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Survey

The innovation effects of environmental policy instruments — A typical case of the blind men and the elephant?

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ABSTRACT

In this paper we examine the innovation effects of environmental policy instruments in four literatures: theoretical models on incentives for eco-innovation, econometric studies based on observed data, survey analysis based on stated information and technology case studies. The aim of this paper is to critically examine the methods and the results. We argue that the case studies literature, even when its results are specific and difficult to generalise, is a necessary source of empirical evidence about policy impacts and the factors responsible for these impacts, pointing to issues that are neglected in the theoretical and econometric literature such as the specifics of the innovation context and policy interaction effects. The paper states five synthesised findings and makes a plea for multi-method analysis. One other important synthesised finding is that the influence of market-based instruments on innovation (such as emission trading and taxes) is far weaker than assumed.

1. Introduction

The economic desirability of environmental policy instruments depends on (1) the value of the expected environmental benefits, and (2) the costs at which environmental improvements are achieved. Both the environmental gains and costs depend on technical change, which means that from a dynamic efficiency point of view a relevant criterion for the evaluation of environmental policy is (3) the extent to which it stimulates innovation at the supply side or user side.

Different research streams have investigated the role of environmental policy instruments in influencing the innovation process. The research streams can be seen as belonging to one of four bodies of literature: (a) theoretical models of incentives for eco-innovation, (b) econometric studies about the effects of environmental policy instruments on technical change based on official statistical data and (c) case studies of the effects of environmental policy instruments on innovation, and (d) surveys of firms seeking to distinguish the influence of different environmental policy instruments, amongst various other factors, on eco-innovation. Eco-innovation is a broad concept, comprising innovation in pollution control (new, better or cheaper abatement technology), green products, cleaner process technologies, green energy technology and transport technologies and waste-reduction and handling techniques. The innovation may be new to the world or new to the adopter, an improvement of what exists or something radically new. As we will see, these distinctions are insufficiently used.

In this paper we examine the innovation effects of environmental policy instruments reported in four literatures. We also look for evidence to the claim that market-based instrument are superior to regulatory ones in promoting environmental innovation (where we look in great detail to the effects of the EU emission trading system for carbon whose innovation effects have been disappointing). The goals of the paper are to offer synthesised findings and to make recommendations for how to study the relationship between environmental innovation and policy.

In Sections 2 to 5 we describe the state-of-art of these four literatures. Section 6 discusses research based on mixed-methods which in our view deserve to be used more. Conclusions about the link between environmental policy instruments and innovation are offered in Section 7 in the form of synthesised findings. Methodological lessons and recommendations for research are provided in Section 8.

2. Theoretical Models of the Incentives for Innovation in Pollution Control

Innovation in pollution control and prevention is investigated in theoretical models of the incentives for such innovation. The theoretical literature compares policy instruments of equal stringency, as a maintained assumption. Cost savings under the different regulatory regimes are indicative for the probability that innovation in pollution control will occur. Innovation in pollution control is in fact modelled as a downward shift in the marginal cost curve of emission reduction — not just for some infra-marginal units of control.

The seminal study in this field is Milliman and Prince (1989) who assess and rank firm incentives to promote technological change in pollution control for polluting innovators, non-innovators and outside suppliers under two appropriability regimes (with and without patent protection), before and after optimal agency control, for all five

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regulatory regimes. They find that incentives under emission taxes and auctioned permits are equal to or higher than incentives under direct controls, free permits and emission subsidies in all cases, except for control adjustment with a non-industry innovator. Moreover only emission taxes and auctioned permits clearly reward positive gains to an industry innovator from the entire process of technological change by providing economic incentives for continuous innovation.

The superiority of incentive-based instruments is called into question by later studies. For instance the study by Fischer et al. (2003) found that no unequivocal ranking was possible between pollution taxes, auctioned permits and free (grandfathered) permits. The relative welfare ranking of instruments depends on the costs of innovation, the extent to which innovations can be imitated, the slope and level of the marginal environmental benefit function, and the number of pollution firms.

Requate and Unold (2003) and Requate (2005) provided a comprehensive review on the theoretical inquiries on the incentives for adoption and development (including R&D) of innovations provided by environmental policy. Requate (2005) examined in total 28 different models and concludes that "it seems to be difficult to draw clear conclusions on which policy instruments dominate other policy instruments. I think, however, one can draw the main conclusion that instruments which provide incentives through the price mechanism, by and large, perform better than command and control policies" (Requate, 2005, p. 193). Requate also observed that some relevant aspects like the innovation output market and the conflicts between short and long term incentives provided by environmental policy instruments are missing in traditional models and they should be brought into the analysis.

3. Results from Econometric Studies Using Observed Data

The econometric studies look at real outcomes of real policies and have been used to study a broader range of eco-innovations. They therefore may be used to examine the effects of environmental policies on products, clean processes and waste management activities. Most studies use patents as the measure for innovation.

Reasons of space prevent us from providing a survey of our own. Instead of giving our summary we present the conclusions of two authoritative studies together with the results from two important studies into the innovation effects of emission trading in the USA and Europe. The first survey of econometric studies is that of Jaffe et al. (2002a, 2002b). It is not exclusively limited to econometric studies but they feature prominently in it. The focus is on the US. The main conclusion of this study is that "market-based instruments for environmental protection are likely to have significantly greater, positive impacts over time than command-and-control approaches on the invention, innovation, and diffusion of desirable, environmentally-friendly technologies"(Jaffe et al., 2002a, 2002b).

The findings of more recent studies are incorporated in the OECD report "Impacts of environmental policy instruments on technological change" prepared by Vollebergh (2007). The OECD report is an updated survey of the empirical literature addressing the question whether there is any evidence that different environmental policy instruments are having different effects on the rate and direction of technological change.

The main conclusion of the OECD review is that environmental regulation has a demonstrated impact on technological change in general. Effects on invention, innovation and diffusion of technologies are clearly observable (Vollebergh, 2007, p. 5). With regard to the hypothesised superiority of market-based mechanism, it is stated that it is difficult to compare the impacts of different instruments, because the studies analysed vary greatly in methods and the instruments are different in design features and local circumstances (Vollebergh, 2007, p. 23). It is said that "the common (and rather broad) distinction between command and control regulations and market-based instruments may sometimes be too general, and may require modification. Nevertheless, in choosing between both sets of instruments, it is still important to note that *financial incentives for technology development are usually stronger under market-based instruments* (e.g. a tax)" (Vollebergh, 2007, p.3, our italics). The proper design of instruments is said to be extremely important.[1]

Few econometric studies based on hard data have compared the influence of different policies on innovation in a certain technology. Exceptions are Greene (1990), Popp (2003) and Newell et al. (1999). Greene (1990) develops a statistical test to discriminate between price and regulatory effects on the fuel economy of American cars and light trucks in the 1978–1989 period, finding that the standards were at least twice as important as market trends in prices (hypothetical taxes).[2] Popp (2003) compared patents before and after passage of the 1990 Clean Air Act which established a market for SO_2 permit trading in the US. Popp finds that the level of number of successful patent applications for Flue Gas Desulphurisation Units fell after the introduction of sulphur trading but that there was an increase in patents in higher control efficiencies. Newell et al. (1999) studied the influence of energy prices and non-price regulatory constraints (in the form of minimum energy efficiency requirements and policy labelling) on the energy efficiency of air conditioners and gas boilers findings. Energy price increases and energy efficiency standards were both found to have a positive influence on energy efficiency improvement although their influence was not in all cases significant and the same across products. A substantial amount of improvement could not be explained and was referred to as "autonomous". These mixed findings do not unequivocally support the conclusion of Vollebergh (2007) and Jaffe et al. (2002a, 2002b) of the superiority of market based instruments, which appears to be based on economic assumptions and evidence of price incentives having an impact on technical change.

It is also interesting to look at the innovation effects in low-carbon technologies of the European Union's Emission Trading Scheme (EU ETS). The issue of innovation effects of the EU ETS is of great significance for the reason that it is the world's biggest tradable permit scheme and the main instrument of climate policy in the EU. After three years of pilot application overall Europe (2003–2005), a series of adjustments and improvement in its design, the ETS is now fully operational in 27 Member States and a significant amount of data on the emissions of the installations covered and CO_2 market prices is available.

The paper from Calel and Dechezleprêtre (2011) is based on the preliminary analysis of patents protecting low-carbon technologies. The authors combine difference-in-differences and matching methods to compare the patenting activities of 233 firms that operate installations covered by the EU ETS in Belgium, France, Germany, and the UK with those of 12,427 similar but unregulated firms. The comparison between regulated and unregulated firms controls for country-specific and sector-specific differences in market and regulatory environment. Patent data are drawn from the European Patent Office PATSTAT database which includes nearly 385,000 patents. The EPO classification identifies low-carbon energy technologies (renewable energy, cleaner coal, nuclear energy, etc.) and other energy efficiency technologies, that represented a share of just over 3% of all the patents filed in 1980, on the back of the third oil shock, subsequently falling to around 2%. The results of this analysis of the patenting activity suggest that companies anticipated the launch of the ETS by increasing their innovative activity, mainly in low-carbon technologies, before the starting of ETS. The EU ETS has had a positive effect on innovation in general, and in particular on low-carbon innovation, especially in France and Germany. After 1997, the share of low-carbon patents took off amongst ETS firms, rising faster than general patents. In particular the empirical findings suggest that there were more

[1] This conclusion, which is also found in Popp et al. (2009) has been taken up by technological change economists, for example, Johnstone and Hascic (2009).

[2] According to Pakes et al. (1993) the increase in miles per gallon was due to changes in the mix of vehicles in the market, a factor not accounted for in the analysis of Greene (1990).

additional patents per year between 2003 and 2005 than either before or after this period. Patenting of low-carbon technologies thus appears to have peaked between 2003 (the year of introduction of the EU ETS Directive) and 2005. The decline observed after 2005 was interpreted as the result of diminishing marginal returns, or as a reaction to the fact that ETS resulted to be less stringent than expected. These are important empirical findings, to which we will return when we discuss the results of other studies using a different methodology.

Econometric analysis is uniquely suited for analysing large sets of data, but any econometric analysis is as good as its data (and model structure). For analysing the topic at hand – the innovation effects of particular policies – there are three particular problems for econometric analysis. The first problem has to do with the difficulty of measuring environmental policy. It is very hard to incorporate design aspects of environmental policy instruments in the econometric analysis (strictness, enforcement, differentiation of standards or taxes with regard to type of polluter, and instrument combination where the effects depend on synergies). For environmental regulation, the most common proxy employed in econometric analysis is PAC (pollution abatement cost) that measures the expenditures for achieving compliance (used *inter alia* by Höglund Isaksson, 2005; Lanjouw and Mody, 1996; Shadbegian and Gray, 2005). As pointed out by Rennings (2000) regulatory compliance expenditures fall short of providing a truly exogenous measure, since PAC reflects the nature of an industry's response to environmental regulation. Other studies (Becker and Henderson, 2000; Greenstone, 2002) use “attainment status of US counties” as a proxy for regulatory stringency. Brunnermeier and Cohen (2003) used the number of inspections as a measure for the intensity of regulation. De Vries and Withagen (2005) used dummy variables for years in which an important environmental act took effect, which allow them to assess the influence of each of various acts. Newell et al. (1999) also used dummies for policy discontinuities, a reasonable but nonetheless crude measure.

The second methodological weakness concerns the measurement of innovation. Between the studies comprehended in the OECD survey, only one (Newell et al., 1999) measures innovation output (based on trade journal information about new product models) instead of inventive activity (patents) or innovation input measures (R&D). However, the majority of environmental innovations are not patented and thus missed,[3] and data on environmental R&D is often not available. The other indicators used relate to firm-internal characteristics like knowledge stocks or indicators of a firm's economic performance such as productivity, investments, operating costs or marginal abatement costs. These indicators are well-established in the innovation literature, however each of them has its limits. The influence of some relevant factors shaping the linkage between environmental policy and innovation cannot be established with general indicators such R&D, which are an input measure, not an output measure. Studies relying on RTD in a certain sector will fail to capture research and innovation realised outside the sector affected by regulation. Patents can be used for measuring inventions in pollution control technologies and alternative energy technologies but they are a poor indicator for inventive activity in the area of process integrated environmentally superior technologies (Oltra et al., 2010).

The third limitation is that the econometric studies based on observed data cannot capture all relevant factors in the analysis, as many of them are not observable, such as business expectations (about market demand for innovation and government support for it), the matrix of institutions which operates on companies and innovation capability of companies acting as a constraint and shaping factor. With special efforts some of these aspects can be brought into the analysis increasing the relevance of the study.[4]

4. Results from Technology Case Studies Examining Innovation Impacts of Identifiable Environmental Policies

We now come to talk about the case study literature looking at real policies and the multitude of factors at work, using interviews as an important source of information for establishing motivations and relevant factors behind eco-innovation.

Contributions are dispersed and already existing systematic reviews are not very up-to-date (Ashford et al., 1985; Kemp, 1997). A wide set of recent empirical studies has been scanned for this purpose, and some of the evidences and outcomes are presented here in order to show the insights emerging from this literature. The findings of the case studies call into question the conclusions from the other types of literature and helps to provide a more comprehensive and realistic picture of the effects of environmental regulations on the eco-innovation process.

The first important study on environmental policy and innovation bringing together empirical evidence about ten regulatory cases in the US is Ashford et al. (1985). The authors provided a history of environmental regulation affecting innovation, for each case it examined the degree of stringency (middle or very strict) and the type (product, process) and degree (diffusion, incremental, radical) of the predominant innovative industrial response.

The analysis of the regulatory cases showed how standard mechanisms encouraged a variety of innovations, both incremental and radical in nature. In a number of cases product regulations called forth product innovations, whereas component or pollutant regulations tend to elicit process innovation. High degree of stringency was found to be a fundamental condition for inducing more innovative compliance responses.

Christiansen (2001) investigated the innovation effects of the Norwegian carbon tax system in the oil industry. The overall analysis is of particular interest since it is one of the very few studies addressing a climate mitigation policy instrument, thus providing an ex-post evaluation of an environmental tax. The methodology employed is mainly qualitative in nature. Semi-structured interviews with industrial managers and technology experts were carried out and official documents and scholarly literature were reviewed.

The author identified the technological solutions and institutional innovations adopted by oil companies operating in the Norwegian Continental Shelf to reduce their carbon intensity. Diffusion of available technologies and incremental process changes were the main innovation pattern observed. Two projects developed in different fields constituted radical innovations. However, the author pointed out that in both cases (a carbon capture and sequestration technology and a system to generate electricity from shore) innovations were carried out in the design phase of new facilities (not as retrofits), and the existence of a carbon tax was but one of the many shaping factors. It provided leverage but did not start the innovation process.

Yarime (2003, 2007) offers a detailed analysis of the policy events in Japan relating to the control of mercury emissions from Chlor-Alkali plants in Japan and the technologies being adopted in response to those regulations. It is an interesting longitudinal analysis, showing the positive and negative power of regulation. Following the discovery from mercury-related diseases in the Minamata area stemming from the consumption of fish containing mercury, Chlor-Alkali plants all over Japan became the focus of public attention, wrongly as it turned out later. Giving in to public pressures to act, the Japanese government established a Council for the Promotion of Counter Measure who decided that all Chlor-Alkali plant should convert the mercury process to

[3] Mazzanti and Zoboli (2006) investigated the factors influencing environmental innovation in a local industrial district. About the 79% of the firms included in their survey reported to have adopted environmental innovation (both process and product innovations), but only 2% of them reported a patent activity.

[4] Dechezleprêtre et al. (2010) offer an example of what can be done, by incorporating absorptive capacity into a study about the transfer of climate change mitigation technologies.

non-using mercury plants. The time plan left industry little choice but to adopt diaphragm technology, an energy intensive technology producing lower-quality soda than the mercury process, making it a clear suboptimal choice from an industry and user point of view.

In Sept 1979 the Council reached another agreement that the remaining mercury plants were to be converted to the better performing ion exchange membrane technology by the end of 1984. This counter measure gave industry time to prepare itself for the use of ion exchange membrane technology, which became the preferred choice, not immediately but after a few years. Here regulation initially forced the use of a suboptimal technology, but later contributed to the development and use of a better process technology.

Mickwitz et al. (2008) examined the role of policy instruments in the innovation and diffusion of environmentally friendlier technologies in two sectors in Finland: Pulp and Paper and the marine engine industry. The main source of information for the analysis is interviews with innovators and companies using the innovation. They tested eight claims concerning the effects of regulations, environmental taxation and R&D funding. They found evidence supporting conventional wisdom that regulation drives diffusion rather than innovation but also contrary evidence.

Responses are found to depend on how the instrument is used and the context in which it is used. How an instrument is used is found to depend on the distribution of the benefits and costs, as an important situational factor besides capabilities and economic opportunities. There is no evidence of one instrument being superior than other instruments in promoting innovation. The experiences with an energy tax and pollution fees however suggest that more can be achieved with fees than with taxes as fees can be more easily designed in a way that makes them effective.

Green product choices are studied by Türpitz (2004). Based on interviews and analysis of company specific documents (environmental reports, eco-balances etc.), the study investigated technological, political, market-related and company-specific determinants for environmentally-friendly product innovations in six companies.[5] Similar to Ashford et al. (1985), Türpitz finds that regulation appears the main driver of product-related eco-innovations: the compliance with existing regulation requirements and the anticipation of future rules was the most influential incentive amongst companies underpinning product innovations.

As for the role of market stimuli, the analysis demonstrated that their influence varies per sector (each of which representing a different techno-economic context) and that green innovators often faced commercial obstacles. The willingness to pay of consumers for the environmental friendliness of a product appeared to be low and strongly dependent upon ecological awareness. Further influencing factors are company-specific factors (size and culture). Eco-labels and lifecycle analysis (LCA) did not come out as main drivers of product-related eco-innovations in the author's analysis.

Nill and Tiessen (2005) studied the effects of environmental standards of the Clean Air Act on compliance choice to reduce atmospheric pollution from cars. The analysis carried out by the authors reveals that the time-schedule of the Clean Air Act, pushing for quick results, favoured the use of the catalytic converter, a fuel-increasing solution, and it "slowed down the development of more radical solutions able to overcome the emission-fuel consumption trade-off". It is hard to tell what would have happened under different policies but the study marshals a great deal of evidence that the particular timing and details of policy affected the choice of compliance. It more or less locked out potentially superior solutions, through early technology closure. The study also bring out the strategic games between industry and government over desirable technologies and appropriate policies.

[5] Siemens Medical Solutions, Toshiba Europe GmbH, Schott Glas AG, Continental, Ergo-Fit, Ensinger Mineral-Heilquellen.

The influence of the time aspects of environmental policy on techno-economic dynamics has been studied for various cases[6] in the Sustime project — the results of which are published in Sartorius and Zundel (2005, p.10). The conclusion of this study is that the time element (called time strategy) is a fundamental design issue for the success (or failure) of an innovation-oriented environmental policy: "Political impulses at the wrong time either barely bring about a worthwhile effect or else they cost too much money and time to bring about a real change in economic behaviour. At the right time, even weak political incentives can stimulate external environmentally friendly innovations" (Sartorius and Zundel, 2005).

Policy interaction effects are studied by Kivimaa (2008). The generalised lessons which she draws from her own case study research in the Nordic Pulp and Paper industry as well as that of others are that the effects of environmental policies on innovation depend on, inter alia (a) the aims and characteristics of an individual policy measure; (b) synergies and conflicts with other policies both within environmental policy and with other policy fields; (c) the timing of the policy effect in relation to innovation process (in anticipation, during, after); (d) the nature of the innovation process (process, product); (e) the nature of the innovation process (process, product).

The case study literature also brings out the importance of foreseeable, flexible and continuously improving environmental policies as well as the importance of innovation capabilities (which may reside outside the problem sector the exploitation of which may require a special innovation support effort) (Kivimaa, 2008; Norberg-Bohm, 1999b).

What is special about case study analysis is that it allows for the reconstruction of causal chains. A wide range of factors can be incorporated into the analysis, including those that cannot be objectified such as anticipation of policy acts and strategic market considerations. Such analysis can reveal how choices are made in situations of uncertainty, conflicting evidence and mutual influence between actors. Interaction effects of policies can be studied, together with how certain policy features shaped choices of compliance. A limitation of case studies is that the results are case-specific. Comparative case study analysis can be used to obtain generalised findings and for generating hypotheses for systematic inquiry, for which itself is less well-suited.

5. Results from Surveys of Firms on the Effects of Environmental Policy Instruments on Eco-innovation

A fourth methodological resource is survey analysis. They can refer to companies in a certain sector and those in various sectors, nationally and internationally (as in OECD, 2007). The nature of the sample influences the generalisation of findings.

Cleff and Rennings (1999) studied the effects of different environmental policy instruments in Germany based on survey data from the Mannheim Innovation Panel.[7] The study revealed that many policies affected the decision to eco-innovate: 1) state regulations and prohibition; 2) liability for environmental risk; 3) sewage, waste and hazardous waste charges; 4) energy charges, taxes; 5) sectoral voluntary commitments; 6) eco-audits; 7) environmental impact assessment; 8) subsidy/state assistance programmes; 9) green dot (for packaging

[6] The cases examined are the ban of ozone-depleting technologies, the regulation of chlorine production, the reduction of transport-based air pollution (competition between catalytic converter and lean-burn engine), the promotion of photovoltaic technologies, the Californian Zero Emission Vehicle Mandate, the promotion of cogeneration technologies, the ban of EDTA (ethylenediaminetetraacetic acid), the promotion of environmental efficient technologies (combined-cyclegas turbines and the smelting reduction technologies), the safety in the design of nuclear power plants and the competition between two different standards in video recording systems.

[7] Companies were considered an "environmental innovator" if they had introduced an innovation between 2003 and 2005 in one of the following areas for environmental protection: product change, process change, recycling, end-of-pipe pollution control. According to this criterion, 72% of the innovators were an environmental innovator.

recycling); 10) eco-labels. Of the different environmental policies, state regulations and prohibition were found to be a more important policy stimulus than charges and taxes. Environmental product innovation was found to depend on strategic market behaviour of firms (a finding confirmed by case study analysis of Kivimaa, 2008).

Frondel et al. (2007) studied the influence of various policy instruments on the choice of end-of-pipe and integrated process changes in Germany. Policy stringency is the most significant determinant. The choice of instrument is found to be less important. Regulation is important especially for end-of-pipe solutions but less important for cleaner production for which cost reduction is an important factor. The study found no significant impacts of market-based instruments. These results are in line with the case study findings (especially the findings of Ashford et al., 1985; Ekins and Venn, 2006) but orthogonal to the conclusions of the theoretical models.

The biggest and most comprehensive survey study of company's innovation responses to environmental policy is the OECD study "Environmental Policy and Firm-Level Management" involving the collection and analysis of data from over 4000 manufacturing facilities in seven OECD countries (Japan, France, Germany, Hungary, Norway, Canada and the United States (Johnstone, 2007)). The survey investigated the role of environmental policy initiatives on environmental management, performance and innovation. Several econometric analyses were undertaken based on the application of different techniques to a database of manufacturing facilities in seven OECD countries. As for the influences wielded by different instruments, it was found that policy instrument choice does not directly affect environmental performance. The influence is through innovation and environmental R&D. It was also found that flexible instruments are more likely to trigger clean technologies instead of EOP solutions. Policy stringency came out as the main determinant for environmental R&D, and environmental accounting was revealed as an intermediating variable, with policy instruments only having an indirect influence through the role of environmental accounting. The measure used for policy stringency is "perceived environmental stringency" being the respondent's view of the relative stringency of the environmental policy regime to which their facility is subject. The environmental stringency of policy as perceived by the respondents was found to be weakly correlated with the reported number of inspections, suggesting that inspections (used by Brunnermeier and Cohen, 2003) are not a good measure.

Rehfeld et al. (2007) analysed the determinants of environmental product innovations in German manufacturing sectors based on a firm level data set[8] with special attention given to the role of organisational-IPP[9] measures. The methodology adopted combines descriptive statistics with an econometric analysis. They used the case study findings from Türpitz (2004) for the survey questionnaire design. What they found was that only 37.2% of the companies interviewed had introduced an environmental product innovation between 2001 and 2003. A far higher percentage of respondents have been instead involved in the implementation of environmental process innovation (69.9%). Surprisingly enough, environment was also an important innovation goal for 64.5% of non-environmental product innovation. As for IPP-measures, 74.9% of the companies who developed a green product applied environmental criteria in product planning and development and half of them were active in waste disposal or take-back systems. A minor role is played by LCA and eco-labels.

Besides IPP measures, the survey directly investigates the role of policies as a determinant for green products innovations. It turned out that "compliance with existing and future legal requirements" was an important innovation goal for 68.9% of environmental product innovators, the corresponding share for non-environmental innovators is 53.3%. Econometrically, the environmental policy variable proved to have only a "weakly significant effect" on environmental product innovation. Environmental policy is depicted as one amongst many others factors (technology-push, market-pull and firm-internal) and the evidence described through simple statistical evidence is partially refuted by the econometric analysis. The two evidences, stemming from different methods of analysis applied to the same sample, complement each other and together provide a more insightful representation of reality.

Table 1
Eco-innovation motivators in German companies[a].
Source: Horbach et al. (2011) based on data from the CIS2008.

Environmental innovations that were introduced in response to	Yes	No
Existing regulations or taxes on pollution	31.5	68.5
Anticipated environmental regulations or taxes	27.0	73.0
Government grants and subsidies	9.9	90.1
Demand from customers	27.4	72.6

[a] Whose activities had a non-negligible environmental impact.

Horbach (2008) analysed German panel data about innovation for the subset of environmental firms. He compared the stimuli for environmental innovation with those for normal innovation, finding that cost savings and compliance with regulation are more significant determinants for environmental innovations. Participation in innovation cooperation and state subsidies also come out as more important for environmental innovation than for normal innovation.

Research on eco-innovation would benefit from panel data information about eco-innovation. Unfortunately, designated panels for eco-innovation do not exist. As a positive event, the 2008 European Community Innovation Survey from EUROSTAT[10] contained 15 questions about eco-innovation, including 5 questions about the influence of particular policies. Results for Germany are given in Table 1. Environmental regulations, taxes, demand from customers and voluntary codes and industry agreements were revealed as important drivers, in contrast to financial support by government. Unfortunately, the influence of regulations and pollution taxes has not been separated. It is also unclear whether the eco-innovation adopted was developed in-house, in cooperation with others, or purchased.

Surveys are an importance source of information about determinants and facilitating factors for eco-innovation. Through the use of dedicated surveys the influence of company internal factors (organisational, human capital, product strategies) can be established for different eco-innovations. Surveys can be used for obtaining information on the economic effects of eco-innovation on sales, production costs, and employment. Surveys are uniquely suited for analysing the link between a wide range of company internal and external factors (across industries). For analysing the influence of individual policies, learning about policy interaction effects, and for studying political economy aspects, surveys are less suited.

6. Results from Mixed-method Studies and Meta-analysis

Innovation impacts of policy can also be examined by applying different methods simultaneously (mixed-method), allowing the researcher to assess the robustness of the results and weigh the evidence of different data sources. One of the best studies into the environmental technology effects of policy is the study of Taylor et al. (2005), into the policy determinants of innovation in SO_2 control technology. The study used different measures for innovation (patents, R&D expenditures, technologies, experience curves) in analysing the role of various policies on the innovation in SO_2 control technology. The study is extremely rich in empirical detail. The main goal of the

[8] Data were collected using a telephone survey carried out in 2003. 588 manufacturing companies (out of a population of 2511) participated in the survey.

[9] Integrated Product Policy refers to a set of guidance principles set by the EU in the "Green Paper on Integrated Product Policy" aimed at reducing environmental impacts of final goods in a cradle-to-the-grave perspective.

[10] http://epp.eurostat.ec.europa.eu/portal/page/portal/microdata/cis.

study was to establish the influence of three types of policy on innovation: (1) SO_2 control regulations, (2) public research support, and (3) the emission trading system for sulphur emissions introduced as part of the Clean Air Act Amendments (CAA) in 1990. The effects of the different policy approaches were analysed in three different ways: (i) through econometric analysis using information about patent activity and government regulatory activity, (ii) through interviews with technology vendors and specialists, and (iii) through a content analysis of the yearly proceedings of the SO_2 symposium at which FGD vendors met with government and university researchers, utility pollution control operators. The study found that patent activity predated the actual regulations (anticipation effect) and stayed at a high level thanks to SO_2 control regulations introduced in the 1970–1990 period. A second finding is that the regulations curtailed invention in precombustion technologies that cleaned coals. Patenting in these technologies fell after the introduction of the 1979 New Source Performance Standards regulations. The emission trading system introduced in 1990 as part of the Clean Air Amendments did not restore patenting levels for precombustion technology and was found to have little effect on invention. The 1990 CAA did cause a shift in the compliance options, away from dry FGD and sorbent injection systems, which were less economical than the use of low sulphur coal with limited wet FGD application.

The results of the study of Taylor et al. (2005) appeared two years after a publication on the innovation effects of the Clear Air Act on innovation in sulphur control by David Popp (2003). Using patent data and data about the scrubbers installed, Popp found that the emission trading system for sulphur did not lead to an increase in patents in sulphur control technologies but noted that the control efficiencies of the scrubbers installed were higher than those installed prior to 1990. Removal efficiency of new FGD Units went up from 84% in 1990–1992 to 94% in 1997, an increase of 10% points, leading him to the conclusion that the ETS led to a change in the direction of technical change (towards higher control efficiencies). The increase in greater control efficiencies features prominently in the overview articles of Jaffe et al. (2003) and Vollebergh (2007) where it is singled out as “a telling example”. But as the study of Taylor et al. (2005) shows, scrubbers with control efficiencies of 90% and more were already available and being used prior to 1990 in reaction to the SO_2 control regulations.

Pontoglio (2010) did a mixed-method case study of EU ETS based on a survey to companies in the paper industry, completed by interviews to machinery suppliers and a detailed analysis of the complex design of the scheme and of the implementation process in Italy. What emerges from the analysis of the companies' reaction to the introduction of a marketable cap to their carbon emissions, is that in the first phase of application of EU ETS (2005–2007), companies by and large adopted a “wait and see” strategy. Paper mills in shortage of allowances preferred to postpone abatement decisions to later years, borrowing allowances from subsequent periods.

Innovation responses of power companies to the ETS were studied by Rogge et al. based on interviews and survey analysis. In the power sector in Germany and Europe, the ETS was found to have strongly increased RD&D[11] in carbon capture technologies and corporate procedural change (Rogge et al., 2010). Its impact on RD&D for wind and other renewables and on gas efficiency RD&D was negligible. Overall its impact on innovation new to the world was low, which is surprising for a system involving hundreds of billions in trade. The auctioning of (lower amounts) of carbon rights will achieve more, but the authors believe that promoting emerging renewables regimes requires other policies than the ETS (Rogge et al., 2010).

Martin et al. (2011) undertook a more comprehensive study of ETS based on multiple methods. The authors conducted approximately 800 interviews with managers in six European countries, to explore the reasons behind innovation performance and its dimension (process/product innovation), manager's expectations about future carbon price and the role of expectations in investment's decisions, together with the link between innovation and stringency and other prominent policy design issues (e.g. auctioning). Descriptive analysis of interview results demonstrates that almost 70% of firms are engaged in some form of clean process innovation and 40% on product innovation, with country differences. Regression analysis showed that there is no strong evidence that ETS firms in general differ in their innovativeness from non-ETS firms. Anticipated reductions in the amount of allowances proved to play a crucial role, greater than price, in influencing innovation decisions: firms that expect a more stringent EU ETS cap in Phase III are more likely to engage in product innovation. However, there is no clear evidence that the same is true for process innovation.

It is interesting to compare the results of this analysis with Calel and Dechezleprêtre (2011). This second study is more positive about ETS spurring innovation, and finds a stronger evidence of the difference between ETS and non-ETS companies. However, the innovation activity in ETS companies shows a decline after 2005, when the interview of Martin et al. (2011) were conducted.

There is also a need for meta-analysis, to critically scrutinise the results of various studies. A good example of such a study is the meta-analysis of empirical studies into the Porter hypothesis performed by Ambec et al. (2011). The study examines the conflicting evidence from studies into the Porter hypothesis that strict environmental regulations can induce efficiency and encourage innovations that help improve commercial competitiveness (Porter, 1991), paying special attention to the different ways in which the Porter hypothesis is understood and tested. One of their conclusions is that “most previous studies have not adequately taken into account the dynamic dimension of the Porter Hypothesis” by not taking account time lags between regulation and innovation offsets. They also note that the Porter hypothesis was premised on flexible, market-based regulation — not rigid command-and-control regulation. A third aspect neglected in the studies investigating the Porter hypothesis is the interaction of environmental regulations with other government policies. The meta-conclusions are that the “weak” version of the hypothesis that stricter regulation leads to more innovation is fairly well established; the evidence on the “strong” version (that stricter regulation enhances business performance) is rather mixed. The results of a number of studies on the issue are found to be flawed in not considering the time lag, thus overestimating the costs of regulation. It is also said that the evidence speaks “in favour of policies that provide incentives for innovation, are stable and predictable, make use of suitable transition periods, focus on end results rather than means, and economic policy instruments” (Ambec et al., 2011, p. 12).

The use of mixed method analysis and meta-analysis is a way to overcome inherent limitations of single methods, helping the researcher to see “the whole elephant” and not just a part of it.

7. Synthesised Findings

This section formulates five synthesised findings about understanding the innovation effects of environmental policy instruments which are based on various literatures, especially the case study literature. Future investigations will benefit from a discussion over these issues that are currently poorly integrated in the research traditions.

The first issue for understanding is that *we should not talk about innovation and environmental innovation in an unqualified way*. Within the innovation literature, a distinction is made between incremental innovations and radical innovation (Arundel et al., 2003; Freeman, 1982; Kemp, 1997; Kemp and Pearson, 2008; Rennings et al., 2003). Incremental innovations are minor modifications of existing processes or products, while radical innovations imply a technological discontinuity based on a break with existing competencies and technologies. The analysis from Pontoglio (2010) and Rogge et al. (2010) demonstrated

[11] RD&D stands for Research, Development and Demonstration.

that this distinction is of great relevance in the context of innovative technological solutions to reduce carbon the emissions. It is also important to make a distinction about innovations new to the world and innovation adoption. Econometric research typically focuses on innovations new to the world using a measure for invention (patents), different from survey analysis which tends to focus on the implementation of a product or process change. The analysis from Frondel et al. (2007) demonstrates that in the OECD, companies have shifted to cleaner production and consequently end-of-pipe solutions are no longer the most important technology for dealing with environmental issues.

The second issue is that *the link between regulator and regulated is not unidirectional and that innovation is affected by multiple policies*. This suggests that the stimulus–response model is too simple, as it assumes that environmental innovation starts with a regulation or some other policy (Klemmer, 1999), which is most often not the case. The development of an innovation may *precede* a policy and even exert influence over the policymaking process, with new innovations paving the way for the regulations (Kemp, 1997; Kivimaa, 2007). As for the influence of multiple policies over innovation, the studies by Fischer (2008) and Popp (2006, 2010) show that environmental and technology policies work best in tandem. Innovation policy is especially needed for the creation of radical innovations whose uncertainty, long-term payoff (because of long development time) and problems of appropriating the benefits amongst contributing actors, work against their development (Kemp, 2011; Newell, 2010; Popp, 2010). It is being observed that eco-innovation suffers from two market failures — the public good nature of knowledge and non-internalisation of externalities (Jaffe et al., 2002b; Newell, 2010; Popp, 2010; Rennings, 2000), calling for policies of push and pull, raising questions about the proper balance (Foxon and Kemp 2007; Kemp 2000; Popp et al., 2009).

The third issue of understanding is that *impacts of environmental policy instruments on innovation may depend more on design features than on the type of instrument chosen*. Relevant aspects of design and implementation are:

1. Stringency
2. Predictability
3. Differentiation with regard to industrial sector or the size of the plant
4. Timing: the moment at which they become effective, the use of phase-in periods
5. The credibility of policy commitments to future standards
6. Possibilities for monitoring compliance and discovering non-compliance
7. Enforcement (inspection and penalties for non-compliance)
8. Combination with other instruments of policy

The influence of the above design aspects constitutes an important avenue for research. Important work on the effects of particular policy features has been done by Blazejczak et al. (1999), Norberg-Bohm (1999a, 1999b), Kivimaa (2008) and Johnstone and Hascic (2009). Flexibility is found to have a positive impact on eco-innovation: “For a given level of policy stringency, countries with more flexible environmental policies are more likely to generate innovations which are diffused widely and are more likely to benefit from innovations generated elsewhere” (Johnstone and Hascic, 2009, p.1).[12] On the other hand, the flexibility of ETS in the form of banking and borrowing worked against the development of innovations (Pontoglio, 2010).

[12] The measure used for regulatory flexibility is based on executive respondents' scores about the extent to which they had freedom to choose different options in order to achieve compliance with environmental regulations in the nation they are operating in. Different scores for environmental regulatory flexibility are computed for different nations, based on stated information from the Executive opinion survey of the World Economic Forum.

The fourth issue follows from the previous one, which is that *there is not one single best instrument* to foster innovative response to environmental regulations. According to the theoretical literature, taxes and emissions trading systems are superior in promoting innovation than regulation. This may be true for low-cost improvement innovations but does not appear to be true for radical innovation. There is more evidence of regulation promoting radical innovation (Ashford et al., 1985; Taylor et al., 2005; Türpitz, 2004) than evidence of market based instruments promoting radical innovation. Burtraw (2000) found that the ETS for SO_2 in the US stimulated fuel substitution and organisational innovation rather than “patentable discoveries”. About half of the reductions in sulphur during Phase I of the programme have been achieved by changing to coal with lower sulphur content. This conclusion fits with the arguments of Driesen (2003, 2006) that ETS weakens net incentives for innovation by offering a cheap way out. Particularly market-based instruments, such as eco-taxes, are often watered down in the political process (Frondel et al., 2007, p. 579). Political economy factors and fears of carbon leakage and competitive disadvantages tend to work against their effective use.

The fifth issue of understanding is that *environmental policy can have both a positive and a negative influence* on the development and adoption of particular environmental innovations. More attention should be given to how particular policies favour or disfavour particular innovations. In Japan regulatory preference for quick results favoured the adoption of an environmentally and economically sub-optimal solution to control mercury emissions (Yarime, 2007). More research should be done on how environmental policies influence the direction of innovation and compliance choices, and whether the influence is accidental, related to the nature of the policies and political economy reasons behind these.

8. Conclusions

In this paper we reviewed the findings from four literatures on the innovation effects of environmental policy instruments. The conclusion of the paper, stated in the form of five synthesised findings is that policy instruments cannot be usefully ranked with regard to their effects on eco-innovation, and the often expressed view that market-based approaches such as pollution taxes and emission trading systems are better for promoting eco-innovation is not brought out by the case study literature or by survey analysis, and seems only warranted for non-innovative, or marginally-innovative, changes.

What the case study literature shows is that the specifics of policy and the situation in which they are applied are all-important for the outcomes. Increasingly this is acknowledged in the economic literature, but the common wisdom still is that market based instruments are superior in soliciting innovative responses. Regulation is generally viewed as stimulating merely the diffusion of environmental technology but we show that there is more evidence of regulations stimulating radical innovation than of market-based instruments doing so.

More research should be done on analysing policy interaction effects, the role of policy shocks, and the complementarity of different barriers.[13] Survey analysis and case study analysis can be used for this.

The second conclusion emerging from this analysis is that ideally one should employ different research methods, as Taylor et al. (2005) did. When doing econometric analysis, it is advisable to speak to industry and technology suppliers about the drivers for technology development and adoption. This allows the readers to assess the robustness of the results and the relevance of the findings. There is a divide between quantitative and qualitative studies. An

[13] Interaction effects of barriers to innovation have been studied by Mohnen and Röller (2005) using data from the first Community Innovation Survey, finding evidence of complementarity between various barriers, which suggests the need for targeted policies for addressing different barriers.

analysis of the econometric studies reviewed in Vollebergh (2007) learned that of the 24 studies only two refer to case study findings. Interview results are reported in only one case. All methods have their own specific strengths and limitations. Any analysis is as good as the data or its assumptions. In limiting oneself to one method there is a danger of coming up with partial truths, and make unjustified generalisations. As this paper has shown, innovation is something multifarious, policy impacts depend on the design of the policies and context in which they are used. Research should be more concerned to the generation of robust knowledge than it presently is. In this paper we offered synthesised findings, along some methodological pointers for research. We also outlined topics for further research about the innovation impacts of environmental policies, a topic which will long occupy us as there is no single truth about it: the influence of policies is bound to differ across places and sectors.

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