firms, roughly a third of which are regulated under the EU ETS, Löfgren et al. (2013) estimate that the EU ETS has had no impact on the adoption of low-carbon technologies. Meanwhile, Martin et al. (2011) conduct interviews with nearly 800 European manufacturing firms, of which almost 450 operated some EU ETS regulated installations. Using their interview-based measure of innovation, they find that the expected future stringency of EU ETS is causing EU ETS regulated firms to innovate more.

We thus have several observations to contend with. Fuel switching in the power sector appears to have been one of the main responses to the EU ETS. The case-study literature suggests that comparable efficiency-enhancing measures also characterise the broader response of regulated firms. On the other hand, what few systematic comparisons there are suggest that just the opposite may be true. The typical response to the EU ETS may instead have been to place greater emphasis on developing new low-carbon technologies, but the rate of efficiency improvements have not substantially diverged from the rest of the economy. There is clearly a need for more

---

[7] This point is developed in greater detail in Chapter 1.

[8] A study of four large EU ETS regulated Portuguese chemical companies suggested that the EU ETS may have encouraged some energy efficiency improvements (Tomás et al., 2010). A survey of Irish EU ETS firms tentatively suggests that almost no resources were available for low-carbon R&D, while many of the firms had pursued more operational innovations like installing new machinery or equipment, making process or behavioural changes, and employing fuel switching to some degree (Anderson et al., 2011). Case studies of the German electricity sector found that the EU ETS has had an effect on decisions about small-scale investments with short amortization times, but not on R&D efforts (Hoffmann, 2007). See Martin et al. (2012b) for a review of these and other studies performing *ex post* evaluation of the impacts of the EU ETS.

evidence to resolve the tension between these conflicting accounts. Let us turn our attention, therefore, to our new data set and to the issue of measuring low-carbon innovation.

4.3 Measuring innovation

Between them, the studies cited in the previous section employ several different measures of innovation. Few rely on anything other than responses to more or less idiosyncratic survey questions that measure innovation with less consistency across firms and across studies, and none compare multiple independent measures of innovation. This chapter investigates the impact of the EU ETS on three objective measures of low-carbon innovation: CO_2 intensity, patenting for low-carbon technologies, and low-carbon R&D expenditures. Though it is rarely done, there are important advantages to studying multiple indicators of innovation together (Martin, 1996; Hagedoorn & Cloodt, 2003; Lanjouw & Schankerman, 2004; Arvanitis et al., 2010). Each measure allows us to learn about a different aspect of innovation:

- changes in CO_2 intensity reflect efficiency improvements already achieved,
- changes in patenting for low-carbon technologies indicate efforts to development and make available new technologies, and
- low-carbon R&D spending reflects developing innovation efforts and is a signal of technological advances still to come.

Moreover, when analysed together these three indicators also speak more broadly to the question of whether the EU ETS has substantively altered the incentives for low-carbon innovation.

In the context of emissions trading there are additional advantages to studying multiple innovation indicators. As we saw in the previous section, emissions trading encourages largely technologically undemanding innovation (e.g. switching fuels, or adopting existing technologies), with a much more modest response in the direction of technological development. On the other hand, there are indications from two studies that this pattern may have been reversed in the EU ETS (Martin et al., 2011; Löfgren et al., 2013). It is of great interest to actually examine the pattern within the context of a single data set with a consistent set of methods applied.

This is all the more important for the EU ETS since a repetition of the historical pattern would be less than desirable in the context of climate change, owing to the limited technological opportunities for abating carbon emissions in the short term at a manageable cost (Delarue et al., 2008; International Energy Agency, 2012).[9] It would be of great value, therefore, to better understand whether an emissions trading programmelike the EU ETS can in fact spark the changes necessary for a country to meet its targets in both the short and the long run.

Let us then consider in more detail how our three innovation indicators are defined and what they measure.

CO_2 intensity: Out of the three measures used here, changes in CO_2 intensity is the least studied. While CO_2 is often used as a summary measure of deployment of low-carbon technologies at the global, national, or sectoral level in macroeconomic studies, it has very rarely been studied at the level of the firm.[10] It is therefore necessary to devote a bit more space to the properties of this indicator.

Data on CO_2 emissions are derived from the Quarterly Fuels Inquiry (Department of Energy & Climate Change, 2011), a survey that collects information about fuel and energy purchases relating to heat and power for a representative panel of UK firms (Martin, 2006). CO_2 emissions are calculated by applying fuel-specific conversion factors published annually by the UK Department for Environment, Food & Rural Affairs for company reporting purposes. CO_2 intensity is then calculated by dividing the firm's CO_2 emissions by its turnover for the same period, obtained from the UK's Business Structure Database (Office for National Statistics, 2012).

Changes in the average quantity of CO_2 emissions per unit of the firm's output obviously capture efficiency improvements that have already taken place. Due to the lags usually involved in developing new technologies, it seems that changes we will observe are most likely going to be achieved mostly through operational innovations and adoption of technologies already

---

[9] This point is more fully developed in Chapter 1.

[10] Firm-level CO_2 intensity appears in a study of UK firms by Martin et al. (2011). Its relation to other resource efficiencies is studied by Lansink & Silva (2003) for Dutch firms, its relation to trade is studied by Forslid et al. (2011) for Swedish firms, and Cole et al. (2013) conduct an exploratory analysis of the determinants of firm-level CO_2 emissions for Japanese firms.

on the market, rather than development and adoption of new technologies. We must note two important caveats to our measure, however.

Firstly, CO_2 emissions are calculated from fuel and energy purchases. This will omit all CO_2 emissions that derive from sources other than the carbon contained in the fuels purchased. While heat and power are typically the most important sources of emissions, and "combustion" does form by far the largest part of emissions regulated under the EU ETS, other chemical process sometimes account for significant emissions as well, e.g. in the production of cement clinker. If cement companies switched to a less polluting process for producing cement clinker, it would only affect our measure in so far as the new process required less heat and power per unit of output. Our measure of CO_2 intensity is limited to the efficiency improvements in the use and production of heat and power.

Secondly, one needs to be mindful of the fact that anything that reduces CO_2 intensity is considered a 'low-carbon innovation' by this measure. In addition to the types of emissions-saving strategies that typically spring to mind, changes in CO_2 intensity will in principle also measure 'exogenous' and 'accidental' low-carbon innovation. The first category would include, for instance, any secular improvements in energy efficiency. The second category would include, for instance, any efficiency improvements that arise as a by-product of changes in aggregate demand.[11] To separate these types of changes from those attributable to the EU ETS, an empirical strategy must try to net out any changes in CO_2 intensity that does not vary systematically with EU ETS participation. Section 4.4 presents a strategy that addresses these demands.

Patents: Patent-based measures of innovation are a much better known quantity. Patents have been extensively used to measure technological change in the recent induced innovation literature (Popp, 2002, 2006; Johnstone et al., 2010; Aghion et al., 2012). The advantages and drawbacks are by now well understood (see OECD, 2009, for a survey), and it will suffice to highlight only a few key points here.[12]

---

[11] Changes in aggregate demand would result in changes in efficiency as long as emissions are not proportional to output.

[12] Further discussion of this measure can also be found in Chapter 5, Section 5.2.

Because a patent application requires a “description [that] contains enough information for others to carry out your invention” (Intellectual Property Office , 2013, p. 8), patents are necessarily filed at a relatively late stage of the innovation process. Indeed, lagged R&D expenditures have commonly been found to exert important influence on patenting (Pakes & Griliches, 1984; Hausman et al., 1984; Blundell et al., 2002; Gurmu & Pérez-Sebastián, 2008). Consequently, patents are thought to measure the output of the innovation process. It is also worth noting that patented technologies tend to be of greater economic value than unpatented technologies, and to have greater spill-over effects (Moser, 2005, 2012, 2013; Khan, 2012). Patent-based measures do not treat all innovations as equals, therefore, but are instead particularly sensitive to changes in the number of new high-quality technologies at a comparatively late stage of the innovation process.

Patent records were extracted from PATSTAT, the worldwide patent database maintained by the European Patent Office. The total number of patent families were counted for each firm and year. A patent family is the set of patents protecting the same innovation, so this measure counts innovations no matter at what patent office the patent is filed, yet avoids double counting innovations protected under multiple patents. Patent families were designated as ‘low-carbon’ or ‘other’ according to the European Patent Office’s specially 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.[13] 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).[14] A complete description of the various sub-classes for low-carbon patents used here can be found in Appendix B.

---

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

[14] 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.

R&D: R&D expenditures, like patents, are a commonly used measure of innovation (Hall & Mairesse, 1995; Jaffe & Palmer, 1997; Parisi et al., 2006). R&D is often considered almost synonymous with innovation, and indeed, many government programmes aim specifically to increase private sector R&D expenditure as if this was an end in itself. The impact of a policy on R&D expenditures is therefore likely to be of direct interest to policy makers.

Although it is rarely feasible to apportion R&D expenditures to specific innovations, the bulk of the resources spent to invent and develop new technologies is usually expended before the technology is advanced to the point where it can patented and commercialised (Intellectual Property Office , 2013). Consequently, R&D expenditures are generally considered an input for the innovation process. Indeed, empirical research confirms that R&D expenditures are a reliable predictor to innovation (Bound et al., 1984; Acs & Audretsch, 1988; Parisi et al., 2006).

The data set analysed here comprises R&D expenditures extracted from three separate surveys. Total R&D expenditures were extracted from the UK Innovation Survey (Department for Business, Innovation & Skills et al., 2012) and the Business Enterprise Research and Development survey (Office for National Statistics, 2011). The former is a large repeated cross-sectional study, but containing within it a smaller panel. The latter is a longitudinal study. Since the two samples do not entirely overlap, the two sources can be combined to obtain a larger sample. In addition, a one-time cross-sectional survey of low-carbon R&D expenditures in 2008 was administered by the Department of Energy & Climate Change (Department of Energy & Climate Change & Office for National Statistics, 2012).

In addition to our three innovation indicators, the data set measures a number of key company characteristics like historical turnover, employment, and economic sector (extracted from the Business Structure Database), and it also identifies firms covered by any of the UK's major national climate change policies: the Climate Change Levy, Climate Change Agreements, and the UK Emissions Trading Scheme (identified from publicly available documentation).[15] The full data set covers over 5 million firms active in the UK between 2002 and 2009, and identifies 431 firms operating 966 installations regulated under the EU ETS.[16] The UK houses a total

---

[15] These three policies are described in more detail in the next section.

[16] I use the terms "company" and "firm" interchangeably to refer what the UK Data Service calls an "enterprise".

of 1,208 of the roughly 12,000 installations regulated under the EU ETS, but most of the 242 installations that are unaccounted for in our data set were operated by non-firm entities like hospital trusts, councils, the Ministry of Defence, etc., and are therefore not considered here.

The various data sources were linked together using company registration numbers and Inter-Departmental Business Registry (IDBR) enterprise reference numbers. Because the underlying data sets do not have complete coverage for all UK firms, in what follows our view will necessarily be restricted to subsets of the 5 million UK firms, and of the 431 EU ETS firms.

Next, let us turn to the task of developing a strategy to identify the impact of the EU ETS on innovation.

4.4 Matching with pre- and post-EU ETS attrition

For the purposes of the EU ETS, power stations and industrial plants in Britain were classified according to their main activity: "production of cement clinker", "manufacture of ceramics by firing", "production of paper or cardboard", etc.. Only sufficiently large installations of each type would be regulated by the EU ETS. For instance, only clinker plants with a production capacity in excess of 500 tonnes per day were included, only ceramics plants with a capacity in excess of 75 tonnes per day, only paper factories with a production capacity exceeding 20 tonnes per day, etc.. These are only three examples from a longer list, but the consequence of this design is that EU ETS firms and non-EU ETS-firms can in principle be virtually identical in all other respects relevant to innovation, except for the size of a single installation.

The EU ETS launched in 2005, but the UK already had three major national carbon pricing policies in place: the Climate Change Levy (CCL), Climate Change Agreements (CCAs), and the UK Emissions Trading Scheme (UK ETS). The CCL taxes commercial fossil fuel use,

---

They define an enterprise as follows: "The enterprise is the smallest combination of legal units that is an organisational unit producing goods or services, which benefits from a certain degree of autonomy in decision-making, especially for the allocation of its current resources. An enterprise carries out one or more activities at one or more locations. An enterprise may be a sole legal unit." To the extent that this differs from definitions used elsewhere, figures reported here may differ from other published sources. Note also that any results reported as a percentage change in a firm's innovation efforts, however measured, are necessarily dependent on how the firm is defined. If only some part of the firm's activities are affected, defining the firm more broadly to include more unaffected activities will shrink the percentage change. Conversely, defining the firm more narrowly will inflate the percentage change.

amounting to an implicit carbon tax of between roughly £4.50 and £8.50 per tonne of CO_2 depending on the fuel type (Bowen & Rydge, 2011). The CCAs were Agreements negotiated at the sectoral level by industry associations, and signing up some of its installations to such an Agreement meant that the firm committed to reduce emissions at those installations by the negotiated amount. In return, the firm would receive an 80% discount on its CCL-bill (de Muizon & Glachant, 2004). Once a firm had signed onto a CCA, it was also automatically eligible to trade its emissions quota in the UK ETS. For installations not already covered by a CCA, an auction provided an alternate route into the UK ETS. With a fixed budget of £215 million the British government managed to purchase 4 million tonnes-worth of abatement commitments from the 32 companies that entered some of their installations into the UK ETS as Direct Participants (National Audit Office, 2004; Smith & Swierzbinski, 2007).[17]

Because the UK had these other carbon pricing policies in place, they had obtained permission from the European Commission to temporarily exempt some installations (and hence certain firms) from the EU ETS if they were already regulated under some of the national climate change policies. Payment of the CCL did not enable firms to opt out of the EU ETS, but firms could opt out any installations that had entered the UK ETS as Direct Participants until 2007, and any installations covered by CCAs until 2008. Consequently, though in most countries firms fell under the EU ETS in 2005, in the UK a substantial proportion of firms also entered the Scheme for the first time in 2007 or 2008.

This situation calls for a technique called risk-set matching (Li et al., 2001). The 'simple matching' procedure would start by labelling each firm as either 'EU ETS' or 'non-EU ETS' according to whether they have operated an EU ETS installation at any point since 2005 and then estimate the relevant counterfactual by matching each EU ETS firm to a similar non-EU ETS firm using only pre-2005 characteristics. This procedure offers a reasonable approach for most of Europe, though in the particular circumstances of the UK it may introduce attrition bias. Firms could

---

[17] While only a superficial treatment of the intricacies of UK climate policies is justified here, Bowen & Rydge (2011) offer a more comprehensive review. For discussions and evidence on the CCL and CCAs see ACE (Association for the Conservation of Energy) (2001); Richardson & Chanwai (2003); Varma (2003); Agnolucci et al. (2004); Cambridge Econometrics et al. (2005); Pearce (2006); Bailey & Rupp (2006); Dresner et al. (2006); Ekins & Etheridge (2006); National Audit Office (2007); Barker et al. (2007); Martin et al. (2009); Martin & Wagner (2009). On the UK ETS see National Audit Office (2004); Hill et al. (2005); von Malmborg & Strachan (2005); Smith & Swierzbinski (2007); Nye & Owens (2008); Nye (2008). On the interactions between the national policies and the EU ETS see Sorrell (2002, 2003); Sorrell et al. (2003).

Table 4.1: EU ETS implementation in the UK

Year of entry into the EU ETS	Reason	Prior regulation
2005	Firm operates at least one installation that meets EU ETS inclusion criteria and is not opted out (either because it was not covered by either a CCA or the UK ETS, or because the opt-out provision was not exercised).	(i) full CCL, (ii) CCA, (ii) full CCL + UK ETS, or (iv) CCA + UK ETS.
2007	Firm opted out all relevant installations in 2005, at least one of which under the UK ETS opt-out provision.	(i) full CCL + UK ETS or (ii) CCA + UK ETS.
2008	Firm opted out all relevant installations in 2005 under the CCA opt-out provision.	(i) full CCL, (ii) CCA, or (iii) CCA + UK ETS (if the UK ETS installation(s) did not meet EU ETS inclusion criteria).
No entry in study period.	Does not operate any installations that meet EU ETS inclusion criteria.	(i) nothing, (ii) full CCL, (iii) CCA, (iv) CCA + UK ETS (iii and iv only if none of the CCA and UK ETS installations meet EU ETS inclusion criteria).

A noteworthy feature of this table is that each of the 'prior regulation'-regimes listed in the first cell of the third column appears at least once further down in the column. The same goes for the second and third cells. This implies that at the time any given firm enters into the EU ETS, there will in principle exist a firm remaining outside of the EU ETS that shares the same regulatory history.

be labelled 'non-EU ETS' either because they did not operate any sufficiently large installations at any point after 2005 *or* because they ceased operations before such a time that they would have become regulated (attrition). Firms that fell under the EU ETS in 2007 or 2008, however, did so by virtue of their continued operations (zero attrition). The 'simple matching' procedure may therefore cause EU ETS firms to appear more innovative simply because they were more likely to be in business by design.

Risk-set matching corrects this bias by finding a match for an EU ETS firm at the time it entered into the EU ETS. Firms that entered the EU ETS in 2005 are therefore matched to similar firms that had not entered by 2005 using pre-2005 characteristics, firms that entered in 2007 are matched to firms that had not entered by 2007 using pre-2007 characteristics, and so forth. In addition to correcting for the possible attrition bias, risk-set matching also has the advantage of not assuming that the non-EU ETS firm will remain outside the EU ETS forever. The most appropriate counterfactual experience for each EU ETS firm is simply determined by whichever treatment the matched firm received subsequently. Risk-set matching therefore accounts for the fact that in some instances the most realistic counterfactual for an EU ETS firm is merely a delay of entry into the EU ETS.

While risk-set matching corrects for a possible pre-treatment attrition bias, the data confronts us with a second potential source of attrition bias relevant to estimating the impact of the EU ETS on low-carbon R&D. Information about low-carbon R&D expenditures in 2008 was collected with a one-shot cross-sectional survey by the UK Department of Energy & Climate Change in 2009. Some firms may have been omitted from this survey because they had ceased operations by 2009 (attrition), while survey respondents are selected from the subset of surviving firms (zero attrition). Both EU ETS firms and non-EU ETS firms may drop out of the sample in this way, causing a bias in an unknown direction.

Post-treatment attrition of this sort fundamentally requires us to make an assumption about the probability that a liquidated firm would have been surveyed had it waited until after 2009 to officially cease operations. The survey's sampling methodology—selecting the largest innovators in the UK—makes it clear that it is fairly safe to assume this probability is zero. I will, nevertheless, investigate the robustness of the impact estimate for low-carbon R&D expenditures with respect to this assumption.[18]

4.5 Impact of the EU ETS

4.5.1 Changes in CO_2 intensity

Out of the population of 431 British EU ETS firms, historical firm-level CO_2 intensity is observed for only 96.[19] Although one might in principle match each of these remaining 96 firms to a similar non-EU ETS firm, data constraints limit our pool of potential matches to only 258 non-EU ETS firms. Our interest centres on the intersection of these two sets in pre-EU ETS characteristics-space. It is only for this subset of firms that our identification strategy has any chance of providing an unbiased estimate. Restricting ourselves to more closely matched firms will inevitably reduce the number of EU ETS companies for which a good match can be found, and the number of non-EU ETS firms that could be considered good matches. What is lost in

---

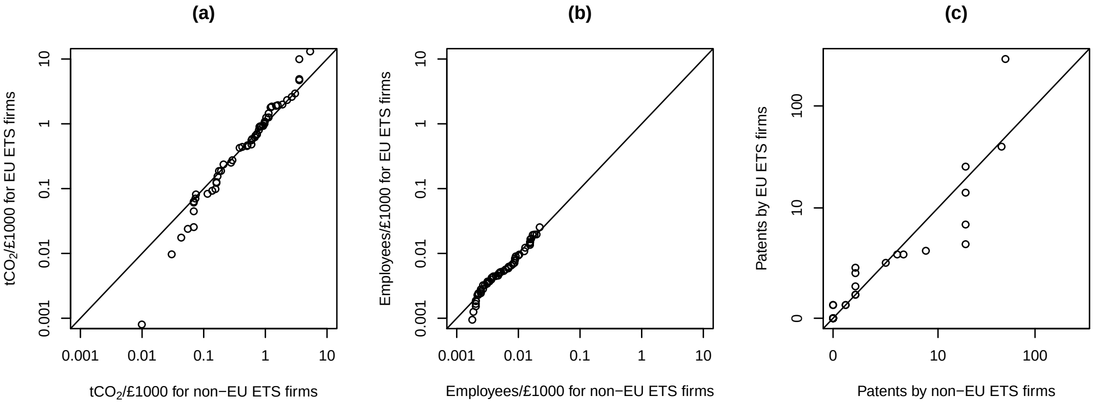
[18] See Appendix A for more details on how the matching procedure was implemented.

[19] If one was willing to assume that firm-level CO_2 emissions were equal to those emissions reported for EU ETS regulated installations, this number would naturally increase during the EU ETS period. However, comparing such a measure to CO_2 emissions calculated from the QFI would create a systematic bias in favour of EU ETS firms, since a measure based only on their emissions from EU ETS installations would count any within-firm 'leakage' as a real reduction of emissions. Although a larger sample of EU ETS firms would become available for analysis, the results would be less reliable.

sample size, however, is gained in terms of accuracy (Dehejia & Wahba, 1999; Smith, 1997, and Appendix A).

In the end it has been possible to construct 58 pairs, each containing one EU ETS firm and one non-EU ETS firm. Each pair of firms operate in the same economic sector (defined at the level of 3-digit SIC codes), which means they are likely to be exposed to similar trends and shocks to input prices, and the same business and regulatory environment at large. Taking extra caution to isolate the impact of the EU ETS from the UK's national climate policies, firms were matched for CCA participation and direct participation in the UK ETS prior to entering the EU ETS (CCL being the default). The firms were also matched to have similar levels of turnover, patenting records, CO_2 intensity, and labour intensity during the 3-year period preceding the entry of one firm into the EU ETS. Turnover serves both as an indicator of firm size and ability to make investments to improve resource efficiency.[20] Patenting records testify to the availability of new technologies developed before the EU ETS that firms would likely have proceeded to deploy without further inducement. Finally, matching on CO_2 and labour intensity ensures that, at least initially, the firms operate at a similar level of resource efficiency.

Figure 4.1: Comparison of matched EU ETS and non-EU ETS firms



Panels (a) and (b) display the empirical quantile-quantile (e-QQ) plots for average CO_2 intensity and average labour intensity in the 3-year period preceding the year of entry into the EU ETS. Panel (c) shows the e-QQ plot for the average annual number of patents over the same period. All panels are drawn with logarithmic scales, and panels (a) and (b) share the same scale, to facilitate comparisons.

Figure 4.1 and Table 4.2 compare the empirical distribution of characteristics across the matched

---

[20] Matching on both CO_2 intensity and the level of turnover serves the additional function of effectively matching on the level of CO_2 emissions.

EU ETS and non-EU ETS firms. EU ETS firms are on average larger, and produce their output with relatively more emissions and less labour. There is greater variation in CO_2 intensity relative to labour intensity, perhaps a consequence of CO_2 having been underpriced for so long. Despite these slight differences, however, we are able to reject the hypotheses that the two groups were systematically different prior to the EU ETS at the 5% significance level. Observable pre-EU ETS characteristics do not help us predict which firm in each pair will (first) fall under EU ETS regulations, so in a naive sense we have recovered the identifying conditions present in a randomised experiment.

Table 4.2: Equivalence tests for matched EU ETS and non-EU ETS firms

	Difference between EU ETS and non-EU ETS firms	Equivalence range	Critical equivalence range (5% sign. lev.)
Turnover (in £Mil.)	8.57	±145.34	±127.52
CO_2 intensity	0.05	±0.35	±0.26
Labour intensity	0.0002	± 0.0011	±0.0011
Patents	0	±5.40	±1.67
Low-carbon patents	0	±0.14	–
CCA participation	1.38 (83% vs. 78%)	–	$(3.35^{-1}, 3.35)$
UK ETS direct participation	1.00 (2% vs. 2%)	–	$(39.15^{-1}, 39.15)$
Economic sector	Exactly matched	–	–

The first column from the left reports the difference between EU ETS and non-EU ETS firms in our sample. The median difference is reported for nominally continuous variables (turnover, CO_2 intensity, labour intensity, and patenting), while the odds ratio is reported for the binary variables (CCA and UK ETS participation, with participation rates in brackets), and the only categorical variable (economic sector) is exactly matched. For nominally continuous variables, the empirical distributions of EU ETS and non-EU ETS firms 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. This range is conventionally specified as ± 0.2 standard deviations of the distribution of the pooled sample (Cochran & Rubin, 1973; Ho & Imai, 2006). The final column reports the smallest symmetric range about zero for which we reject the hypothesis of difference at the 5% significance level. As can be seen from the fact that the critical ranges lie within the equivalence ranges, the null hypothesis of difference is reject for all variables except for low-carbon patenting, where the small number of firms with any low-carbon patents means that we cannot reject the hypothesis of zero differences either. For the binary variables as well, the small sample size combined with the highly skewed proportions limit our ability to effectively constrain the odds ratios. The critical equivalence range for the odds ratios (about 1), reported in the final column, are computed using Fisher's exact test. (Note that we define a symmetric range around an odds ratio of 1 as $(\frac{1}{x}, \frac{x}{1})$, or equivalently (x^{-1}, x).)

The annual CO_2 intensity is measured for each firm, and then we calculate the change in the average intensity from the 3 years before the EU ETS to the years after it (up to and including 2008). 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. If the EU ETS had no impact on CO_2 intensity one would expect to find about as many positive as negative comparisons. By contrast, a more consistent pattern of positive or negative difference-in-differences would rarely arise by chance, in which case the EU ETS would be a prime candidate for explaining the appearance of a systematic divergence between EU ETS and non-EU ETS firms.

Applying this logic, I use Wilcoxon's signed-rank test to calculate the probability that the observed differences-in-differences were due to chance alone, and employ the standard procedure of inverting the test to obtain a point estimate and confidence interval for the effect of the EU ETS. Briefly, in estimating the effect of the policy, one searches for a percentage τ that, if added to the outcome of each EU ETS firm, would as nearly as possible equate their outcome distribution with that of the control group. For each value of τ I calculate the adjusted difference-in-differences,

$$\Delta = (T_t - T_{t-1}) \times (1 + \tau) - (C_t - C_{t-1}) \tag{4.1}$$

where T_t and T_{t-1} measure the CO_2 intensity of the EU ETS firm in the treatment period t and the pre-treatment period $t-1$, 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 τ is the value which maximises the p-value of Wilcoxon's signed-rank test, and the $(1-\alpha)$ confidence interval is the set of values of τ for which one cannot reject the alternative of difference at the α% level of significance.

Having arrived at the set of firms we can use to estimate the effect of the EU ETS, and having set out the mode of estimation, it is worth pausing to consider what we can realistically expect to learn about the impact of the EU ETS on CO_2 intensity. Despite painstaking efforts to assemble the best available data on which to make a determination about the impact of the EU ETS, the population of 431 British EU ETS firms has ultimately been whittled down to a sample of 58 due to limitations imposed by data availability and restrictions necessary for identification. It is, of course, possible to provide a best estimate of the impact of the EU ETS from this sample, but there are clearly going to be limits to our ability to reject alternative hypotheses.

The EU ETS firms in our sample reduced their emissions intensity by 3.8% compared to the pre-EU ETS period, and our best estimate is that the EU ETS had no impact, with a 95% confidence interval of (-20%, 19%). This is obviously a wide margin of error, but turning this on its head, we can test for statistical equivalence as we did for the pre-EU ETS sample. This test applies the same criterion used to establish substantive equivalence in the pre-EU ETS period, and asks if we would reject the same hypothesis of difference for our 58 firm pairs in the post-EU ETS period. This test just fails to reject the hypothesis of difference at the 5% significance level, but does reject it at the 10% level. Put plainly, while we are more confident that our pairs had ostensibly the same levels of CO_2 intensity before the EU ETS, we are still able to claim with more than 90% confidence that the differences between EU ETS and non-EU ETS firms in the post-EU ETS period are due to chance alone. The evidence thus seems to point us in the direction that the EU ETS has had no impact on CO_2 efficiency improvements.

If it does turn out that the EU ETS has induced firms to reduce their CO_2 intensity, though, one may be concerned that such efforts have diverted resources from other forms of resource-saving innovation (Popp & Newell, 2012). To address this concern, we can compare the changes in labour intensity among our matched firms (recall that prior to the EU ETS the distributions of labour intensity were substantively equivalent for EU ETS and non-EU ETS firms). Here our best estimate is that the EU ETS has induced firms to change their labour intensity by -3.7% (-14.3%, 9.6%). Clearly, we cannot rule out the possibility of crowding out, but we can say with 95% confidence that the 58 pairs meet the same equivalence criterion we applied in the pre-EU ETS period.

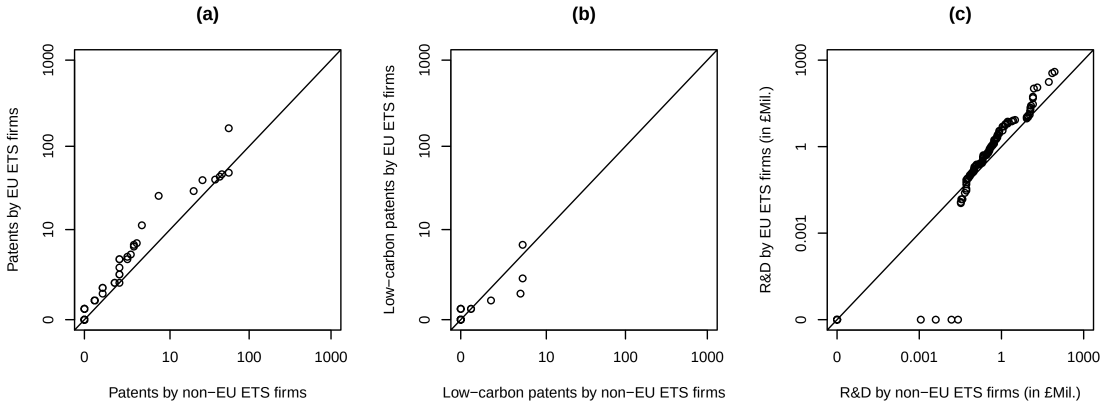
In sum, our best estimates indicate that the EU ETS has had no substantive impact on firms' CO_2 intensity in the UK. We can also say with a reasonable degree of confidence that the EU ETS has not had very large positive or negative effects on either CO_2 intensity or labour intensity. Nevertheless, despite our best efforts to conduct the most comprehensive set of comparisons possible, one must acknowledge that there is a paucity of strong evidence.

4.5.2 Changes in patenting

The EU ETS may not yet have sparked reductions in CO_2 intensity, but perhaps it has encouraged greater efforts to develop and bring new low-carbon technologies to market. To estimate the impact of the EU ETS on patenting, we must identify a set of non-EU ETS firms that best reflect how the EU ETS firms would have patented had they escaped EU ETS regulation. As before, firms are matched for economic sector, turnover, and CCA and UK ETS participation. Since we are interested in the change in patenting behaviour, firms are once again matched to have similar patenting records from the years before the EU ETS. In addition, past R&D expenditures signal innovation that would likely have resulted in some amount of patents without further inducement from the EU ETS. Firms are therefore matched to have similar R&D expenditures in the pre-EU ETS period.

Since both patenting and R&D expenditures are recorded for a much larger number of firms than CO_2 intensity, we are now starting in the more favoured position of having the necessary data for 178 EU ETS firms and over 30,000 non-EU ETS firms. From this information it has been possible to construct 130 pairs of similar EU ETS and non-EU ETS firms. Figure 4.2 and Table 4.3 compare the empirical distribution of characteristics across the matched EU ETS and non-EU ETS firms. EU ETS firms are on average slightly larger, but with respect to patenting and R&D expenditures, the two groups are very similar.

Figure 4.2: Comparison of matched EU ETS and non-EU ETS firms



Panels (a) and (b) display the empirical quantile-quantile (e-QQ) plots for average number of patents and low-carbon patents filed in the 3-year period preceding the year of entry into the EU ETS. Panel (c) shows the e-QQ plot for average R&D expenditures over the same period. All panels are drawn with logarithmic scales, and panels (a) and (b) share the same scales to facilitate comparisons.

As the numbers in Table 4.3 report, we are able to reject the hypotheses that the two groups were systematically different prior to the EU ETS, except with respect to low-carbon patenting. This last failure hints that we may once again have a problem concerning our sample size. Although our actual sample is now more than twice what it was earlier, the *effective* sample

Table 4.3: Equivalence tests for matched EU ETS and non-EU ETS firms

	Difference between EU ETS and non-EU ETS firms	Equivalence range	Critical equivalence range (5% sign. lev.)
Turnover (in £Mil.)	35.75	±378.05	±141.15
Patents	0	±2.73	±1.00
Low-carbon patents	0	±0.13	±2.00
R&D expenditure (in £Thd.)	0.12	±7.31	±1.43
CCA participation	1.68 (68% vs. 55%)	–	$(2.66^{-1}, 2.66)$
UK ETS direct participation	1.00 (1% vs. 1%)	–	$(38.79^{-1}, 38.79)$
Economic sector	Exactly matched	–	–

The null hypothesis of difference is reject for all variables (where applicable), except for low-carbon patenting. This failure stems from the small number of firms with any low-carbon patents in the pre-EU ETS period, as can be seen from our failure to also reject the hypothesis of equivalence. At the 5% level of significance we are just able to reject the hypothesis that EU ETS firms filed 2 low-carbon patents per year more or less than non-EU ETS firms. See the caption of Table 4.2 for more details on how to read this table.

size is substantially smaller because most firms file zero patents. These zeros are not strictly informative, however, but are the likely consequence of the same kind of censoring that usually motivates the use of the Tobit estimator. We can imagine patenting as a latent variable that can take any value, but we can only observe numbers of zero or greater.

To implement the Tobit estimator in our case, though, we would have to explicitly model 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 & Powell, 2001). Instead, we can account for censoring at zero using a Tobit-modified version of the difference-in-differences estimator outlined in the previous section (see Rosenbaum, 2009, ch. 2). The idea is as follows: instead of assuming a constant treatment effect that applies to all firms, including those with zero patents, we can adjust our observed difference-in-differences in a way that takes the censoring into account, and estimate the treatment effect using these zero-adjusted difference-in-differences. Each of the difference-in-differences, Δ, is adjusted according to the formula:

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

Applying to these adjusted difference-in-differences the procedure of inverting Wilcoxon's signed-rank test provides us with a non-parametric alternative to the Tobit estimator. It is worth noting that the treatment effect is here defined additively, instead of multiplicatively as it was in the previous section. The reason for this change is the same that motivated the use of the Tobit model in the first place—censoring. A multiplicative model assumes that every firms with zero patents before the EU ETS will file zero patents after the EU ETS, while an additive model allows switching from one category to the other. Still, we can, and will, translate the additive treatment effect into the total number of patents added, and from this compute the percentage change relative to the counterfactual.

It is also worth noting that, because zero-differences are uninformative about the impact of the EU ETS, the effective sample size will be reduced from 130 pairs to only those in which at least one firm filed a patent in the pre- or post-EU ETS period. Our ability to estimate the impact on low-carbon patenting with precision, therefore, will depend on how many firms changed their observed patenting behaviour after the EU ETS began.

Our best estimate is that EU ETS firms filed on average 0.37 additional low-carbon patents per year in the post-EU ETS period. In more intuitive terms, our sample of EU ETS firms filed a total of 26 low-carbon patents in the post-EU ETS period. Subtracting our point estimate from each firm (accounting for censoring at zero) and multiplying by the number of years spent in the EU ETS, we find that EU ETS firms would have filed 9.94 fewer low-carbon patents in the absence of the EU ETS. In percentage terms, we would attribute to the EU ETS a 62% increase in low-carbon patenting in our sample. Were we to extrapolate this calculation to all 431 EU ETS firms, the number of additional low-carbon patents increases to 42.57, or an increase of 53% compared to the counterfactual. With nearly 2,000 low-carbon patents filed by UK firms since 2005, though, 42.57 low-carbon patents would represent nearly a 2.3% increase compared to the counterfactual scenario without the EU ETS.

Our estimate, though perhaps indicative, lacks precision. We are unable to effectively constrain our uncertainty around our point estimate. We are unable to reject either hypotheses of difference or those of equivalence with any reasonable degree of confidence. Out of our 260 matched firms, only 30 have actually changed their low-carbon patents in the post-EU ETS period (15 EU ETS firms and 15 non-EU ETS firms), hardly enough information to draw confident conclusions about the impact of the EU ETS. Our best guess—however poor—must be that the EU ETS has had a marked positive impact on the low-carbon patenting of EU ETS firms, perhaps even causing an economically meaningful effect in the broader context of UK low-carbon innovation.

If further evidence supports our preliminary assessment that the EU ETS has encouraged low-carbon patenting, one may also be concerned that it has crowded out patenting for other technologies (Popp & Newell, 2012). Indeed, our best estimate of the impact of the EU ETS on patenting for other technologies is $\tau = -0.15$ (-3.53, 1.33). This translates into 123 fewer patents protecting other technologies, with our 95% confidence interval including the quite contrary possibilities that the EU ETS is responsible for crowding out 1,765.68 patents and that the it is responsible for adding 118.11 patents. These are quite substantial numbers. In percentage terms, they correspond to a 6.7% (-7.4%, 50.8%) reduction in patenting for other technologies among our sample of EU ETS firms. Extrapolated to the population of British EU ETS firms, our estimate implies a 1.1% reduction (-7.8%, 21.0%) in patenting for other technologies. Economy-wide, this amounts to a 0.1% reduction (-0.7%, 2.6%) in patenting. The available evidence thus suggests there may have been a degree of crowding out, most likely of a negligible order, but we are unable to rule out the possibility that there was indeed some crowding in.

4.5.3 R&D expenditure

To summarise so far, our best estimates indicate that the EU ETS has not impacted CO_2 intensity, but has boosted low-carbon patenting. An approving observer may interpret these responses, were we momentarily to take them to be facts, as indicating that while EU ETS firms can quite easily cope with regulations in the short term, they are simultaneously developing and bringing to market new low-carbon technologies that will become increasingly valuable in longer term when climate change regulations are expected to grow more stringent. A cynic, on the other hand, would read these observations as evidence that the EU ETS is having no real impact on CO_2 intensity, and only encouraging firms to patent a larger share of low-carbon technologies they have in their R&D pipeline to capitalise on the regulator's passing commitment to mitigating CO_2 emissions. Our estimates above do not lead us to adjudicate between the optimist and the cynic. An analysis of investment in low-carbon R&D,

though, may provide us with a clue. R&D expenditures could tell us whether the changes in patenting are due to short term opportunism or reflect genuine investments in innovation for the longer term.

In matching EU ETS firms with similar non-EU ETS firms, the availability of information about R&D expenditures provides a binding constraint. On the one hand, low-carbon R&D expenditures were only solicited for roughly 4,000 of the UK's largest innovators in DECC's Low-emissions R&D survey. The survey was sent out in 2009, and asked firms to report how much they spent on low-carbon R&D in 2008. On the other hand, total R&D expenditures in the pre- and post-EU ETS period are only available for repeat participants in either the Business Enterprise Research and Development survey or the UK Innovation Survey. There is sufficient information for only 93 out of the 431 EU ETS firms, and for around 3,000 non-EU ETS firms.

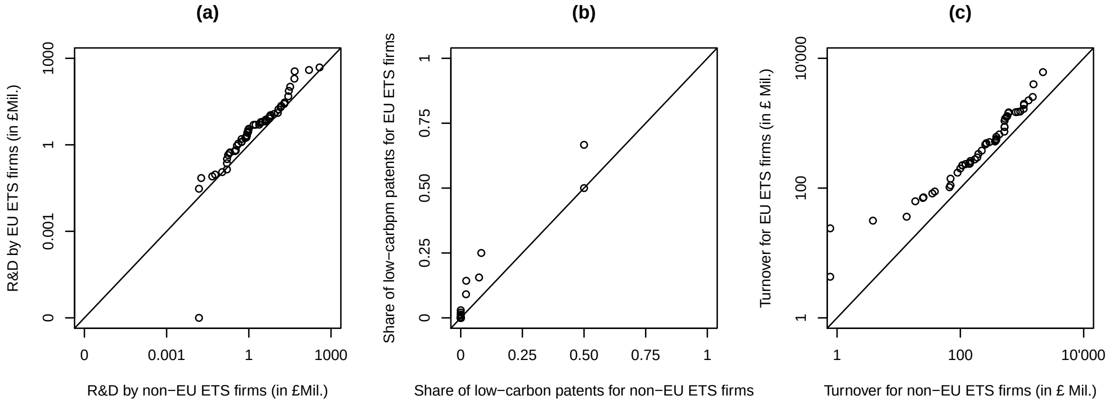
From this information, it has been possible to construct a set of 58 matched pairs. Firms are matched to operate in the same economic sector, and to have similar levels of turnover and R&D expenditure, as well as whether or not they received any government support for R&D. To proxy for low-carbon R&D expenditures, for which we do not have historical data, firms are matched to have similar shares of low-carbon patenting in the pre-EU ETS period. Firms are also matched for CCA and UK ETS participation. EU ETS firms in our sample are slightly larger on average, but not in a statistically significant way, and the two groups are very similar in terms of past R&D expenditures and emphasis on low-carbon patenting. Figure 4.3 and Table 4.4 provide further details.

Table 4.4: Equivalence tests for matched EU ETS and non-EU ETS firms

	Difference between EU ETS and non-EU ETS firms	Equivalence range	Critical equivalence range (5% sign. lev.)
Turnover (in £Mil.)	93.56	±420.45	±342.84
Share of low-carbon patents	0	±0.02	±0.50
R&D expenditure (in £Mil.)	0.32	±15.45	±5.46
R&D support	0.62 (79% vs. 86%)	–	(4.34^{-1}, 4.34)
CCA participation	2.05 (76% vs. 60%)	–	(4.38^{-1}, 4.38)
UK ETS direct participation	2.02 (3% vs. 2%)	–	60.02^{-1}, 60.02)
Economic sector	Exactly matched	–	–

The null hypothesis of difference is reject for all variables (where applicable), except for the share of low-carbon patents. As before, the failure to reject stems from the small number of firms with any low-carbon patents in the pre-EU ETS period, and we also cannot reject the hypothesis of equivalence. For all binary variables, we are unable to reject the hypothesis that the odds ratio is different from one. See the caption of Table 4.2 for more details on how to read this table.

Figure 4.3: Comparison of matched EU ETS and non-EU ETS firms



Panels (a), (b), and (c) display the empirical quantile-quantile (e-QQ) plots for average R&D expenditure, average share of low-carbon patents, and average turnover in the 3-year period preceeding the year of entry into the EU ETS.

In estimating the impact of the EU ETS on low-carbon R&D expenditure, we must be aware of the low response rate to DECC's survey, only 52%, much lower than for the statutory surveys. If the probability of responding depends on being an EU ETS firm, this might be interpreted as warning that respondents have self-selected in a way that varies systematically with EU ETS participation, in which case an analysis of responses alone is prone to bias. In fact, the response rates for EU ETS firms and non-EU ETS firms are 64% and 57% respectively (odds ratio = 1.33). We cannot reject the hypothesis that the odds ratio is different from one, and we can reject with 95% confidence the hypotheses that the true odds ratio lies outside the interval (2.67^{-1}, 2.67). This provides a *prima facie* case for assuming responses do not systematically favour EU ETS or non-EU ETS firms.

At this point, it is worth pausing to consider again the various factors restricting our sample size. First we have limitations due to the size of the survey, second are limitations imposed by similarity in the matching process, third is the low response rate for the DECC survey, and fourth is the fact that, as with patenting, most firms are unlikely to undertake any low-carbon R&D. Together, these four factors are likely to leave very little data with which one can estimate the impact of the EU ETS.

In fact, we are left with only 14 pairs where both firms responded to the survey, and only 3 pairs in which at least one firm did any low-carbon R&D. To deal with the large proportion of zeros we employ the same Tobit-like model of the treatment effect as employed in the preceding section, with the modification that we are no longer able to compute the difference over time. The remaining data, however, is insufficient even for a point estimate. We are only able to make the very weak statement that it appears about twice as likely that the effect is positive rather than negative.

If we were to interpret non-responses as zeros, though, the full set of 58 matched pairs become available, of which 8 contain at least one firm that made some investment in low-carbon R&D. With this assumption our best estimate is that, among the firms likely to do any low-carbon R&D, the EU ETS increased their investments by £146,950 in 2008 compared to the counterfactual scenario. Across our sample of 58 EU ETS firms, this amounts to an additional £553,850 of spending on low-carbon R&D in 2008, or an increase of 23% against the counterfactual. It would translate into a 0.85% increase against the counterfactual to the total £66 million in low-carbon R&D spending reported in the DECC survey. Due to data limitations, however, we cannot meaningfully constrain our uncertainty around the point estimate.

There are two main reasons why this estimate might be biased in favour of EU ETS firms: EU ETS firms receiving favourable treatment with respect to government R&D support, and selection bias. Let us address each in turn.

In terms of general R&D support, EU ETS firms were no more likely than non-EU ETS firms to receive help in the post-EU ETS period (odds ratio = 0.92). Nor do they appear to have been more likely to receive R&D support specifically targeted to help with low-carbon innovation (odds ratio = 0.59). Government R&D support, therefore does not appear to offer a compelling alternative explanation for the additional R&D expenditure of EU ETS firms in our sample.

Selection provides another mechanism by which our above estimate would be biased in favour of EU ETS firms. Firstly, if non-EU ETS firms were more likely to close down during the post-EU ETS period up until 2009, it is likely that they would be underrepresented among the DECC survey participants, even though they may have conducted low-carbon R&D. Secondly, the same problem would arise if the response rate among actual participants was systematically lower among non-EU ETS firms. To address concerns about selection bias, let us intentionally bias our estimate in favour of non-EU ETS firms by assuming that non-response can be interpreted as being equal to the maximum expenditure reported in the survey. Though it seems much less likely, this arguably provides a lower bound for the point estimate with respect to selection bias. With this assumption, we estimate a treatment effect of £0, with a 95% confidence interval of (£0, £6,400). Of course we should not attach much weight to this estimate, but the fact that we are unable to generate a negative treatment effect even under such unfavourable assumptions suggests we can be moderately confident that the EU ETS has actually encouraged firms to invest resources in researching and developing new low-carbon technologies. As to the amount, our best guess must lie somewhere close to £146,950, especially if non-respondents are as likely as respondents to spend no money on low-carbon R&D.

One should note that, due to the DECC survey sampling from among the UK's top innovators, it would be inappropriate to extrapolate our estimate to the whole of the EU ETS. On the other hand, extrapolating to the 93 EU ETS firms participating in the survey will, by comparison, be more likely to capture the full scale of the EU ETS's impact on 2008 low-carbon R&D spending. If we extrapolate our point estimate we find that the EU ETS is responsible for just over £1.3 million in additional low-carbon R&D spending. This corresponds to a 5.8% increase among surveyed EU ETS firms against the counterfactual scenario, or a 2.1% increase in the total R&D expenditures across both EU ETS and non-EU ETS firms. Compared to the £341 million the UK government estimates that firms invested in low-carbon R&D in 2008, this represents less than a 0.4% increase.[21]

In addition to looking at low-carbon R&D expenditures, we may also estimate the impact of the EU ETS on total R&D expenditures. Utilising once again the time-series dimension of our data set (which is available for total R&D expenditures but not for low-carbon R&D), our best estimate of the impact on total R&D expenditures is an increase of £20,000 (-£570,000, £1,110,000). To the extent that the EU ETS has encouraged low-carbon R&D, this estimate would suggest an almost pound-for-pound substitution from other R&D at the level of the individual firm. However, since firms undertaking low-carbon R&D are only a small subset of innovating firms, the net effect is likely to be a small crowding in of R&D (or, perhaps,

---

[21] The UK-wide estimate is taken from unpublished documentation for the DECC survey, available through the UK Data Service.

it is an increase in low-carbon R&D not measured by the DECC survey). These are hardly impressive numbers, however, and do not amount to much in economic terms even when extrapolated to a larger set of firms. For all intents and purposes, our best guess must be that whatever encouragement the EU ETS has provided for investment in low-carbon R&D, most of the additional resources invested here have been effectively diverted from other research and development activities.

4.6 Discussion

One of the principal objectives of emissions trading programmes like the EU ETS is to achieve reductions in carbon emissions by encouraging firms to innovate and become more efficient. This chapter has brought together data on UK firms from a range of sources in order to investigate to what extent the EU ETS actually has affected innovation.

Despite painstaking data collection efforts, the primary conclusion concerns the paucity of evidence available on which to make any inference about the impact of the EU ETS. The limitations of available data often prevent us from constraining our uncertainty about the Scheme's impacts in an economically meaningful way. Any story told on the basis of the evidence presented must therefore be tentative, and any effort to gain more confidence about the elements of this story must necessarily draw on additional sources of data or on an identification strategy which justifies imposing additional statistical restrictions for the purpose of estimation.

Nevertheless, our estimates do provide a tentative account of the impact of the EU ETS. It does not appear that EU ETS firms have been induced to cut the CO_2 intensity of their output, yet they do appear to have increased their low-carbon patenting and R&D spending in response to the EU ETS. These findings may be surprising for a number of reasons. Firstly, the absence of a reduction in CO_2 intensity might be seen to contradict the studies showing that the EU ETS is responsible for a moderate reduction in emissions compared to a counterfactual without the EU ETS (Ellerman & Buchner, 2008; Ellerman et al., 2010; Anderson & Di Maria, 2011; Zachmann et al., 2011), the surveys showing how EU ETS firms are implementing energy saving measures (Petsonk & Cozijnsen, 2007), and the energy models showing how the EU ETS is encouraging fuel switching in the power sector (Delarue et al., 2008, 2010). There are a number of ways to redress this apparent discrepancy. Several studies reach less flattering conclusions about the impact of the EU ETS on emissions (Jaraite & Maria, 2011; Cooper, 2010; Kettner et al., 2011), suggesting that the aforementioned estimates may be overstating the effect to start with. With regards to surveys showing increased adoption of energy saving technologies among EU ETS firms, it is extremely rare that the answers are compared with similar non-EU ETS firms, allowing for the possibility that the improvements in CO_2 intensity may be the result of some broader trend rather than the EU ETS. Indeed, in our data the CO_2 intensity declines for both groups of firms over the period, but at the same rate. Finally, with respect to fuel switching, it is worth noting that power producers will necessarily constitute a minority of any reasonably large sample of EU ETS firms, especially when the sample is selected on the basis of the availability of suitable non-EU ETS comparators. In practice, the estimates of the present study will best reflect the typical response of industrial firms in the UK. As such, our finding that the EU ETS has not encouraged a reduction of industrial CO_2 intensity might even read as evidence supporting earlier conclusions that the lion's share of emissions saving has occurred through fuel switching in the power sector. Moreover, our results conform with predictions that the EU ETS allowance allocation methodology would seriously compromise incentives to increase fuel and CO_2 efficiency (Neuhoff et al., 2006c), and more recent evidence that EU ETS firms have been no more likely to install low-carbon technologies (Löfgren et al., 2013). Our results are consistent with these observations, indicating either that a mere continuation of exogenous efficiency improvements proved sufficient for the firms in our sample to comply with the EU ETS, or that they could shift the burden of compliance onto the firms outside our sample (perhaps the power companies) through the permit market mechanism. The reduction in output associated with the 2008 recession may have further lessened the need to improve efficiency in order to comply with the EU ETS.

A second surprising feature of our findings is that although CO_2 intensity has not been cut, low-carbon patenting and R&D do appear to have increased in response to the EU ETS. This pattern seems to fit with recent evidence (Martin et al., 2011; Löfgren et al., 2013), but appears to contradict historical experience with emissions trading. The trading provisions of the US phase-down of leaded petrol, for instance, encouraged refiners to adopt an octane-boosting technology (to replace the octane lost when lead usage is reduced), but did not appear to affect a reduction in the cost of the technology or an introduction of new better technologies (Kerr & Newell, 2003). Similarly, the Acid Rain Program encouraged US power producers to rely more heavily on coal with lower-sulphur content (Schmalensee et al., 1998), and to a more limited extent install the technology to scrub sulphur dioxide from emissions (Burtraw & Szambelan, 2009). Development of scrubber-technology was much more limited (Lange & Bellas, 2005; Popp, 2003). In both cases, firms' compliance strategies relied heavily on existing technologies and there was no great response in the development of new technologies. By contrast, our estimates suggest a stronger response of low-carbon patenting and R&D to the EU ETS than of CO_2 intensity. We must be careful not to overstate the economic significance of the estimated response, but one might nevertheless speculate that the new pattern, supposing it is confirmed by further research, reflects a recognition about firms that while the technologies available to boost octane-ratings and to scrub sulphur emissions were sufficient to achieve abatement targets at a reasonable cost, technologies available today are not going to allow firms to dramatically cut their emissions in line with longer term carbon emissions targets without incurring substantial costs.

Whether or not there is any truth to this interpretation, one should note the suggested magnitude of these responses. While the response may be impressive among EU ETS firms—53% more low-carbon patents and 5.8% more low-carbon R&D than in the counterfactual scenario—in the context of the UK economy these responses amount to more modest increases on the order of 2.3% and 0.4% respectively, and would probably be discovered to be even more modest if more complete data was available on non-EU ETS firms. These effects may very well be of economic significance, but it is debatable whether they are enough to justify pronouncements to the effect that the EU ETS is the "engine of low-carbon growth" (European Commission, 2012). What is more, our best estimates suggests that these increases in low-carbon innovation may not be additional to the economy, but rather reflect a redirection of resources from other innovation activities.

This study provides a first detailed systematic analysis of the EU ETS's impact on innovation.

Our estimates of the Scheme's impact on CO_2 intensity, low-carbon patenting, and low-carbon R&D outline a reality in which EU ETS firms in the UK (mostly industrial firms) have largely kept pace with non-EU ETS firms in terms of emissions intensity, but have placed somewhat greater emphasis on developing and bringing to market new low-carbon technologies. However, the evidence available so far is weak. There is substantial uncertainty around our estimates that can only be reduced or resolved by more powerful means of statistical identification or by analysis of larger data sets. Each path involves compromises, whether in the plausibility of the estimates or in the richness of the data. Facing up to the latter of these two compromises, perhaps the most immediate next step would be to investigate whether individual elements of our story (e.g. the impact on patenting) is born out on a European scale. Regardless of whether such an exercise would reinforce our present findings or cause us to rethink them, it would without doubt further advance our understanding of the impact of emissions trading on innovation. It is therefore to this topic that we turn our attention next.

Chapter 5

Emissions Trading and Directed Technological Change: Evidence from the European carbon market

5.1 Introduction

Over 80% of the global carbon trade is currently accounted for by the EU Emissions Trading Scheme (EU ETS). It launched in 2005, and accounts for nearly half of the EU's total greenhouse gas emissions. It is today the world's largest cap-and-trade programme, allocating tradeable emissions permits to over 12,000 power stations and industrial plants across Europe. The primary aim of the EU ETS is to reduce carbon emissions through innovation.[1] 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 John Hicks (1932) and restated in the context of environmental policy by Porter (1991) and Acemoglu et al. (2012), 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

---

[1] This point is more fully articulated in Chapter 1.

has been articulated many times by EU policy makers, who envisage the EU ETS as a driving force of low-carbon economic growth.

In this paper we conduct the first comprehensive investigation of 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 exploit these installation-level inclusion criteria to 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 & Gayer, 2009). To the authors' knowledge, though, this is the first time that these methods have been employed to study the impact of environmental policy on directed technological change.

We use a newly constructed data set that records patenting activities, key company characteristics, and regulatory status with respect to the EU ETS. Our data set includes information on over 30 million firms across 23 countries, of which 18 countries 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 able to compare unregulated and would-be regulated firms both before and after the EU ETS launched. The low-carbon patent classification recently developed by the European Patent Office (EPO) allows us to identify emissions reduction technologies. 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.),

---

[2] As in the previous chapter, 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.

as well as firm-level heterogeneity (Heckman et al., 1998a,b; Smith & Todd, 2005; Abadie, 2005). Our estimates provide the first comprehensive empirical assessment of the impact of the EU ETS on directed technological change.

A casual look at aggregate patent data reveals a surge in low-carbon patenting since 2005. The increase appears larger among EU ETS-regulated companies, and 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. Put another way, only 2% of the post-2005 surge in low-carbon patenting can be attributed to the EU ETS.

With respect to concerns that low-carbon innovation would crowd out development of other technologies (Popp & 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 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 12,000 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), but in its current form the EU ETS may not be providing incentives for low-carbon technological change on a large scale. It is perhaps partly such concerns that animate the current debate about reforming the EU ETS.

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 & Schultze, 1975; Pizer & 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 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 (Popp, 2004; 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, often with innovation measured at the level of economic sectors or countries (Newell et al., 1999; Brunnermeier & Cohen, 2003; Popp, 2002; Aghion et al., 2012 and many others. See Popp et al., 2009, Popp, 2010, and Ambec et al., 2013, for recent surveys). Our study contributes to this literature, and analyses the policy impacts at the firm-level. The handful of studies that have begun to investigate the innovation impact of the EU ETS tend to rely on interview-based methodologies and most analyse small unrepresentative samples (Hoffmann, 2007; Tomás et al., 2010; Anderson et al., 2011). Martin et al. (2011) take extra precautions to ensure consistency across interviews with different firms, and they conduct the largest study to date covering 450 EU ETS firms in 6 countries. We use patent portfolios as an objective measure of technological change, and our study considers over 5,500 EU ETS firms in 18 countries, accounting for roughly 80% of the programme as a whole. With this, we provide the first comprehensive empirical estimates of the Scheme's impact on directed technological change.

The paper proceeds as follows. In Section 5.2 we familiarize ourselves with our newly constructed data set, and use it to begin unpacking the characteristics of low-carbon technological change. In Section 5.3 we turn our eye to estimating the impact of the EU ETS on regulated firms, and in Section 5.4 we examine its indirect impact on third-party technology providers and purchasers. Section 5.5 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.

5.2 Unpacking low-carbon technological change

In 2005, the EU ETS launched in 24 countries across Europe, covering over 40% of the EU's total greenhouse gas emissions.[3] For the purposes of the EU ETS, power stations and industrial plants across Europe were classified according to their main activity: "production of cement clinker", "manufacture of ceramics by firing", "production of paper or cardboard", etc. Only sufficiently large installations of each type would be regulated by the EU ETS. For instance, only clinker plants with a production capacity in excess of 500 tonnes per day were include, only ceramics plants with a capacity in excess of 75 tonnes per day, only paper factories with a production capacity exceeded 20 tonnes per day, etc. These are only three examples from a longer list.

A consequence of the design of the EU ETS inclusion criteria, therefore, is that EU ETS firms and non-EU ETS firms can, in principle, be virtually identical in all respects relevant to innovation, except for the size of a single installation. And though EU ETS regulations apply at the level of the installation, innovation takes place at the level of the firm. Thanks to recent advances in linking patent data with company data, it is possible to construct firm-level patent portfolios. This chapter 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.[4]

Patents have been used extensively as a measure of technological change in the recent induced innovation literature (Popp, 2002, 2006; Johnstone et al., 2010; Aghion et al., 2012), 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 inno-

---

[3] 7 countries have subsequently joined the EU ETS.

[4] The definition of a firm or company in this chapter follows that of Bureau van Dijk's data set, and is therefore different from that used in Chapter 4.

vation 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.[5] Nevertheless, as a robustness test we also repeat our analysis to using quality-weighted patent counts.[6]

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 at present provides the most accurate means for identifying low-carbon patents (Veefkind et al., 2012).[7] These low-carbon technologies include, to name a few, efficient combustion technologies, carbon capture and storage, and energy storage. This class helps us measure the direction of technological change.[8] A more complete description of the various sub-classes for low-carbon patents used in the paper can be found in Appendix B.

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

---

[5] 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 in which they are filed (van Zeebroeck, 2011). Patents filed at the EPO get patented in 6 EPO member countries on average.

[6] 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 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 patents filed with national patent offices to gauge whether our findings depend on how narrowly we define the patents of interest.

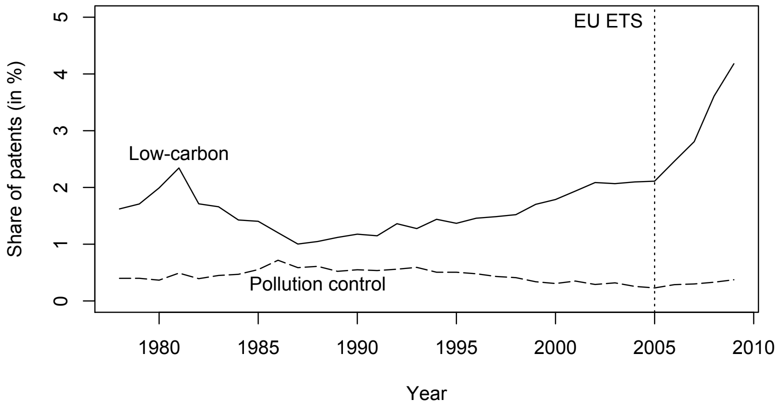
[7] A fuller description of this category can also be found in Chapter 4, Section 4.3.

[8] 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.

newly constructed data set includes the patent portfolios of over 30 million firms located in 23 countries (22 European 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.[9]

The share of patents protecting low-carbon technologies shows a distinct pattern over time (Figure 5.1). 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 rejects the hypothesis that there is no structural break in 2005 ($P < 0.001$).

Figure 5.1: 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 5.1 also plots the share of patents protecting non-greenhouse gas "pollution control technologies", as

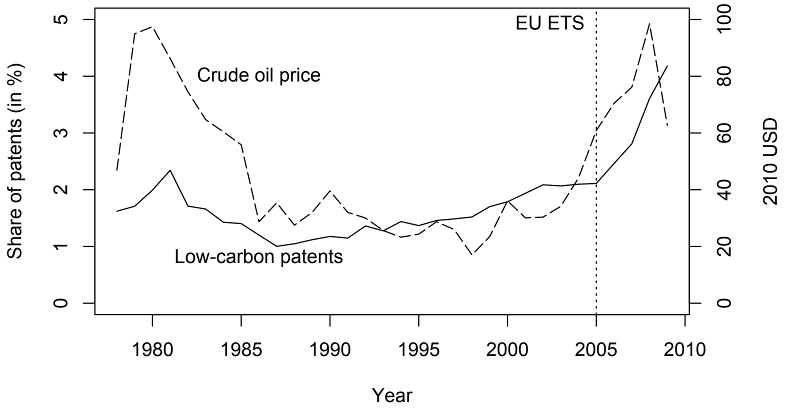
---

[9] 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 patent filings at the EPO which are associated with high administrative costs for the applicant.

defined by Popp (2006),[10] 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 as the increase in low-carbon patenting in the early 1980s has been attributed to the oil price shock, the recent surge might also be due to rising oil prices. When comparing the share of low-carbon patenting with the evolution of oil prices (see Figure 5.2), 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 that it has stayed flat recently. Looking at the aggregate trends over time, clearly, is not enough to 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 5.2: 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

---

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

fuels" are included only if their annual thermal input exceeds a threshold of 20 MWh. For steel plants, the relevant inclusion criterion is instead that the installation has 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 5.1).[11]

Table 5.1: Coverage of the EU ETS

	Number of installations	Mtonne 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

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 a proportion of the EU ETS as a whole.

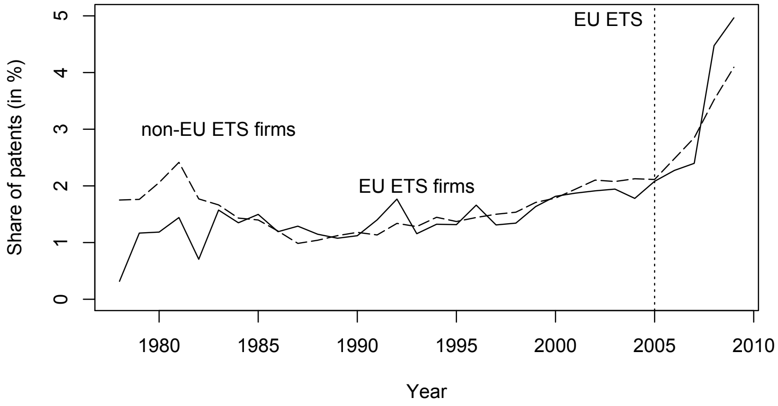
Having identified the subset of firms directly affected by the EU ETS, we can now look separately at the EU ETS and non-EU ETS trends in low-carbon patenting. Figure 5.3 shows that

---

[11] See Appendix D for more details on how the link between firm data and regulatory data was constructed.

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 & 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.[12] 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 all, be a consequence of the EU ETS?

Figure 5.3: Comparing the share of low-carbon patents (1978–2009)



Let us naively suppose for a moment that the differences visible in Figure 5.3 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

---

[12] This argument is developed in greater detail in Chapter 3, Section 3.3.5.

[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.

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 × 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 in terms of 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.

5.3 The direct impact of the EU ETS

5.3.1 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 with a greater degree of similarity 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 & 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 D). However, 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,

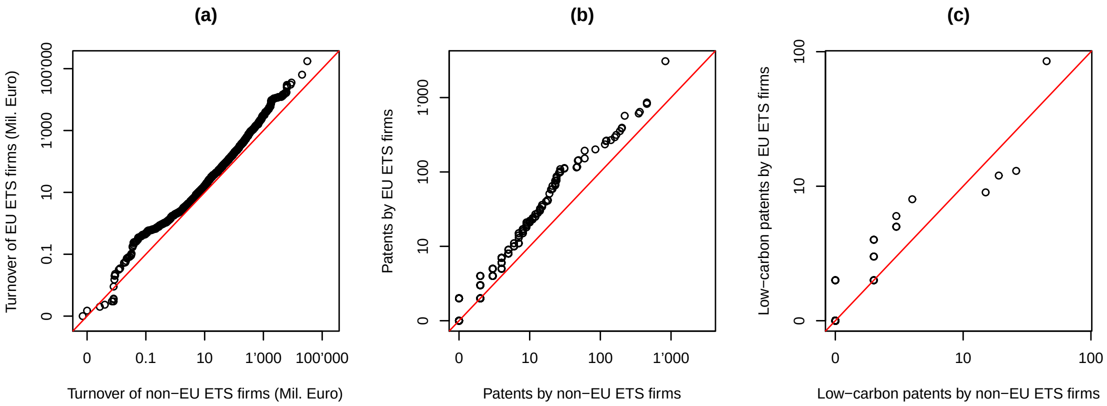
---

[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”.

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 5.3.3, 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 5.4: 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.

---

[15] See appendix A for technical details about how the matching was implemented.

Figure 5.4 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 5.2, we reject the hypotheses that the empirical distributions differ between the EU ETS and non-EU ETS firms.

Table 5.2: 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 5.4, 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 & Rubin, 1973; Ho & 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 '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 5.3 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).

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 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 randomised experiment (though we subject this claim to further scrutiny below).

5.3.2 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 the Tobit estimator in our case, though, we would have to explicitly model 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 & Powell, 2001). Instead, we can account for the censoring at zero using a Tobit-modified 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.[16]

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 the 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 compared to the counterfactual. 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 5.3). 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,

---

[16] See also Chapter 4 for a discussion of this estimator.

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 & 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 $(1.00, 1.99)$. This translates into 305.0 $(305.0, 512.9)$ 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 5.3: 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 5.2.

Our results are summarised for convenience in table 5.3, along with comparable naive estimates for the full sample of EU ETS firms (calculated as in Section 5.2). 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. Putting it another way, of the post-2005 surge in low-carbon patenting seen in Figure 5.1, roughly 2% can be attributed to the EU ETS.[17] 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.

5.3.3 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 randomised 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

---

[17] The number of low-carbon patents filed at the EPO increased by 9,054 from the period 2000-2004 to 2005-2009. The 188 additional low-carbon patents we have attributed to the EU ETS correspond to 2% of this increase. Even under the more generous framing that the upward trend from 2000-2004 would have continued unabated in 2005-2009, the post-2005 'surge' was only 4,725.5 low-carbon patents, of which the 188 additional low-carbon patents would amount to barely 4%.

observed similarity by construction, so similarity on matched characteristics cannot be read 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 5.5 and table 5.4 show, the empirical distributions of the 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 randomised experiment.

Figure 5.5: Comparison of matched EU ETS and non-EU ETS firms on 'unobserved' variable

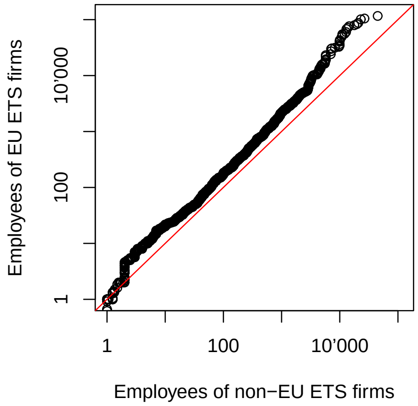


Table 5.4: Equivalence test for matched EU ETS and non-EU ETS firms on 'unobserved' variable

	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 5.2 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 & 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 1,062 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 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.[18] 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 it 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

---

[18] 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 & Silber (2009).

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.[19]

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 randomised 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. This is a question of selection bias.

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

---

[19] 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 for $\Gamma = 1.45$.

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 $(1.00, 5.99)$ for low-carbon patents and 1.00 $(1.00, 1.99)$ 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 $(49.00, 133.89)$ additional low-carbon patents and 318.00 $(318.00, 530.85)$ 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 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 is not so helpful for addressing 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 previous difference-in-differences, we can then estimate the upper bound of the treatment effect.[20] This procedure produces point estimates of 13.00 $(4.00, 43.99)$ for low-carbon and 6.00

---

[20] 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'.

$(4.00, 10.99)$ 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 524.0 $(275.0, 952.9)$ additional low-carbon patents and $2,093.00$ $(1,582.00, 3,176.95)$ 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 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 5.1). In order for the EU ETS to have boosted low-carbon patenting by 5%, say, EU ETS firms would together have to have filed 1,062 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 our sample of 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 one of which has 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 E 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 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 E for more details).

- Is there some other hidden bias? Perhaps we are only picking up the low-carbon technology component of a broader trend toward environmental technologies among our EU ETS firms. 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 (2006). 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, perhaps some unknown omitted variable, would manifest itself as finding a treatment effect here that is significantly different from zero. Our estimated treatment effect is $\tau = 0.75$, but it is not significantly different from zero.[21]

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 are few and therefore 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.[22]

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 5.1, might the EU ETS still be indirectly responsible? Has it encouraged third parties to develop low-carbon technologies in the hope

---

[21] 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.

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

of selling or licensing them to newly regulated EU ETS firms? We investigate this question next.

5.4 The indirect impact of the EU ETS

The preceding analysis 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 firms than for third parties (Milliman & Prince, 1989; Fischer et al., 2003). The asymmetry arises because the latter group is not discharging costly emissions themselves and receives 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 comparatively small, but all claims about the indirect effect need to be met with the same level of scepticism 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 firm 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.[23] Figure 5.6 and table 5.5 show the properties of our matched sample.[24]

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,

---

[23] 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.

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

Figure 5.6: Comparison of matched co-patenters and non-co-patenting firms

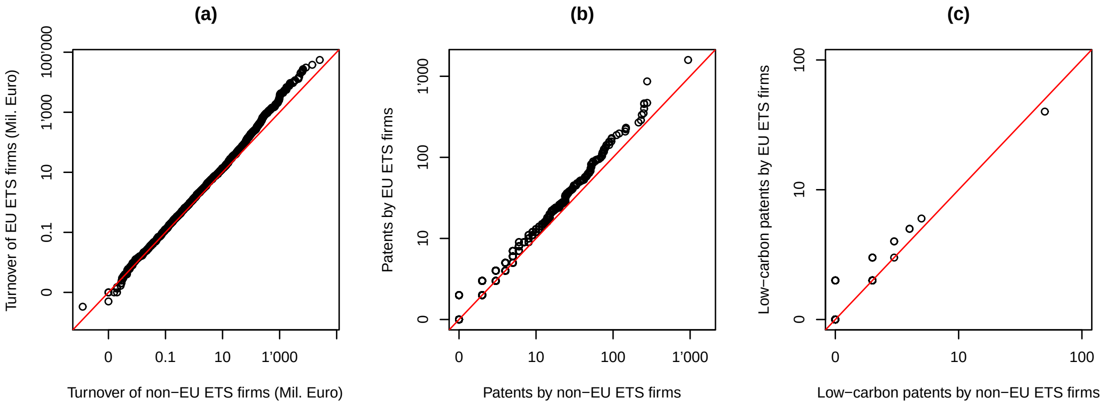


Table 5.5: Equivalence tests for matched co-patenters and non-co-patenting firms

	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 5.2 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.

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 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 differently 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.

5.5 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 energy 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 company 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 company 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, reported to two significant digits).

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 & Mody, 1996; Brunnermeier & Cohen, 2003; Popp, 2002, 2003, 2006; 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 & Bellas, 2005). Our results indicate that this discrepancy may be a consequence not of weaker innovation incentives provided by emissions trading instruments, but of the fact that previous studies have used aggregate measures of innovation while cap-and-trade programmes tend 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 programme 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 to be of central importance (Kneese & Schultze, 1975; Pizer & 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 that we have not answered in this chapter. 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.[25] 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

---

[25] This is well illustrated by our attempts in Chapter 4.

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 changes (in the power sector rather than among industrial firms, if the evidence considered in Chapter 4 offers any indication) rather than technological changes, much like in past emissions trading programmes. 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 on a relatively small group of firms, their response appears 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.

Chapter 6

Conclusion

6.1 Summary of findings

The principal objective of emissions trading programmes is to reduce harmful emissions through innovation. While an environmental policy's success is perhaps most determined by its ability to encourage development of new less polluting technologies (Kneese & Schultze, 1975), the impact of these policies on technological change remains poorly understood (Pizer & Popp, 2008). This thesis has collected four essays that approach this gap in our collective understanding from different perspectives—one historical, one theoretical, and two empirical—in the hope of shedding light on the link between emissions trading and technological change.

When emissions trading has been leveraged in the past to mitigate other environmental problems (e.g. lead pollution and acid rain) it has encouraged adoption of pollution control technologies, and emissions reductions targets were ultimately achieved at relatively low cost. A closer examination of the historical context, however, at least tempers hopes of having such experiences repeated with carbon markets (see Chapter 2). The political process of conflict and compromise that has given rise to carbon markets may be familiar from historical experience, but it has not guaranteed the same preconditions for success.

The most important such precondition, perhaps, is the availability of the operational and technological means needed to achieve the emissions trading programme's ultimate abatement target at a manageable cost. Emissions trading programmes appear to have worked successfully when they have been able to nudge technological trends along. The technology to boost octane levels at a manageable cost without adding lead was available even before the leaded petrol phase-down began in the US. Competitive substitutes for CFCs were available even before the Montreal Protocol entered into force. Low-sulphur coal and the technology to scrub sulphur dioxide from emissions releases were widely used even before the Acid Rain Program launched. Emissions trading programmes sometimes also encouraged further technological advances that allowed cheaper or more effective pollution control, but these advances were marginal relative to the technological opportunities for abatement already at the emitters' disposal.

In this respect, carbon markets represent an unprecedented endeavour. The operational and technological opportunities now available to reduce harmful emissions to a level consistent with avoiding the most dangerous consequences of climate change are much more limited (Delarue et al., 2008; International Energy Agency, 2012), and policy makers are to a much greater degree relying on the new generation of emissions trading programmes to deliver technological change on a scale not seen before (European Commission, 2005, 2011). Past experience with emissions trading does not directly undermine the possibility that carbon markets can serve as the "engine" of technological change, but nor does past experience support it. Emissions trading has never been used for such a purpose before, or prompted such an outcome. There is therefore a special need to gather direct evidence on the impacts of carbon markets on technological change.

With an aim to understanding the impacts anticipated by the same economic reasoning that had once recommended emissions trading to economists, and partly with the hope of obtaining testable predictions for use in empirical study, Chapter 3 synthesised the economic theory of emissions trading and innovation with the aid of a simple but general model of the firm's innovation decision. A full consideration of the range of possible abatement technologies and the variety of empirical settings in which an emissions trading programme might be introduced—with market power, firm heterogeneity, policy adjustment, etc.—reveal, however, that economic theory does little to restrict the general relationship between emissions trading and innovation, at least in a way that may be of use for empirical study. Economic theory affords both the possibility that a higher price on emissions encourages innovation, and the possibility that it discourages it. The prediction will depend on detailed knowledge of economic conditions and of the types of technological opportunities available for emissions abatement, generally beyond the reach of the empirical investigator. A general economic framework serves best to highlight some potentially perverse impacts of emissions trading programmes, and to help explain why one might observe such effects, but it provides few testable predictions about the impacts of emissions trading on innovation.

Since economic theory in this case does not offer justification for presuming much about the nature of the relationship between a firm's participation in an emissions trading programme and its innovation decisions, empirical research must proceed with a bare minimum of artificial restrictions. When in chapters 4 and 5 I turned to investigate the effects of the EU ETS on technological change, therefore, I devised a non-parametric estimation strategy that combines matching and difference-in-differences methods.

Chapter 4 presented a detailed analysis of the impact of the EU ETS on the innovation activities of UK firms. I exploited installations-level inclusion criteria to estimate the impact of the EU ETS on carbon intensity of output at the firm-level, on low-carbon patenting, and on low-carbon R&D expenditure. These measures respectively serve as indicators of changes in efficiency, of the development and bringing to market of new low-carbon technologies, and as a precursor to future technological advances. Together, these three indices also speak more broadly to the question of whether the EU ETS has substantively altered the incentives for low-carbon innovation. The analysis reveals important data restrictions that limit our ability to draw confident conclusions about the Scheme's impact on innovation. Nevertheless, the evidence suggests that the principal impact of the EU ETS has been an increase in low-carbon R&D and patenting—large increases for EU ETS firms, but in the context of the UK economy the increases are roughly in the order of 2%. There are also indications, however, that these gains in low-carbon innovation may have come at the expense of other innovative activities. These results provide an informed sketch of the EU ETS' impact on innovation, which can serve a basis for further investigation. Further evidence must be brought to bear on individual elements of this story in order that we may either revise or reinforce our preliminary conclusions.

With this objective in mind, Chapter 5 presented the first comprehensive EU-wide empirical assessment of the impact of the Scheme on technological change. Once more exploiting installations-level inclusion criteria, I estimate the impact of the EU ETS on patenting for low-carbon technologies. I find that the EU ETS has increased low-carbon patenting among regulated firms by as much as 10%, while not crowding out patenting for other technologies. I also find evidence to suggest that the EU ETS has not had an impact on patenting beyond the set of regulated companies. These results imply that the EU ETS accounts for nearly a 1% increase in European low-carbon patenting compared to a counterfactual scenario without the EU ETS. These findings speak to impact of emissions trading on the rate, the direction, as well as the distribution, of technological change.

Although Chapter 4 presents only tentative conclusions, one should note the remarkable agreement with the EU ETS' estimated impact on low-carbon patenting reported in Chapter 5. The best estimate in Chapter 4 was that the EU ETS is responsible for 1.85 additional low-carbon patents for a typical EU ETS firm over the five-year period 2005–2009. In Chapter 5, the corresponding estimate attributes 2 additional low-carbon patents to the EU ETS. The difference is neither economically nor statistically significant. When the effects are computed for larger samples, the results are once again comparable across chapters, although the estimates from chapter 5 are slightly smaller than the preliminary estimates from Chapter 4. On the question of whether the EU ETS has crowded out patenting for other technologies, Chapter 5 reverses the earlier conclusion. When looking at a larger sample of firms across Europe, there is no evidence of crowding out. On the central question, the results in Chapter 5 broadly reinforce the conclusion that the EU ETS has impacted the rate and direction of technological change in a way that favours low-carbon technologies, but also show the limited reach of this effect.

6.2 Discussion

Taken together, the evidence presented in this thesis advances our understanding of the impact of emissions trading on technological change in at least one important respect. While previous programmes have provided neither support for, nor contradiction of, the statement that emissions trading can be relied upon to deliver large scale technological change, a systematic analysis of the EU ETS—the first programme to profess such ambitions—has revealed evidence against the proposition. This is not to say that the EU ETS has been totally ineffectual. Indeed, though a like-for-like comparison is impossible, the impact of the EU ETS appears quite substantial in comparison with historical emissions trading programmes. Our investigation has uncovered a technological response to the EU ETS—for a subset of firms even a quite dramatic response—but considered as part of the wider economy, the Scheme appears to have produced only a modest effect on technological change.

Provided one is satisfied that confounding technical and causal influences have been adequately addressed, one may consider possible explanations for our findings. First, consider the often voiced argument that perhaps an emissions trading programme with a more draconian cap would deliver the serious R&D investments and ultimately a forward leap of our technological ability to control the CO_2 emissions from production. Since we do not have a control group of this sort, it is difficult to speak directly to the validity of this explanation. Of course, one is compelled to consider whether the political economy of emissions trading is antithetical to such a cap ever being imposed, a proposition for which we have seen some historical support in Chapter 2 and in the current EU ETS.

Second, a more sophisticated but almost as frequently read explanation, is that emissions trading programmes fail to deliver technological change because they address only one of the market failures responsible for the underprovision of low-carbon innovation (Jaffe et al., 2005; Fischer & Newell, 2008; Newell, 2010). Only when the market failures pertaining to the appropriation of knowledge are also addressed could one expect to see the full effect of carbon pricing. An investigation of the EU ETS alone cannot address this point, since there is likely to be too great a similarity in how intellectual property is protected across and within participating countries. We may learn something about the reliability of this explanation, however, if instead we consider the EU ETS as a point of comparison against earlier US emissions trading programmes—the first non-US comparator. Viewed through this lens, one must acknowledge that the emissions trading programmes in the US and in Europe—regions with different regulatory regimes and cultures as regards innovation—have produced remarkably similar outcomes with respect to technological change.

Third, one must consider the possibility that the modest impact on technological change stems from a more fundamental limitation of emissions trading (including such persistent features as over-allocation). In past emissions trading programmes, there was neither technological necessity for innovation nor a robust technological response. The former could quite happily serve as an explanation of the latter, as well as grounds for relative indifference to it. In the case of the EU ETS, technological change appears necessary. The findings presented in this thesis reveal how technological change has responded to emissions trading in this setting—and perhaps they even reflect an unprecedented response—but maybe emissions trading programmes cannot be expected to achieve much more than this in practice. The sum of evidence presented in this thesis is best interpreted, perhaps, as testifying to a practical limitation of emissions trading in this domain.

I have revealed a slight preference for one particular hypothesis as the main explanation of why emissions trading programmes have not yet produced substantial technological change. This is based on very thin evidence, and I must reiterate that empirical investigation has so far been unable to convincingly distinguish between the different explanations. Fundamentally, researchers often lack the sort of variation in policy necessary to construct compelling counterfactual scenarios. This does, nevertheless, point us toward potentially fruitful avenues of future inquiry.

6.3 Future research

Our empirical understanding of the impact of emissions trading on technological change is limited by the opportunities we have to construct compelling counterfactual scenarios. Future research, therefore, might benefit from proceeding in two directions. First, more careful consideration of how emissions trading programmes have been implemented for different for groups of emitters unearth unexploited policy variation capable of addressing questions already raised by policy makers and researchers. Second, for those questions that such unexploited variation cannot answer, a closer collaboration of researchers and the agencies implementing emissions trading schemes may reveal opportunities to integrate policy experiments directly into the design of the programmes. Consider each point in turn.

Take, for instance, one of the key questions for policy makers and researchers in this field: how do emissions trading programmes interact with pre-existing environmental regulations? When can they be expected to work in harmony, and when might the layering of several policies produce unintended consequences? This is a very important question to ask, given the multiplicity of environmental policy instruments used in real-world economies. Economic theory can greatly aid our thinking about this question (Fankhauser et al., 2010), but the intricacy of actual environmental policies makes it difficult to fully anticipate and calculate all of the policy interactions in the abstract. This is a question for which applied empirical analysis would be a perfect complement to our economic theory.

Empirical study of this issue is difficult, though, and consequently very rare (a recent study by Fowlie (2010) is an exception). Because new emissions trading programmes usually overlap completely with the jurisdiction of other environmental policies, it is often not feasible to construct credible counterfactual scenarios using observational data. For this purpose, though, some features of the EU ETS experience provide almost as good a policy experiment as researchers could hope for. Three features of the EU ETS implementation are worth highlighting here:

1. The EU ETS was introduced alongside different pre-existing regulatory regimes across Europe. For instance, some EU countries already had carbon taxes in place when the EU ETS was introduced, while others did not. What is more, these carbon taxes differ in a number of interesting ways—in their level, in their coverage, and in respect to exemptions offered to EU ETS regulated firms. This variation provides an opportunity to compare firm behaviour systematically across countries with different pre-existing environmental policy regimes to study how the two different forms of carbon pricing—emissions

permits and a tax—interact in practice.

2. The EU ETS did not launch at the same time everywhere. Phase 1 of the EU ETS launched in most places in 2005, but some countries entered later in Phase 1 or did not join until Phase 2 of the Scheme. This time variation creates an opportunity to compare like-with-like installations (i.e. where all installations in the comparison meet the inclusion criteria) under environmental policy regimes that include or exclude the EU ETS at a given point in time.

3. The EU ETS was introduced only in some countries, while other countries—sometimes with very similar environmental regulatory regimes—have remained outside the programme. For instance, while Sweden joined the EU ETS in 2005, neighbouring Norway initially remained out. Such differences in EU ETS participation provides opportunities to study the interaction of emissions trading with other policies. One can compare the impact of the EU ETS in Sweden with its impact in other EU ETS countries, while using the behaviour of Norwegian firms to partial out the impact of the pre-existing regulatory regime. Similar neighbour comparisons are possible for several countries in Eastern Europe.

These features of the EU ETS experience provide ample opportunity to apply quasi-experimental techniques to investigate the interaction of the EU ETS with other policies—chiefly carbon taxes, though perhaps also with electricity market regulations. Matching techniques similar to those used in this thesis may be able to identify groups of initially very similar firms, but which experience different regulatory shifts at later dates. While the diverging experiences of a single such group may reveal little, similar divergences displayed across thousands of matched groups would provide a strong indication as to how the effects of emissions trading depend on the pre-existing policy regime. In addition, these methods can be fruitfully combined with economic modelling. As Fowlie (2010) demonstrates in her work on the interaction of the NO_X Budget Program and electricity market regulation, combining quasi-experimental methods with a more explicit model of regulated installations, firms, and of the other policies, can yield an even richer understanding.

The interaction of emissions trading programmes with other policies is rightfully an important concern for policy makers. So far, however, only very limited evidence is available to them on how these policies interact in practice. Economic theory provides a useful starting point, but empirical analysis is necessary to gain a more detailed understanding of this issue. Studying the EU ETS experience can substantially advance our understanding of how environmental policies interact, and provide practical lessons on how to design not just a single policy, but an environmental policy regime.

Such unexploited variation will not be sufficient to answer all of the policy makers' questions about emissions trading. To address the most important of these questions, one may consider integrating policy experiments directly into the design of the programmes. Inclusion criteria could be modified, exemptions from auctioning could be manipulated, different allocation methodologies could be applied, all with an aim to learn about the impacts of emissions trading and with a view to incorporate those lessons into future programmes. Even something so basic as to start the policy implementation process by identifying and collecting data on installations and firms that will become regulated, as well as on those that might in the future serve a useful purpose as comparators, would provide opportunities to greatly advance our understanding of emissions trading. Closer collaboration between the researchers and environmental agencies that write and implement emissions trading may uncover many such opportunities, where the information gained about how to improve the programme in the future may outweigh the concerns that often accompany experimentation. Similar initiatives already exist for education and healthcare policy. Extending the domain of experimentation to environmental policy could turn climate change mitigation, like climate science, into a truly evidence-based enterprise.

Appendix A

Implementation of matching

Matching techniques build on an analogy with randomised experiments. In a randomised experiment, the researcher randomly assigns subjects to one of several treatments. By the law of large numbers, the distribution of subject characteristics will be the same in each treatment group, which provides the basis for attributing systematic differences in outcomes to the treatments applied.

To further ensure similarity across the different treatment groups and to increase the precision of one's estimates, without relying on the law of large numbers, the researcher may opt for a paired (or grouped) experimental design. In a paired randomised experiment, the researcher starts by creating pairs of similar subjects. Treatment is then randomly assigned within each pair.

There are many further variations in the design of randomised experiments. For instance, in a critique of early studies on the benefits of heart transplantation, Gail (1972) noted that subjects that had undergone the procedure were, by definition, those that had survived long enough for a suitable donor heart to became available. This would unfairly favour the group that had undergone the operation, introducing a selection bias that would exaggerate the longevity benefits of the procedure. To address these concerns, Gail (1972) proposed an experiment that paired subjects and randomised treatment on the day the surgery, and measured longevity from that date.

Observational studies attempt to estimate the differential effect(s) of two or more treatments when random assignment to treatments is unfeasible. In analogy with a randomised experiment, one can select samples for an observational study by matching on observed pretreatment characteristics, in this case both increasing the precision and reducing the bias of estimates of the treatment effect (see Rubin (1973), and Cochran (1983, chap. 5)). Computing capability limited early observational studies to relatively simple matching techniques, such as matching on only two or three variables, ‘nearest neighbour’ matching, sub-classification, and caliper matching (Billewicz, 1965; Rubin, 1973; Cochran, 1983). Rosenbaum & Rubin (1983) introduced the idea of matching on the ‘propensity score’—the conditional probability of being assigned to the treated group—in observational studies. Estimated propensity scores still form the basis of many matching techniques.

In the context of economic policy evaluation, matching techniques began receiving attention after the publication of a study comparing different techniques for evaluating an experiment to provide subsidised employment (LaLonde, 1986). Matching estimators have subsequently been shown to reduce or remove bias in observational studies (Rubin, 1979; Dehejia & Wahba, 1999, 2002; Abadie & Imbens, 2006).

As computing capabilities have improved, several matching techniques have been developed that make better use of metrics such as propensity scores. For instance, optimal matching and full matching use a non-greedy algorithm to construct a partition of subjects that minimises the sum of differences between treated and control groups in terms of the estimated propensity score (Rosenbaum, 1989; Hansen, 2004). An alternative approach searches the space of distance metrics for a metric that achieves optimal balance on all variables (Sekhon, 2007).

The researcher faces several choices when implementing a matching estimator in an observational study. Should matching be combined with regression techniques to further adjust the sample (Rubin, 1979)? How many control subjects should be matched to each treated subject (Smith, 1997)? Should control subjects be removed or replaced from the population after having been matched once (Rosenbaum, 1989)? The answers to these questions have implications for the efficiency and bias of estimated treatment effects, and will determine what matching algorithms can be used.

The matches in chapters 4 and 5 were constructed using a multivariate and propensity score matching technique developed by Sekhon (2007). Briefly, a genetic search algorithm searches the space of distance metrics for a specification that minimises imbalances on the whole set of variables (see Sekhon, 2007, for details). Variable ratio matching with replacement is used, 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. This procedure minimises dissimilarities between treated and control groups, but reduces the variance of the estimate compared to optimal matching by retaining information about 'equally similar' controls. Based on the experimental design proposed by Gail (1972, see above), I also take into account the time of treatment in Chapter 4. This procedure is known as risk-set matching (Li et al., 2001). Matching is implemented using `GenMatch()` from the `R`-package `Matching`.

Appendix B

Details of low-carbon patent classification

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 B.1, adapted from Veefkind et al. (2012), summarises the main patent classes along with some examples of technologies for each class.

Table B.1: 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	N_2O, 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

The full list of low-carbon patent classes include:

B. ENERGY GENERATION FROM RENEWABLE AND NON-FOSSIL SOURCES

B.1. RENEWABLE ENERGY GENERATION

B.1.1. Wind energy: Y02E10/7

B.1.2. Solar thermal energy: Y02E10/4

B.1.3. Solar photovoltaic (PV) energy: Y02E10/5

B.1.4. Solar thermal-PV hybrids: Y02E10/6

B.1.5. Geothermal energy: Y02E10/1

B.1.6. Marine and hydro energy: Y02E10/3

B.2. ENERGY GENERATION FROM FUELS OF NON-FOSSIL ORIGIN

B.2.1. Biofuels: Y02E50/1

B.2.2. Fuel from waste: Y02E50/3

C. COMBUSTION TECHNOLOGIES WITH MITIGATION POTENTIAL (e.g. using fossil fuels, biomass, waste, etc.)

C.1. TECHNOLOGIES FOR IMPROVED OUTPUT EFFICIENCY (Combined combustion): Y02E20/1

C.2. TECHNOLOGIES FOR IMPROVED INPUT EFFICIENCY (Efficient combustion or heat usage): Y02E20/3

D. TECHNOLOGIES SPECIFIC TO CLIMATE CHANGE MITIGATION

D.1. CAPTURE, STORAGE, SEQUESTRATION OR DISPOSAL OF GREENHOUSE GASES

D.1.1. CO2 capture or storage (CCS): Y02C10

D.1.2. Capture or disposal of greenhouse gases other than CO2: Y02C20

E. TECHNOLOGIES WITH POTENTIAL OR INDIRECT CONTRIBUTION TO EMISSIONS MITIGATION

E.1. ENERGY STORAGE: Y02E60/1

E.2. HYDROGEN TECHNOLOGY: Y02E60/3

E.3. FUEL CELLS: Y02E60/5

Additional patent classes for “extended” low-carbon patents definition include:

Energy-efficient cement (see Dechezleprêtre et al., 2011, for list of codes)

Natural pozzuolana cements: C04B 7/1213

Cements containing slag: C04B 7/1421

Iron ore cements: C04B 7/22

Cements from oil shales, residues or waste other than slag: C04B 7/24-30

Calcium sulfate cements: C04B 11/00

HEATING (incl. water and space heating; air-conditioning)

Hot-water central heating systems - in combination with systems for domestic hot-water supply: F24D3/08

Hot-water central heating systems - using heat pumps: F24D3/18

Hot-air central heating systems - using heat pumps: F24D5/12

Central heating systems using heat accumulated in storage masses - using heat pumps: F24D11/02

Other domestic- or space-heating systems - using heat pumps: F24D15/04

Domestic hot-water supply systems - using heat pumps: F24D17/02

Use of energy recovery systems in air conditioning, ventilation or screening: F24F12

Combined heating and refrigeration systems, e.g. operating alternately or simultaneously: F25B29

Heat pumps: F25B30

Appendix C

Details on data set used in Chapter 4

The company registration numbers of the companies operating EU ETS regulated installations were identified from public documents produced by the UK Department of Energy & Climate Change, the Environment Agency, and from the Community Independent Transactions Log (CITL) (the EU body to which national registries report). A combination of exact and approximate text matching methods were used to identify the companies' registration numbers. This was complemented by further manual searches, and extensive manual double-checking. Using company registration numbers, the operators were subsequently linked to Inter-Departmental Business Registry (IDBR) enterprise reference numbers. The same procedures were applied to identify direct participants in the UK ETS. CCA participants were identified from a list previously compiled by Martin et al. (2009), complemented by some updated information available from the Department of Energy and Climate Change.

Using IDBR enterprise reference numbers, I excluded all non-EU ETS firms that were part of the same enterprise group as an EU ETS firm. This reduces the chance of matching two potentially dependent observations.

Appendix D

Details on data set used in Chapter 5

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 CITL. 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 an owner, a sister company, or a subsidiary to an EU ETS firm. This reduces the chance of matching two potentially dependent observations.

Appendix E

Details of other robustness tests in Chapter 5

Are matched non-EU ETS firms also responding to EU ETS? One can imagine several reasons why the matched firms that are not regulated by the EU ETS nevertheless respond to it by altering their innovation efforts. They might respond directly to the EU ETS because it sees the programme as having augmented the market for low-carbon technologies, or expect it to do so in the future (Martin et al., 2011). These firms might respond indirectly because the EU ETS alters the input prices they face or the terms of access to their inputs. They might respond because they engage in competition with EU ETS firms, or even just because they expect EU ETS firms to respond. Any of these effects would distort out estimates of what EU ETS firms would have done in the absence of the EU ETS, and would therefore potentially 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 underestimate the impact of the EU ETS. If very similar unregulated firms are responding by innovating less, this comparison will overestimate 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.

Table E.1: Treatment effect estimates using 'distant' matches

Norway, Switzerland, Romania, and Bulgaria	1 (0.00, 1.99)
USA	-1 (-1.99, 0.99)
Original estimate	2 (1, 5)

Table E.1 reports the estimated treatment effects for both the European and US re-matched samples, along with our original estimates for comparison. The re-matched point estimates are smaller than our original estimate (and both insignificantly different from zero), which would tend to indicate that very similar unregulated firms in EU ETS countries perhaps are innovating less than they would have without the EU ETS. This would be the case if, say, the EU ETS diverted resources for innovation from non-EU ETS firms, or if non-EU ETS firms perhaps sat back with the expectation that EU ETS firms would now produce the technologies they would need in the future. Our original estimate, then, may if anything have overestimated the impact of the EU ETS.

Due to between-country differences, however, which these re-matched estimates cannot control for, one should exercise caution in recommending such an interpretation. For instance, patenting has been historically lower in countries like Bulgaria and Romania, which could in part account for the lower estimate obtained from the re-matched sample. The fact that Bulgaria, Romania and Norway all joined the EU ETS toward the end of the period under consideration may also introduce certain biases. Neither of the re-matched estimates differ significantly from our original estimate, and as such do not seem to offer a substantive challenge to our findings.

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 an expanded definition of "low-carbon technologies", the result does not appear to change materially (see Table E.2). 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 E.2: 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 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 E.3, indicate that the EU ETS has not had a significant impact on patent quality.

Table E.3: Changes in quality of low-carbon patents

Additional citations per firm	2.25
	(-0.99, 17.99)

References

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

Abadie, A. & Imbens, G. W. (2006). Large Sample Properties of Matching Estimators for Average Treatment Effects. *Econometrica*, 74(1), 235–267.

Abrego, L. & Perroni, C. (2002). Investment subsidies and time-consistent environmental policy. *Oxford Economic Papers*, 54(4), 617.

ACE (Association for the Conservation of Energy) (2001). The climate change levy and the negotiated agreements. *Discussion Paper*, (DP05).

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

Acs, Z. J. & Audretsch, D. B. (1988). Innovation in Large and Small Firms: An Empirical Analysis. *The American Economic Review*, 78(4), 678–690.

Adar, Z. & Griffin, J. (1976). Uncertainty and the choice of pollution control instruments. *Journal of Environmental Economics and Management*, 3(3), 178–88.

Aghion, P., Dechezleprêtre, A., Hemous, D., Martin, R., & Reenen, J. V. (2012). Carbon Taxes, Path Dependency and Directed Technical Change: Evidence from the Auto Industry. *NBER Working Paper Series*, (18596).

Aghion, P., Veugelers, R., & Serre, C. (2009). Cold start for the green innovation machine. *Bruegel Policy Contribution*, (12), 1–12.

Agnolucci, P., Barker, T., & Ekins, P. (2004). Hysteresis and Energy Demand: the Announcement Effects and the effects of the UK Climate Change Levy. *Tyndall Centre Working Papers*, (51).

Alexeeva-Talebi, V. (2010). Cost pass-through in strategic oligopoly: Sectoral evidence for the EU ETS. *ZEW Discussion Paper*, (10-056), 1–50.

Ambec, S., Cohen, M. A., Elgie, S., & Lanoie, P. (2013). The Porter Hypothesis at 20: Can Environmental Regulation Enhance Innovation and Competitiveness? *Review of Environmental Economics and Policy*, 7(1), 2–22.

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

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

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

Arvanitis, S., Donzé, L., & Sydow, N. (2010). Impact of Swiss technology policy on firm innovation performance: an evaluation based on a matching approach. *Science and Public Policy*, 37(1), 63–78.

Bailey, I. & Rupp, S. (2006). The evolving role of trade associations in negotiated environmental agreements: the case of United Kingdom Climate Change Agreements. *Business Strategy and the Environment*, 15(1), 40–54.

Banzhaf, H. S., Burtraw, D., & Palmer, K. (2004). Efficient emission fees in the US electricity sector. *Resource and Energy Economics*, 26(3), 317–341.

Barker, T., Ekins, P., & Foxon, T. (2007). Macroeconomic effects of efficiency policies for energy-intensive industries: The case of the UK Climate Change Agreements, 2000–2010. *Energy Economics*, 29(4), 760–778.

Barrett, S. (2005). *Environment and statecraft: the strategy of environmental treaty-making*. Oxford University Press.

Bauman, Y., Lee, M., & Seeley, K. (2008). Does technological innovation really reduce marginal abatement costs? some theory, algebraic evidence, and policy implications. *Environmental and Resource Economics*, 40(4), 507–527.

Baumol, W. & Oates, W. (1971). The use of standards and prices for protection of the environment. *The Swedish Journal of Economics*, 73(1), 42–54.

Baumol, W. J. & Oates, W. E. (1979). *Economics, Environmental Policy, and the Quality of Life*. Prentice Hall College Div.

Bernstein, S. F. (2001). *The compromise of liberal environmentalism*. Columbia University Press.

Billewicz, W. Z. (1965). The Efficiency of Matched Samples: An Empirical Investigation. *Biometrics*, 21(3), 623–644.

Blundell, R., Griffith, R., & Windmeijer, F. (2002). Individual effects and dynamics in count data models. *Journal of Econometrics*, 108(1), 113–131.

Blyth, W. & Baron, R. (2003). *Green investment schemes: Options and issues*. Technical Report 9, OECD.

Bolin, B. (2007). *A History of the Science and Politics of Climate Change*. Cambridge University Press.

Bound, J., Cummins, C., Griliches, Z., Hall, B. H., & Jaffe, A. B. (1984). Who Does R&D and Who Patents? In Z. Griliches (Ed.), *R&D, Patents, and Productivity* chapter 2, (pp. 21–54). University of Chicago Press.

Bowen, A. & Rydge, J. (2011). Climate-change policy in the United Kingdom. *OECD Economic Survey of the United Kingdom*, 886.

Bréchet, T. & Meunier, G. (2012). Are clean technology and environmental quality conflicting policy goals? *European University at Saint Petersburg Working Paper Series*, (Ec-01/12).

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

Bruyn, S. M., Markowska, A., & Nelissen, D. (2010). *Will the Energy-intensive Industry Profit from EU ETS Under Phase 3?: Impacts of EU ETS on Profits, Competitiveness and Innovation*. Technical report, CE Delft.

Burton, E. & Sanjour, W. (1968). *A Cost-Effectiveness Study of Particulate and SOx Emission Control in the New York Metropolitan Area*. Technical report, Washington, DC: Ernst and Ernst.

Burton, E. & Sanjour, W. (1969a). *A Cost-Effectiveness Study of Air Pollution Abatement in the Greater Kansas City Area*. Technical report, Washington, DC; Ernst and Ernst.

Burton, E. & Sanjour, W. (1969b). Multiple Source Analysis of Air Pollution Abatement Strategies. *Federal Accountant*, XVIII, 48–69.

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

Burtraw, D., Krupnick, A., Mansur, E., Austin, D., & Farrell, D. (1998). Costs and benefits of reducing air pollutants related to acid rain. *Contemporary Economic Policy*, 16(4), 379–400.

Burtraw, D., Palmer, K., Bharvirkar, R., & Paul, A. (2002). The effect on asset values of the allocation of carbon dioxide emission allowances. *The Electricity Journal*.

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

Calel, R. (2011). Market-based instruments and technology choices: a synthesis. *Grantham Research Institute on Climate Change and the Environment Working Paper*.

Calel, R. (2013). Carbon markets: a historical overview. *Wiley Interdisciplinary Reviews: Climate Change*, 4(2), 107–119.

Calel, R. & Dechezleprêtre, A. (2012). Environmental Policy and Directed Technological Change: Evidence from the European carbon market. *CEP Discussion Paper*, (1141).

Cambridge Econometrics, Department of Applied Economics, University of Cambridge, & Policy Studies Institute (2005). Modelling the initial effects of the Climate Change Levy. *Report submitted to HM Customs and Excise*, 8.

Carlson, C., Burtraw, D., Cropper, M., & Palmer, K. L. (2000). Sulfur Dioxide Control by Electric Utilities: What Are the Gains from Trade? *Journal of Political Economy*, 108(6), 1292–1326.

Chay, K. Y. & Powell, J. L. (2001). Semiparametric censored regression models. *Journal of Economic Perspectives*, 15(4), 29–42.

Coase, R. (1959). The federal communications commission. *Journal of Law and Economics*, 2, 1–40.

Coase, R. (1960). The problem of social cost. *Journal of Law and Economics*, 3, 1–44.

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

Cochran, W. G. (1983). *Planning and Analysis of Observational Studies*. John Wiley & Sons.

Cole, M. A., Elliott, R. J., Okubo, T., & Zhou, Y. (2013). The carbon dioxide emissions of firms: A spatial analysis. *Journal of Environmental Economics and Management*, 65(2), 290–309.

Consulate Mumbai (2008). Carbon credits sufficient but not necessary for sustaining clean energy projects of major Indian business groups. Wikileaks reference ID: 08MUMBAI340.

Convery, F. J. (2009). Origins and Development of the EU ETS. *Environmental and Resource Economics*, 43(3), 391–412.

Cook, B. J. (1988). *Bureaucratic Politics and Regulatory Reform: The EPA and Emissions Trading*. Greenwood Press.

Cooper, R. N. (2010). Europe's emissions trading system. *The Harvard Project on Climate Agreements Discussion Paper Series*, (10-40).

Cramton, P. & Kerr, S. (2002). Tradeable carbon permit auctions: How and why to auction not grandfather. *Energy Policy*, 30(4), 333–345.

Crocker, T. D. (1966). The Structuring of Atmospheric Pollution Control Systems. In H. Wolozin (Ed.), *The economics of air pollution* chapter 5, (pp. 61–86). W. W. Norton, first edition.

Dales, J. H. (1968a). Land, water, and ownership. *The Canadian Journal of Economics / Revue canadienne d'Economique*, 1(4), 791–804.

Dales, J. H. (1968b). *Pollution, Property and Prices: An Essay in Policy-making and Economics*. Toronto: University of Toronty Press.

Daley, B. (2008). Emissions down, but lasting efforts may suffer. *The Boston Globe*.

de Muizon, G. & Glachant, M. (2004). The UK climate change levy agreements: Combining negotiated agreements with tax and emissions trading. In A. Baranzini & P. Thalmann (Eds.), *Voluntary approaches in climate policy*. Edward Elgar Publishing.

Dechezleprêtre, A., Glachant, M., Haščič, I., Johnstone, N., & 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. & Wahba, S. (1999). Causal effects in nonexperimental studies: Reevaluating the evaluation of training programs. *Journal of the American Statistical Association*, 94(448), 1053–1062.

Dehejia, R. H. & Wahba, S. (2002). Propensity Score-Matching Methods for Nonexperimental Causal Studies. *The Review of Economics and Statistics*, 84(1), 151–161.

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

Delarue, E., Ellerman, A., & D'haeseleer, W. (2010). Short-term CO$_2$ abatement in the European power sector: 2005-2006. *Climate Change Economics*, 1(2), 113–133.

Delarue, E., Voorspools, K., & 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.

Department for Business, Innovation & Skills, Office for National Statistics, & Northern Ireland Department of Enterprise, Trade & Investment (2012). *UK Innovation Survey, 1994-2010: Secure Data Service Access [computer file]*. Colchester, Essex: UK Data Archive [distributor], 2nd edition. SN: 6699.

Department of Energy & Climate Change (2011). *Quarterly Fuels Inquiry, 1993-2008: Secure Data Service Access [computer file]*. Colchester, Essex: UK Data Archive [distributor]. SN: 6898, http://dx.doi.org/10.5255/UKDA-SN-6898-1.

Department of Energy & Climate Change & Office for National Statistics (2012). *DECC Low Emissions RD Survey, 2008: Secure Data Service Access [computer file]*. Colchester, Essex: UK Data Archive [distributor]. SN: 6894, http://dx.doi.org/10.5255/UKDA-SN-6894-1.

Downing, P. B. & White, L. J. (1986). Innovation in pollution control. *Journal of Environmental Economics and Management*, 13(1).

Dresner, S., Jackson, T., & Gilbert, N. (2006). History and social responses to environmental tax reform in the United Kingdom. *Energy Policy*, 34(8), 930–939.

Dudek, D. J. & LeBanc, A. (1990). Offsetting New CO$_2$ Emissions: A Rational First Greenhouse Policy Step. *Contemporary Economic Policy*, 8(3), 29–42.

Egenhofer, C., Alessi, M., Georgiev, A., & Fujiwara, N. (2011). The EU Emissions Trading System and Climate Policy Towards 2050: Real Incentives to Reduce Emissions and Drive Innovation? *CEPS Special Reports*.

Ekins, P. & Etheridge, B. (2006). The environmental and economic impacts of the UK climate change agreements. *Energy Policy*, 34(15), 2071–2086.

Ellerman, A. & 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. (2007). US Experience with Emissions Trading. *CESifo DICE Report*.

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

Elsworth, R. & Worthington, B. (2010). *International Offsets and the EU 2009: An update on the usage of compliance offsets in the EU Emissions Trading Scheme*. Report, Sandbag Climate Campaign.

Emissions Trading Scheme Review Panel (2011). *Doing New Zealand's Fair Share. Emissions Trading Scheme Review 2011: Final report*. Wellington: Ministry for the Environment.

European Commission (2005). EU action against climate change: EU emissions trading—an open scheme promoting global innovation. http://ec.europa.eu/environment/climat/pdf/emission$_{t}rading2_{e}n.pdf$.

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

European Commission (2012). Emissions trading: annual compliance round-up shows declining emissions in 2011. Press Release IP/12/477.

European Environment Agency (2008). *Application of the Emissions Trading Directive by EU Member States — reporting year 2008*. Technical Report 13/2008.

Fankhauser, S., Hepburn, C., & Park, J. (2010). Combining multiple climate policy instruments: How not to do it. *Climate Change Economics*, 01(03), 209–225.

Fischer, C. & Newell, R. G. (2008). Environmental and technology policies for climate mitigation. *Journal of Environmental Economics and Management*, 55(2), 142–162.

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

Fleming, J. R. (1998). *Historical Perspectives on Climate Change*. Oxford University Press.

Forslid, R., Okubo, T., & Ulltveit-Moe, K. H. (2011). Why are firms that export cleaner? International trade and CO_2 emissions. *CEPR Discussion Paper*, (8583).

Fowlie, M. (2010). Emissions Trading, Electricity Restructuring, and Investment in Pollution Abatement. *American Economic Review*, 100(3), 837–869.

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

Gail, M. H. (1972). Does Cardiac Transplantation Prolong Life? A Reassessment. *Annals of Internal Medicine*, 76(5), 815–817.

Garnaut, R. (2011). Update paper 7: Low emissions technology and the innovation challenge. In *Garnaut Climate Change Review – Update 2011*. Commonwealth of Australia.

Gorman, H. & Solomon, B. (2002). The Origins and Practice of Emissions Trading. *Journal of Policy History*, 14(3), 293–320.

Greenstone, M. & 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. (1989). *The greenhouse effect: negotiating targets*. Royal Institute of International Affairs.

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

Gurmu, S. & Pérez-Sebastián, F. (2008). Patents, R&D and lag effects: evidence from flexible methods for count panel data on manufacturing firms. *Empirical Economics*, 35(3), 507–526.

Hagedoorn, J. & Cloodt, M. (2003). Measuring innovative performance: is there an advantage in using multiple indicators? *Research Policy*, 32(8), 1365–1379.

Hahn, R. (1984). Market power and transferable property rights. *The Quarterly Journal of Economics*, 99(4), 753–765.

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

Hall, B. H. & Mairesse, J. (1995). Exploring the relationship between R&D and productivity in French manufacturing firms. *Journal of Econometrics*, 65(1), 263–293.

Hanemann, M. (2009). The role of emissions trading in domestic climate policy. *The Energy Journal*, 30(2), 73–108.

Hanemann, M. (2010). Cap-and-trade: a sufficient or necessary condition for emission reduction? *Oxford Review of Economic Policy*, 26(2), 225–252.

Hansen, B. B. (2004). Full Matching in an Observational Study of Coaching for the SAT. *Journal of the American Statistical Association*, 99(467), 609–618.

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

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

Hausman, J., Hall, B. H., & Griliches, Z. (1984). Econometric Models for Count Data with an Application to the Patents-R & D Relationship. *Econometrica*, 52(4), 909–938.

Heckman, J., Ichimura, H., Smith, J., & Todd, P. (1998a). Characterizing Selection Bias Using Experimental Data. *Econometrica*, 66(5), 1017–1098.

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

Helm, D., Hepburn, C., & Mash, R. (2003). Credible carbon policy. *Oxford Review of Economic Policy*, 19(3), 438–450.

Hepburn, C. (2007). Carbon Trading: A Review of the Kyoto Mechanisms. *Annual Review of Environment and Resources*, 32(1), 375–393.

Hepburn, C., Grubb, M., Neuhoff, K., Matthes, F., & Tse, M. (2006). Auctioning of EU ETS phase II allowances: how and why? *Climate Policy*, 6(1), 137–160.

Hervé-Mignucci, M. (2011). Operating and Financial Investments by European Utilities Over 2004-2009: What Role for European Mitigation Policies? *Mission Climat Working Paper*, (2011-9).

Hibbard, P. J., Tierney, S. F., Okie, A. M., & Darling, P. G. (2011). *The Economic Impacts of the Regional Greenhouse Gas Initiative on Ten Northeast and Mid-Atlantic States*. Technical report, Analysis Group.

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

Hill, M., McAulay, L., & Wilkinson, A. (2005). UK emissions trading from 2002–2004: corporate responses. *Energy & Environment*, 16(6), 993–1007.

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

Hoffman, A. (2005). Climate change strategy: The business logic behind voluntary greenhouse gas reductions. *California Management Review*, 47(3), 21–46.

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

Intellectual Property Office (2013). PATENTS: Application Guide.

International Energy Agency (2012). *Energy Technology Perspectives 2012: Pathways to a Clean Energy System*. IEA/OECD Paris.

IPA Energy Consulting (2005). Implications of the EU Emissions Trading Scheme for the UK Power Generation Sector. *Report to the UK Department of Trade and Industry*.

IPCC (1996). *Climate Change 1995: Economic and Social Dimensions of Climate Change: Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

Jaffe, A., Newell, R., & Stavins, R. (2005). A tale of two market failures: Technology and environmental policy. *Ecological Economics*, 54(2-3), 164–174.

Jaffe, A. B. & Palmer, K. (1997). Environmental Regulation and Innovation: A Panel Data Study. *The Review of Economics and Statistics*, 79(4), 610–619.

Jaffe, J., Ranson, M., & Stavins, R. N. (2009). Linking tradable permit systems: a key element of emerging international climate policy architecture. *Ecology Law Quarterly*, 36, 789–851.

Jaraite, J. & Maria, C. D. (2011). Did the EU ETS Make a Difference? A Case Study of Ireland and Lithuania. *Presented at EARE 2011, cited with author permission*.

Johnstone, N., Haščič, I., & 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.

Kennedy, P. & Laplante, B. (1999). Environmental policy and time consistency: emissions taxes and emissions trading. *World*.

Kennedy, P. W. & Laplante, B. (1995). Equilibrium incentives for adopting cleaner technology under emissions pricing. *World*.

Kerr, S. & Newell, R. G. (2003). Policy-Induced Technology Adoption: Evidence from the U.S. Lead Phasedown. *The Journal of Industrial Economics*, 51(3), 317–343.

Kettner, C., Kletzan-Slamanig, D., & Köppl, A. (2011). The EU Emission Trading Scheme–Sectoral allocation patterns and the effects of the economic crisis. *WIFO Working Papers*, (408).

Khan, B. Z. (2012). Of Time and Space: Technological Spillovers among Patents and Unpatented Innovations in the Nineteenth Century. *Working paper*.

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

Kossoy, A. & Guigon, P. (2012). *State and Trends of the Carbon Market 2012*. Annual report, World Bank.

Laffont, J. & Tirole, J. (1996a). Pollution permits and compliance strategies. *Journal of Public Economics*, 62(1-2), 85–125.

Laffont, J. & Tirole, J. (1996b). Pollution permits and environmental innovation. *Journal of Public Economics*, 62(1-2), 127–140.

LaLonde, R. J. (1986). Evaluating the Econometric Evaluations of Training Programs with Experimental Data. *The American Economic Review*, 76(4), 604–620.

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

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

Lanjouw, J. O. & Schankerman, M. (2004). Patent Quality and Research Productivity: Measuring Innovation with Multiple Indicators. *The Economic Journal*, 114(495), 441–465.

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

Lansink, A. O. & Silva, E. (2003). CO2 and Energy Efficiency of Different Heating Technologies in the Dutch Glasshouse Industry. *Environmental and Resource Economics*, 24(4), 395–407.

Lewis, M. C. & Curien, I. (2010). *Carbon Emissions Hard to Credit: ETS Offsets Use Again in Spotlight*. Technical report, Deutsche Bank.

Li, Y., Propert, K., & Rosenbaum, P. (2001). Balanced risk set matching. *Journal of the American Statistical Association*, 96(455), 870–882.

Linacre, N., Kossoy, A., & Ambrosi, P. (2011). State and trends of the carbon market 2011. (pp. 1–84).

List, J. A., Millimet, D. L., Fredriksson, P. G., & 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.

Löfgren, Å., Wråke, M., Hagberg, T., & Roth, S. (2013). The Effect of EU-ETS on Swedish Industry's Investment in Carbon Mitigating Technologies. *University of Gothenburg Working Papers in Economics*, (565).

Mäler, K. (1991). *The Acid Rain Game*. Beijer International Institute of Ecological Economics, the Royal Swedish Academy of Sciences.

Malueg, D. (1989). Emission credit trading and the incentive to adopt new pollution abatement technology. *Journal of Environmental Economics and Management*, 16(1), 52–57.

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

Marsiliani, L. & Renstrom, T. (2000). Time inconsistency in environmental policy: tax earmarking as a commitment solution. *The Economic Journal*, 110, 123–138.

Martin, B. R. (1996). The use of multiple indicators in the assessment of basic research. *Scientometrics*, 36(3), 343–362.

Martin, R. (2006). Energy efficiency and productivity of UK businesses: Evidence from a new matched database. *DTI Occasional Paper*, (5).

Martin, R., de Preux, L., & Wagner, U. (2009). The impacts of the Climate Change Levy on business: evidence from microdata. *CEP Discussion Paper*, (917).

Martin, R., Muûls, M., de Preux, L. B., & Wagner, U. J. (2012a). Industry Compensation under Relocation Risk. A Firm-level Analysis of the EU Emissions Trading Scheme. *CEP Discussion Paper*, (1150).

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

Martin, R., Muûls, M., & Wagner, U. (2012b). An evidence review of the EU Emissions Trading System, focussing on effectiveness of the system in driving industrial abatement. *Department of Energy & Climate Change Independent Report*.

Martin, R. & Wagner, U. (2009). Climate change policy and innovation. *Centre for Economic Performance*.

Martinez, K. K. & Neuhoff, K. (2005). Allocation of carbon emission certificates in the power sector: how generators profit from grandfathered rights. *Climate Policy*, 5(1), 61–78.

Mash, R., Helm, D., & Hepburn, C. (2003). Time-inconsistent environmental policy and optimal delegation. *Oxford University Department of Economics Discussion Paper*, (175).

Meckling, J. (2011). *Carbon Coalitions: Business, Climate Politics, and the Rise of Emissions Trading*. MIT Press.

Metcalf, G. E. (2009). Tax Policies for Low-Carbon Technologies. *National Tax Journal*, LXII(3), 519–533.

Michaelowa, A. & Purohit, P. (2007). Additionality determination of Indian CDM projects: Can Indian CDM project developers outwit the CDM Executive Board? *Climate Strategies Discussion Paper*, (CDM-1).

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

Montero, J. (2002a). Market structure and environmental innovation. *Journal of Applied Economics*, 5(2), 293–325.

Montero, J. (2002b). Permits, Standards, and Technology Innovation. *Journal of Environmental Economics and Management*, 44(1), 23–44.

Montgomery, W. D. (1972). Markets in licenses and efficient pollution control programs. *Journal of Economic Theory*, 5(3), 395–418.

Moreno-Bromberg, S. & Taschini, L. (2011). Pollution Permits, Strategic Trading and Dynamic Technology Adoption. *CESifo Working Paper Series*, (3399).

Moser, P. (2005). How Do Patent Laws Influence Innovation? Evidence from Nineteenth-Century World's Fairs. *The American Economic Review*, 95(4), 1214–1236.

Moser, P. (2012). Innovation without Patents: Evidence from World's Fairs. *Journal of Law and Economics*, 55(1), 43–74.

Moser, P. (2013). Patents and Innovation: Evidence from Economic History. *The Journal of Economic Perspectives*, 27(1), 23–44.

Muller, N. Z. & Mendelsohn, R. (2009). Efficient Pollution Regulation: Getting the Prices Right. *The American Economic Review*, 99(5), 1714–1739.

National Audit Office (2004). The UK Emissions Trading Scheme: A New Way to Combat Climate Change.

National Audit Office (2007). The Climate Change Levy and Climate Change Agreements.

Neuhoff, K., Åhman, M., Betz, R., Cludius, J., Ferrario, F., Holmgren, K., Pal, G., Grubb, M., Matthes, F., Rogge, K., Sato, M., Schleich, J., Sijm, J., Tuerk, A., Kettner, C., & Walker, N. (2006a). Implications of announced phase II national allocation plans for the EU ETS. *Climate Policy*, 6(4), 411–422.

Neuhoff, K. & De Vries, L. (2004). Insufficient incentives for investment in electricity generations. *Utilities Policy*, 12(4), 253–267.

Neuhoff, K., Ferrario, F., Grubb, M., Gabel, E., & Keats, K. (2006b). Emission projections 2008–2012 versus national allocation plans II. *Climate Policy*, 6(4), 395–410.

Neuhoff, K., Martinez, K. K., & Sato, M. (2006c). Allocation, incentives and distortions: the impact of EU ETS emissions allowance allocations to the electricity sector. *Climate Policy*, 6(1), 73–91.

New Energy Finance (2009). *Emissions from the EU ETS down 3% in 2008*. Press release.

Newell, R., Jaffe, A., & Stavins, R. (1999). The Induced Innovation Hypothesis and Energy-Saving Technological Change. *Quarterly Journal of Economics*, 114(3), 941–975.

Newell, R. G. (2010). The role of markets and policies in delivering innovation for cliamte change mitigation (draft). *For Oxford Review of Economic Policy*, 26(2), 253—269.

Niskanen, W. A. (1977). *Bureaucracy & representative government*. Aldine De Gruyter.

Nordhaus, W. (1974). Resources as a constraint on growth. *The American Economic Review*, 64(2).

Nordhaus, W. (1977a). Economic growth and climate: the carbon dioxide problem. *The American Economic Review*, 67(1), 341–346.

Nordhaus, W. (1977b). Strategies for the control of carbon dioxide. *Cowles Foundation Discussion Papers*, (443).

Nordhaus, W. (1979). *The efficient use of energy resources*. Yale University Press.

Nye, M. (2008). Understanding business participation in UK emissions trading: dimensions of choice and influence on market development. In R. Antes & P. Letmathe (Eds.), *Emissions trading: institutional design, decision making and corporate strategies*. Springer.

Nye, M. & Owens, S. (2008). Creating the UK emission trading scheme: motives and symbolic politics. *European Environment*, 18(1), 1–15.

Oates, W. E. & Strassman, D. L. (1984). Effluent fees and market structure. *Journal of Public Economics*, 24(1), 29–46.

Oberndorfer, U., Alexeeva-Talebi, V., & Löschel, A. (2010). Understanding the Competitiveness Implications of Future Phases of EU ETS on the Industrial Sectors. *ZEW Discussion Paper*, (10-044).

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

Office for National Statistics (2011). *Business Expenditure on Research and Development, 1994-2008: Secure Data Service Access [computer file]*. Colchester, Essex: UK Data Archive [distributor]. SN: 6690, http://dx.doi.org/10.5255/UKDA-SN-6690-1.

Office for National Statistics (2012). *Business Structure Database, 1997-2011: Secure Data Service Access [computer file]*. Colchester, Essex: UK Data Archive [distributor], 3rd edition. SN: 6697.

Olsen, K. H. (2007). The Clean Development Mechanism's contribution to sustainable development: a review of the literature. *Climatic Change*, 84(1), 59–73.

Pacala, S. & Socolow, R. (2004). Stabilization wedges: solving the climate problem for the next 50 years with current technologies. *Science*, 305(5686), 968–972.

Pakes, A. & Griliches, Z. (1984). Patents and RD at the Firm Level: A First Look. In Z. Griliches (Ed.), *R&D, Patents and Productivity* chapter 3, (pp. 55–72). University of Chicago Press.

Parisi, M. L., Schiantarelli, F., & Sembenelli, A. (2006). Productivity, innovation and R&D: Micro evidence for Italy. *European Economic Review*, 50(8), 2037–2061.

Pearce, D. (2006). The political economy of an energy tax: The United Kingdom's Climate Change Levy. *Energy Economics*, 28(2), 149–158.

Perino, G. & Requate, T. (2012). Does more stringent environmental regulation induce or reduce technology adoption? When the rate of technology adoption is inverted U-shaped. *Journal of Environmental Economics and Management*, 64(3), 456–467.

Petsonk, A. & 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*, (pp. 1–23).

Pizer, W. A. & 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. (2006). International innovation and diffusion of air pollution control technologies: the effects of NO_X and SO_2 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. & 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., & 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).

Requate, T. (2005). Dynamic incentives by environmental policy instruments–a survey. *Ecological economics*, 54(2-3), 175–195.

Requate, T. & Unold, W. (2003). Environmental policy incentives to adopt advanced abatement technology: Will the true ranking please stand up? *European Economic Review*, 47(1), 125–146.

RGGI Inc. (2011). Regional Investment of RGGI CO_2 Allowance Proceeds, 2011.

RGGI Inc. (2013a). RGGI 2012 Program Review: Summary of Recommendations to Accompany Model Rule Amendments.

RGGI Inc. (2013b). RGGI States Propose Lowering Regional CO2 Emissions Cap 45%, Implementing a More Flexible Cost-Control Mechanism.

Richardson, B. & Chanwai, K. (2003). The UK's climate change levy: Is it working? *Journal of Environmental Law*, 15(1), 39–58.

Roberts, M. & Spence, M. (1976). Effluent charges and licenses under uncertainty. *Journal of Public Economics*, 5, 193–208.

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

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

Rosenbaum, P. R. (1989). Optimal Matching for Observational Studies. *Journal of the American Statistical Association*, 84(408), 1024–1032.

Rosenbaum, P. R. (2009). *Design of Observational Studies*. Springer.

Rosenbaum, P. R. & Rubin, D. B. (1983). The central role of the propensity score in observational studies for causal effects. *Biometrika*, 70(1), 41–55.

Rubin, D. (1979). Using multivariate matched sampling and regression adjustment to control bias in observational studies. *Journal of the American Statistical Association*, 74(366), 318–328.

Rubin, D. B. (1973). Matching to Remove Bias in Observational Studies. *Biometrics*, 29(1), 159–183.

Sandbag (2011). Carbon Fat Cats 2011: The Companies profiting from the EU Emissions Trading Scheme.

Schleich, J. & 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*, (pp. 1495–1506).

Schleich, J., Rogge, K., & Betz, R. (2009). Incentives for energy efficiency in the EU Emissions Trading Scheme. *Energy Efficiency*, 2(1), 37–67.

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

Schneider, L. R. (2011). Perverse incentives under the CDM: an evaluation of HFC-23 destruction projects. *Climate Policy*, 11(2), 851–864.

Schwarze, R. (2000). Activities implemented jointly: another look at the facts. *Ecological Economics*, 32(2), 255–268.

Scotchmer, S. (2011). Cap-and-Trade, Emissions Taxes, and Innovation. *Innovation Policy and the Economy*, 11(1), 29–54.

Scotney, R., Chapman, S., Hepburn, C., & Jie, C. (2012). Carbon Markets and Climate Policy in China: China's pursuit of a clean energy future. *The Climate Institute Working Paper*.

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.

Sijm, J., Neuhoff, K., & Chen, Y. (2006). CO_2 cost pass-through and windfall profits in the power sector. *Climate Policy*, 6(1), 49–72.

Skjaerseth, J. & Wettestad, J. (2008). *EU emissions trading: initiation, decision-making and implementation*. Ashgate Pub Co.

Smale, R., Hartley, M., Hepburn, C., Ward, J., & Grubb, M. (2006). The impact of CO_2 emissions trading on firm profits and market prices. *Climate Policy*, 6(1), 31–48.

Smith, H. (1997). Matching with multiple controls to estimate treatment effects in observational studies. *Sociological Methodology*, 27, 325–353.

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

Smith, S. & Swierzbinski, J. (2007). Assessing the performance of the UK Emissions Trading Scheme. *Environmental and Resource Economics*, 37(1), 131–158.

Söderholm, P. (2010). Technological Change and Carbon Markets. *Low Carbon Economy*, 1, 80–85.

Sorrell, S. (2002). The Climate Confusion: Implications of the EU Emissions Trading Directive for the UK Climate Change Levy and Climate Change Agreements. *SPRU working paper, University of Sussex*.

Sorrell, S. (2003). Back to the drawing board? Implications of the EU emissions trading directive for UK climate policy. *SPRU working paper, University of Sussex*.

Sorrell, S., Smith, A., Betz, R., Walz, R., Bemare, C., Quirion, P., Sijm, J., Konidari, D. M. P., Vassos, S., Haralampopoulos, D., & Pilinis, C. (2003). *Interaction in EU Climate Policy*. Technical Report EVK2-CT-2000-0067, SPRU.

Stavins, R. (1988). *Project 88 – Harnessing Market Forces to Protect Our Environment: Initiatives For The New President*. Technical report, A Public Policy Study sponsored by Senator Timothy E. Wirth, Colorado, and Senator John Heinz, Pennsylvania, Washington, D.C.

Stavins, R. (2003). *Experience with market-based environmental policy instruments*, volume 1, chapter 9. Elsevier Science B.V.

Stavins, R. (2007). A US cap-and-trade system to address global climate change. *Regulatory Policy Program Working Paper*, (RPP-2007-04).

Stern, N. (2007). *The economics of climate change: the Stern review*. Cambridge University Press.

Storrøsten, H. B. (2010). *Incentives to invest in abatement technology. A tax versus emissions trading under imperfect competition*. Technical report, Research Department of Statistics Norway.

Stowell, D. (2005). *Climate Trading: Development of Kyoto Protocol Markets*. Palgrave Macmillan.

Swisher, J. N. & Masters, G. M. (1989). International Carbon Emission Offsets: A tradeable currency for climate protection services. *Civil Engineering Department, Stanford University*, (0031).

Tietenberg, T. H. (1985). *Emissions Trading: An Exercise in Reforming Pollution Policy*. Technical report, Washington DC: Resources for the Future.

Tomás, R., Ribeiro, F. R., Santos, V., Gomes, J., & Bordado, J. (2010). Assessment of the impact of the European CO_2 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*, (pp. 172–187).

Transparency International (2011). *Global Corruption Report: Climate Change*. Earthscan, London.

Tripp, J. & Dudek, D. (1989). Institutional guidelines for designing successful transferable rights programs. *Yale Journal on Regulation*.

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

Varma, A. (2003). UK's climate change levy: cost effectiveness, competitiveness and environmental impacts. *Energy Policy*, 31(1), 51–61.

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

Victor, D. (1991). Limits of market-based strategies for slowing global warming: the case of tradeable permits. *Policy Sciences*, 24, 199–222.

Vogt-Schilb, A. & Hallegatte, S. (2011). When starting with the most expensive option makes sense: use and misuse of marginal abatement cost curves. *World Bank Policy Research Working Papers*, (5803).

von Malmborg, F. & Strachan, P. A. (2005). Climate policy, ecological modernization and the UK emission trading scheme. *European Environment*, 15(3), 143–160.

Voß, J.-P. (2007). Innovation processes in governance: the development of 'emissions trading' as a new policy instrument. *Science and Public Policy*, 34(5), 329–343.

Wara, M. (2007a). Is the global carbon market working? *Nature*, 445(8), 595–569.

Wara, M. (2007b). Measuring the Clean Development Mechanism's Performance and Potential. *UCLA Law Review*, 55, 1759–1803.

Weber, T. A. & Neuhoff, K. (2010). Carbon markets and technological innovation. *Journal of Environmental Economics and Management*, 60(2), 115–132.

Weitzman, M. (1974). Prices vs. quantities. *The Review of Economic Studies*, 41(4), 477–491.

Williamson, O. E. (1963). Managerial discretion and business behavior. *The American Economic Review*, 53(5), 1032–1057.

Yohe, G. W. (1977). Comparisons of price and quantity controls: A survey. *Journal of Comparative Economics*, 1(3), 213–233.

Zachmann, G., Ndoye, A., & Abrell, J. (2011). Assessing the impact of the EU ETS using firm level data. *Bruegel Working Papers*.