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IMPACTS OF ENVIRONMENTAL POLICY INSTRUMENTS ON TECHNOLOGICAL CHANGE

Joint Meetings of Tax and Environment Experts

This review of the literature on impacts of environmental policy instruments on technological change has been written by Prof. Herman Vollebergh, Department of Economics, Erasmus University, Rotterdam.

CTPA: Chris Heady, Tel: +(33 1) 45 24 93 22, Email: Christopher.Heady@oecd.org;
ENV: Nils Axel Braathen, Tel: +(33 1) 45 24 76 97, Email: Nils-Axel.Braathen@oecd.org

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FOREWORD

This report was prepared by Professor Herman Vollebergh of Erasmus University, Rotterdam, the Netherlands. It has been prepared as part of the work programme of the OECD Joint Meetings of Tax and Environment Experts.

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EXECUTIVE SUMMARY

The “dynamic effects” on technological change vary between different environmental policy instruments

Environmental policy provides an important incentive for firms and households to develop and adopt new equipment or technologies with more environmentally favourable characteristics. Such “dynamic effects” of environmental policy are likely to differ across different policy instruments, such as emission restrictions through legislation or (changes in) taxes, subsidies or even tradable permits (TDP). Economists generally believe “market-based” instruments can provide stronger incentives than command and control (CAC) regulations to adopt cheaper and better pollution control technologies. CAC policies, like emission limits for installations, provide no reward for *exceeding* the requirements set by the regulations. However, under a market-based policy, firms that perform better than is required by such regulations face continuous rewards, because their tax payments can be lowered (or because they may sell excess pollution permits). Moreover, direct regulations may constrain the potential “space” for innovation, reducing incentives to identify those options that are most cost-effective in the long run.

This report surveys the empirical (economic) literature, asking whether there indeed is any evidence of different effects on the rate and direction of technological change associated with different environmental policy instruments. In particular, the question is whether there is any evidence for the hypothesis that market-based incentives have a stronger impact on rate and direction of technological change than non-market alternatives. The hypothesis that one can expect different effects from differences in environmental policy design is well-founded in recent advances in economic theory. In particular, by allowing for informational complexities and strategic interactions in the regulatory process, as well as a much deeper analysis of the process of technological change, economists have become much more aware of the role of incentives in regulation for consequences such as changes in the rate and direction of technological change. This survey is explicitly concerned with empirical identification of relevant mechanisms, including studies that focus on changes in pollution abatement cost.

It is difficult to identify the exact impacts of a given instrument

To date, few studies exist that explicitly deal with differential impacts of environmental policy instruments. This is hardly surprising, because: (i) environmental regulation has mainly used CAC instruments; (ii) data restrictions often prevent proper identification if a “mix” or “cocktail” of instruments is used (which is usually the case in practice); (iii) controlled laboratory or field experiments are virtually non-existent; and (iv) empirical assessments have a tendency to be biased towards observable information, like changes in abatement costs, number of patents (citations), physical characteristics of technologies, etc. Despite the problems in measuring the differential impact of instruments directly, an increasing amount of material has now become available that documents the impact of environmental policy on technological change.

First, some studies have looked at inducement in a more environmentally friendly direction at a fairly general level. This set of studies tries to measure the impact of *environmental policy* on technological change through commonly used indicators of invention, innovation and diffusion, such as R&D expenditures, patents and adoption of new technologies. If environmental policy instruments have dynamic impacts, one would expect invention and innovation to be affected first. Quite a large literature is now available that measures such impacts by changes in the level and direction of R&D and/or its (imperfect) output measure, patents. This literature demonstrates clearly that environmental regulation does have a serious impact on technological change in general.

The second set of studies analyse the likely effects of *specific instruments* on invention, innovation or diffusion of specific technologies. Such “stand-alone” evaluation of instruments enables comparisons of effects across studies. These studies often claim that effects on technological change exist, but their identification is not always convincing. Moreover, these studies are often difficult to compare.

Finally, the review discusses a third set of studies that explicitly analyse direct and indirect evidence as to whether price or quantity regulation has *different impacts* on technological change. For a long time, comparisons used only indirect evidence, given the lack of market-based instruments applied in practice and/or the availability of data to evaluate them. In particular, several studies looked at CAC instruments versus energy price effects. Only recently have some papers become available that compare the effects of CAC instruments versus market-based instruments. For example, the introduction of SO_2 allowance trading for electric utilities in the US has provided an interesting case to analyse the impact on the direction of technological change.

Environmental policies* do *impact on technological change

The general picture that emerges from the papers reviewed is that they clearly observe changes in invention, innovation and diffusion of technologies; although the direct causal link with environmental policy is not always clear. Not only does environmental regulation make life more difficult for existing firms, by increasing the (implicit) price of pollution; there is also a clear positive impact on invention and innovation of new technologies. Moreover, indirect evidence suggests that an increase in the implicit price of some emissions also boosts patents in complementary areas. The overall conclusion seems justified that environmental policy in general has an impact on at least the direction of technological change. This conclusion holds, regardless of the type of instrument applied, *i.e.* whether CAC or market-based instruments are used. Indeed, in the early days of environmental regulation, the focus was almost entirely on standard-setting through technology prescriptions (*e.g.* prescriptions of “Best Available Technologies”). Such prescriptions are almost by definition technology-forcing and binding, because they imply emission constraints that reduce the number of options in the emission-output possibility set. The most important effect of such (standard-setting) policies is that they induce the dirtiest firms to exit from the market.

Higher energy prices lead to emission reductions

Equally impressive are the strong correlations between specific types of regulations and the R&D process, as measured through patenting behaviour. Apparently, and in line with what economists suggest, innovators look carefully for rent opportunities which, in turn, depend on the specific incentives signalled by the type of (environmental) policy. This is also precisely what could be learned from cases providing indirect evidence of price incentives, like the rise (and decline) in fossil fuel prices. Emission reductions are triggered by higher *implicit* emission prices due to rising energy prices, because most fossil fuel use is closely linked to air pollution emissions. Such changes in energy prices have had strong impacts on invention, innovation and diffusion of more energy-efficient technologies which, in turn, have lowered emission levels as well. Specific design features characterise incentives that, in turn, are likely to have an impact on the efficiency and effectiveness of policy instruments.

However, the studies reviewed in this survey illustrate that it is difficult to identify the exact dynamic impacts of policy instruments; and in particular, the differences in impacts between different instruments. Moreover, one serious drawback is that almost all available studies cover only the US. It would also be interesting to see whether or not the technology impacts of market-based regulation are location- or culture-specific.

Financial incentives for technology development are usually stronger under market-based instruments

Given that the design of signals is crucial, both policy and future research should take this issue more seriously. The common (and rather broad) distinction between CAC 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). Moreover, technology-related information requirements for public authorities are much lower when using a tax compared to when using technology standards. This reduces the space for rent-seeking and the potential to misdirect innovation. In addition, taxes allow for more flexibility from the part of the regulated agent, reducing adjustment costs and optimising entry/exit and capital turnover rates. However, introducing taxes or tradable permits is not devoid of design problems either, and requires proper design as well.

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IMPACTS OF ENVIRONMENTAL POLICY INSTRUMENTS ON TECHNOLOGICAL CHANGE[1]

1. Introduction

1. Nowadays economists and politicians believe that environmental policy also affects technological change. Stylized facts on decoupling, *i.e.* the de-linking of economic or income growth and environmental pollutants, can be observed in several fields of environmental policy (Brock and Taylor, 2004). For instance, acid rain emissions, in particular SO_2-emissions, have been strongly reduced in OECD countries. One reason for these remarkable reductions is the instalment of new (abatement) technologies, like flue gas desulphurization (FGD) equipment in sectors most responsible for those emissions, like electricity plants. This technology became available in response to increasing environmental stringency to curb emissions that spoilt local (and distant) air quality.

2. Economists have already long ago pointed at what they called the potential dynamic effects of environmental policy. In particular, Kneese and Schulze (1975) pointed out that one of the most important criteria on which to judge the performance of environmental policy instruments is the extent to which they "spur new technology toward the efficient conservation of the environment". One would expect environmental stringency through emission restrictions, apart from output reduction or factor substitution to be also a fundamental driver responsible for observing an increase in Research and Development (R&D) investment in abatement technologies, subsequent filings of new patents and, finally, a reduction in emissions.

3. Economists' also believe that these changes in incentives are indispensable. Environmental policy, whether it is through emission restrictions through legislation or changes in taxes, subsidies or even tradable permits (TDP), is an important prerequisite for firms and households to develop and adopt new equipment or technologies with more environmentally favourable characteristics. It is equally likely, that different policy instruments might have different effects on the rate and direction of technological change. In particular, economists generally believe that so-called market-based instruments can provide stronger incentives than command and control (CAC) regulations to adopt cheaper and better pollution control technologies. First, CAC policies, like emission prescriptions for installations, provide no reward for exceeding the requirements set by the regulations. However, under a market-based policy, firms that perform better than is required by such regulations, face continuous rewards because their tax payment can be lowered or they may sell excess pollution permits. Moreover, direct regulations may constrain the potential "space" for innovation, reducing incentives to identify those options that are most cost-effective in the long run.

4. This report surveys the empirical (economic) literature on the influence of environmental policy on technological change. The focus is on whether there is any evidence for the hypothesis that market-based incentives would have a stronger impact on rate and direction of technological change vis-à-vis their

1 The author thanks Nils Axel Braathen, Nick Johnstone, Arik Levinson and David Popp and participants of the OECD Joint Meeting of Tax and Environment Experts for comments and suggestions on an earlier version of the paper.

non-market alternatives. The survey has a clear distinctive focus compared to several recent surveys. For instance, Requate (2005) provides a summary of recent developments in the theoretical literature on this topic. The surveys by Jaffe, Newell and Stavins (2003 and 2005) and Loeschl (2002) mainly focus on the role of technological change in theoretical models, in particular also on the role of modelling endogenous technological change, and their likely implications for the environment. Popp (2005) produces some interesting lessons from his and other peoples' recent empirical work on innovation as measured by patents. However, his focus is not explicitly on the role of instruments nor does he pay attention to other channels and indicators of the impact of environmental policy on technological change. This survey complements and updates the assessment of Jaffe, Newell and Stavins (2002) because many relevant studies have become available in recent years. This survey is also more explicitly concerned with empirical identification of relevant mechanisms, including studies that focus on changes in abatement cost. It does not discuss welfare consequences, such as an overall assessment of economic efficiency aspects of potential changes in the rate and direction of technological change nor does it pay attention at recent work on the effect of instruments on innovation through organisational changes within firms.

5. This survey starts with a demarcation of our topic. Proper identification of different environmental policy instruments is far from obvious. Therefore section 2 explains, first of all, the theoretical prediction underlying expectations of a differential dynamic impact of different type of instruments used in environmental policy. Next, this section reviews the channels through which this linkage could be studied empirically and the prerequisites to proper identification of this linkage. Section 3 reviews attempts trying to measure the impact of environmental policy on technological change through commonly used indicators of invention, innovation and diffusion, like R&D expenditures, patents and adoption of new technologies. If environmental policy (instruments) has a dynamic impact, one would expect invention and innovation to be affected first, and there exist a large literature that tries to measure such impacts by changes in the level and direction of R&D and/or its (imperfect) output measure, patents. Furthermore, several authors have studied the diffusion of new technology as well including studies of abatement cost over time. Sections 4 and 5 review studies that explore the likely effects of specific instruments on the invention, innovation and diffusion of specific technologies. The studies discussed in section 4 identify this linkage for one specific environmental policy instrument, and the studies that explicitly consider comparisons between instruments are reviewed in section 5.Finally, section 6 draws some conclusions.

2. From static to dynamic evaluation of environmental policy instruments

6. This section explains, first of all, the theoretical prediction underlying expectations of a differential dynamic impact of different type of instruments used in environmental policy. To this end we start with the standard benchmark of economic analysis of environmental policy instruments. The benchmark is essentially a timeless exercise and therefore has little to say on (differential) dynamic aspect of the environmental policy regulation. The second subsection discusses how recent advances in economic analysis have extended the traditional analysis to a dynamic setting of the regulatory process and its impact on technological change. Using these recent advances, the last subsection prepares the background for the identification of the (differential) impact environmental regulation on technological change.

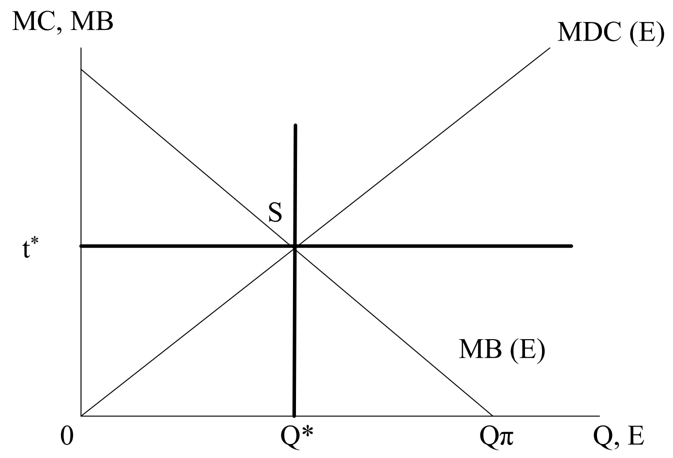
2.1. Some basic static economics

7. Traditionally, economic science treats environmental issues as an example of market failure (Baumol and Oates, 1988; Fullerton, 2002; Jaffe *et al.,* 2002). Environmental problems are described as negative externalities. Negative externalities are a negative by-product (*e.g.* pollution, erosion) delivered unintentionally "behind the back of the market" by one or more economic agents. This causes a welfare loss for some victim who is not properly compensated for this loss, because it does not appear as a cost for the polluter(s). Standard economic analysis simply takes it for granted that the social optimum will only be

attained if adequate instruments induce polluters to internalize the externality either through quantity or price based instruments. Without such instruments agents, like firms or households, typically under-invest in environmental abatement and stay at suboptimal levels of pollution. Figure 1 reproduces this well-known analysis.

8. Assume pollution of some production process generates marginal damage by environmental degradation as depicted by the rising linear curve for marginal environmental costs MDC). They also envisage decreasing marginal net benefits of production (MNPB) as (infra-marginal) profits decline with output on markets with perfect competition. As long as producers maximize profits without taking the environmental damage into account, they typically increase production beyond the level that is optimal from the social perspective, *i.e.* at the intersection S of the MNPB-curve and the MDC-curve, and expand the level of production until marginal net benefits are zero (Q_π in Figure 1).

Figure 1. Optimal pollution through quantity or price controls



9. Similar reasoning applies if environmental damage can be reduced by changing the production process through the instalment of abatement technology or by controlling the effects of emissions on the environment. In that case the MNPB-curve in Figure 1 reflects a marginal abatement cost (MAC) curve starting in Q_π. Obviously, no marginal abatement costs exist if the polluter does not abate any emissions (unrestricted emissions correspond to Q_π), while abatement cost are at a maximum if emissions are completely eliminated (corresponding with the origin of the graph O). Note, however, that the possibility of using abatement technology has the important implication that reducing emissions is likely to be cheaper if emissions can be reduced for a given level of output. It does not matter whether a firm reduces output, uses a filter or a combination of both to adjust its emission level. All options boil down to the same consequence, which is that reducing emissions cause profits foregone to the firm (see Requate 2005, p.176).

10. Incentives are necessary to induce firms and households to change their behaviour and reduce production or consumption levels with their associated (given) levels of pollution. Two broad categories of alternative incentive schemes are generally considered: quantity regulation and price control (Stavins, 2003). Price controlling instruments intervene indirectly in economic processes, for instance, by taxes on

inputs, emissions or outputs (products). The rate of this price per unit of pollution is equal to t*, which reflects the marginal value of pollution in the social optimum. When facing this incentive, profit maximizing producers start reducing pollution until they reach the optimum Q*, because beyond this point marginal reduction costs are lower than the tax rate. Note also that this optimum can also be reached in a partial equilibrium setting using subsidies on (emission) abatement instead.[2]

11. Quantity regulation contains both direct interventions of governmental agencies using non-tradable ("command-and-control approach") or tradable permits. Direct intervention by the government is simply a legal rule that forces polluters to reduce pollution, for instance by prescribing specific (abatement) technologies or emission levels. In that case an individual polluter has no flexibility to react and simply has to comply with this rule. In contrast, the government could also issue an amount of (tradable) permits below the level that is optimal from a private rent perspective to induce agents to trade their quantity restrictions. If the overall issuing of permits is equal to Q* the likely market price for the (remaining) permits will be equal to t*, which is exactly equal to the optimal Pigouvian tax rate. Such permits could be issued for free, *i.e.* at an auction price equal to 0, or they could be sold in an auction. In that case partial equilibrium analysis suggests that this price is equal to t* as well, because this reflects exactly the opportunity cost of a unit of emission.

12. Accordingly, polluters bear the costs of reducing pollution to the optimum Q*, which is equal to the triangle Q^*SQ_π. These costs occur to the polluter irrespective of what type of instrument is used. In addition, when polluters face taxes or auctioned (!) pollution rights, they have also to pay for their remaining pollution, which is equal to Ot*SQ*. In this respect other price or quantity controlling instruments have different (infra-marginal) effects. The most important alternatives are environmental subsidies, which reduce pollution to the optimum Q* without any costs for the polluter, and grandfathered pollution rights.[3] Note, that legal rules only cause cost of pollution reduction and that there is no additional transfer going to the government.

2.2. Pollution control policy in a dynamic setting

13. Dynamic impacts of environmental policy (instruments) have always been recognized by economists (*e.g.* Bohm and Russell, 1985) including the potential differential impact of alternative types of environmental policy instruments (Orr, 1976). Also the link between technological change and the environment has been on the research agenda of economists for a long time (*e.g.* Stiglitz, 1974). Only recently, however, have economists started to provide better micro-foundations to these early contributions, in particular by allowing for informational complexities and strategic interactions in the regulatory process. Similarly, economists started to provide a much deeper analysis of the process of technological change. We start this section with a short summary of both developments and then explain implications of these advances for our field of study, *i.e.* how different environmental policy instruments might have different impacts on the rate and direction of technological change.

2.2.1. Recent advances in economic theory

14. The first relevant development in economics is a shift towards a much more detailed analysis of the regulatory process in terms of information and strategy. In particular, the analysis of the effects of

2. Fullerton has shown in a couple of papers, *e.g.* Fullerton and Wolverton (2003), that a combination of a tax on output and a subsidy on abatement, or a deposit-refund system, is the second best optimal (set of) instruments in a general equilibrium setting.

3. Of course, from a social point of view the costs of pollution reduction is not a loss but an improvement, neither do the proceeds from the Pigouvian tax or from selling pollution rights represent a loss to society as a whole.

environmental policy design on innovation and diffusion requires a much more explicit analysis of the strategy space of both the regulator and the regulated agent. Ranking of policy instruments now strongly depends on how timing and commitment problems are solved. This literature pays much more attention to the micro-foundation of decisions that characterize innovation and diffusion processes in practice, like decisions on how much to invest in R&D or when to adopt a new technology over time, and their impact on (optimal) regulation (see Requate, 2005).

15. The other development of interest is the growing attention for the micro-foundations of technological change itself, which is concisely labelled as endogeneity of technological change.[4] Technological change has been considered as a black box in economics for a long time (Rosenberg, 1982). The underlying mechanisms responsible for economic growth, in particular innovation and diffusion of new technology, came to the notice of a wider audience of economists mainly because of endogenous growth theory (Romer, 1990; Aghion and Howitt, 1992). One important issue is that the willingness of agents to invest time or money in research or learning is fraught with public goods aspects, *i.e.* the problematic appropriation of its social value. Since the seminal paper of Arrow (1962), the standard view is that the investor is often not able to get the full return to his investment because new knowledge, once available, is non-rival and only partially excludable through instruments such as patents. Moreover, diffusion of new knowledge is also less likely to be instant and immediate across a heterogeneous population. Add these problems to the standard view that the production of environmental quality is associated with externality and public good aspects as well, and one immediately realizes the complex nature of choosing optimal policy rules in this area (see *e.g.* Jaffe *et al.,* 2005).

2.2.2. Differential policy impacts and technological change

16. These advances in economic theory are now used to study the differential impact of environmental policy on technological change. Firms typically have to choose how much to invest in R&D to facilitate invention, whether to patent the results of this phase (if any), and whether to produce the new technology or product and commercialize it or not, *i.e.* to sell it to other firms or households. Usually the first two types of decisions are labelled "invention" and the third type of decision "innovation". Note that these decisions are not necessarily restricted to existing firms or should take place within one firm, but are equally likely for new firms or more than one firm. In fact, many firms originate by solving this particular (sub)set of decisions in entirely new ways (Schumpeter,1942). Furthermore, as explained in the previous subsection these decisions are also fraught with externalities, though usually of a positive kind. Finally, if this new technology or product is sold on the market, other firms or households might buy or adopt it. The new technology or product gets penetrated on the (sometimes new) market, a process usually labelled diffusion.[5] Note that the effect of environmental policy on the rate and direction of technological change also includes effects on household decisions. Basically household investment decisions, like buying a new refrigerator or other energy appliances, are also adoption decisions of new technology already available at the market. However, there is some evidence that such decisions of households are quite different from firms, apart from the scale of the investment (DeCanio and Watkins, 1998). So we take it that the diffusion phase typically also includes the penetration of new technologies or products to households. Note also that the cumulative economic or environmental impact of new technology or products results from all three of these stages and is collectively labelled as the process of technological change (Jaffe *et al.*, 2002, p.43).

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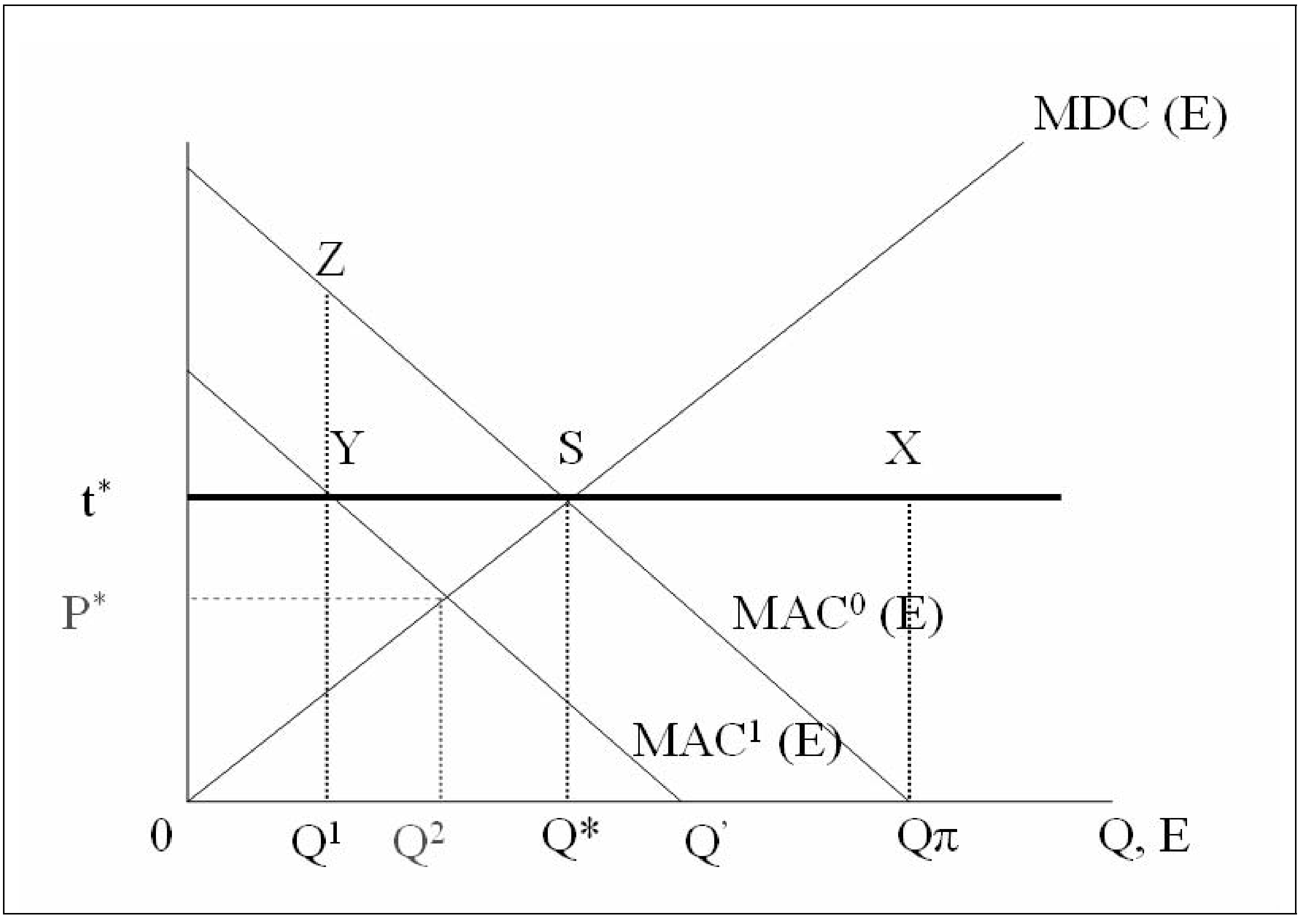
4. Recently, attention has shifted to the link between technological change or innovation on the one hand and (economic) growth on the other hand (see, for instance, Aghion, Blundell, Griffith, Howitt and Prantl, 2006) as well as to the underlying incentives that fuel innovation (Aghion and Tirole, 1994).

5. Note that this distinction associates learning with diffusion of technology and/or knowledge across agents (firms, households) and R&D with innovation, *i.e.* invention and application of new technology and/or knowledge.

Figure 2. Dynamic incentives from environmental regulation



17. The differential impact of environmental policy instruments on technological change could easily be understood using Figure 2. This figure illustrates technological change as an inward shift of the abatement cost curve. The idea behind this shift could be explained as follows. Assume that a firm producing an amount Q_π in the *status quo* faces the introduction of a tax t* on emissions. Then it may avoid paying $0t^*XQ_\pi$ by reducing waste or adopting currently available and relatively inexpensive add-on technologies described by the marginal abatement cost curve $MAC^0(E)$. Equivalent incentives could be expected from CAC regulation that forces the firm to adopt this technology and produce at Q*. With a tax or (a yearly) auctioned tradable permits (TDP), the firm still faces additional payments equal to 0t*SQ*. To avoid paying for the remaining emissions infinitely, this (or other) firm(s) could also invest in invention or innovation to develop new abatement equipment with lower remaining emissions and therefore tax payments. If successful, this leads to an outward shift of the production possibility set (higher emission abatement for a given input), which, as a consequence, induces an inward shift of the abatement cost curve (lower costs per unit of emissions abated). This technology, labelled $MAC^1(E)$, reduces tax payments substantially to $0t^*YQ^1$. So as long as the cost of the new investment are below the tax savings Q^1YSQ^*, it pays for the firm to adopt the new technology.

18. Such incentives for invention and innovation do not exist if a firm does not expect future CAC regulations to be more strict than those currently applied, say at the level of Q*. If the firm complies with these regulations and abatement costs $MAC^0(E)$ are sunk, no additional benefits can be expected from investing in the new abatement equipment labelled $MAC^1(E)$. If the firm, however, expects future

regulations to be stricter, strong incentives remain to invest in the development of new technologies.[6] To date, the firm would save Q^1ZSQ^* from the new technology under this new regulation which could even be larger than the savings under a tax scheme.

19. Note also the remarkable difference between a tax and a TDP system. Whereas the tax level t* will remain at its original level, unless the government explicitly decides to change this, the tradable permit price will automatically be lower in equilibrium (given by P*) because of the induced shift of the MAC curve. As a result pollution will be higher ($Q_2>Q_1$). The new abatement options reduce the shadow price of pollution which is reflected in the new permit price and pollution level, and could also be seen as a rebound effect of the new invention. So much depends upon the timing and commitment of the regulatory policy, which also basically explains why the literature no longer conveys the simple message explained in the previous paragraph. It should be noted, however, that the original conjecture that additional dynamic incentives apply to taxes and (yearly) auctioned permits is still valid ceteris paribus, *i.e.* in a static framework with an equivalent regulatory outcome.[7]

2.2.3. Identification issues

20. There seems to be strong agreement among economists' that different types of regulation matter for the rate and direction of technological change. Indeed, Requate's (2005) survey reveals that it is easy to find evidence for such differential impacts in the theoretical literature. Unfortunately, when it comes to characterize the differences, let alone to rank them, the picture is much less clear cut. Nevertheless Requate defends the conjecture that "instruments which provide incentives through the price mechanism, by and large, perform better than command and control policies. Even so, it is important that the regulator either anticipates the new technologies to a certain extent or reacts in an optimal way on invention and adoption of new technology." (Requate, 2005, p.193).

21. If no theory brings a clear ranking to light, one might hope that empirical studies would do this job. However, only a small literature exists on the empirical evidence of a differential impact of instruments on technological change. This is hardly surprising. First of all, environmental regulation has mainly used CAC instruments and the use of market-based instruments is (still) rather limited (Stavins, 2003). Second, the same environmental issue is often tackled with a mix or cocktail of instruments, *i.e.* different instruments, like (technology) standards, taxes and subsidies, at the same time. Though from an econometric perspective nothing, in principle, prevents identification of the effect of different instruments, such an evaluation requires many data which are often not available. Third, the alternative approach to compare the use of an instrument with the use of another in more or less similar circumstances is also rarely used in practice. Even though such so-called field experiments also produce reliable effect estimates (Train, 1994), concerns about unequal treatment often prevent this kind of experiment in practice. Fourth, studies that compare instruments in environments where economic conditions are controlled (like in an experimental setting) are also virtually non-existent. Finally, current empirical assessments have a tendency to be biased towards observable information, like changes in abatement costs, number of patents (citations), physical characteristics of technologies, etc. Therefore, these studies do not report effects of

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6. Firms might also anticipate that investing in new (cost-efficient) technologies could be observed by the regulator, who in turn responds by tougher regulation. Such expectations clearly make innovation and diffusion more costly to occur.

7. See Requate (2005) for a much more extensive discussion of the recent literature on timing and commitment problems of environmental policy instruments.

regulation on organizational design, change in attitudes, etc.[8] Moreover, there is a serious identification problem as to whether abatement cost measures properly account for technological change (see below).

22. Despite the problems to measure the differential impact of instruments directly, an increasing amount of material becomes available. First of all, several studies now document the impact of environmental policy on technological change and its inducement in a more environmentally friendly direction in several areas (see also Jaffe *et al*, 2002). Furthermore, there is some evidence for "stand-alone" evaluation of instruments which enables comparison of effects across studies. Third, some direct (and indirect) evidence exists as to whether price or quantity regulation makes a difference in a number of cases where market instruments have been applied, in particular in the US. Finally, some studies tried to assess to what extent environmental policy may also have had an effect on the overall rate and direction of technological change.

23. Our hypothesis is that (different) instruments are likely to have a (differential) impact on technological change. To date, in the early days of environmental regulation the focus has been almost entirely on standard setting or technology prescriptions (*e.g.* prescriptions of "Best Available Techniques"). This encouraged the adoption of so-called add-on technologies, like scrubbers. When it appeared that these signals would remain and were likely to become more stringent, firms also started to engage into the development of entirely new (add-on) technologies but also in "integrated technology". This process can be observed in many areas, like water sanitation and purification, air pollution control (smog, acid rain particles, etc) and waste management. The same holds for technologies that are both directly and indirectly responsible for emissions, like energy generation technologies or energy-consuming technologies and products. After an initial phase of retrofitting, usually a search starts for a technology design that captures concerns of energy and/or emission efficiency from the very beginning.

24. Against this background it is useful to explain how our hypothesis could be tested and what indicators might identify this interaction. First of all, the introduction of environmental policy and its subsequent prolongation signals to (new) producers whether it is profitable to engage in R&D or not.[9] If so, one would expect to observe a rise in R&D activity specifically dedicated to the invention of new technologies (products) or the improvement of existing ones. Invention of new technologies (products) is usually identified by proxies that:

- measure the (cost of) input to (additional) R&D, like number of researchers or R&D "expenditures";
- measure observable output, like "patents" and their citations.

25. Note that spillovers and economies of scale in research make it difficult to identify R&D input specifically dedicated to environmental technology, in particular if we consider integrated technology. Similarly, measuring invention of new technologies through patents also has drawbacks. For instance, firms may not always patent to protect their rents or "over"-patent as strategic deterrence (Cohen, Nelson and Walsh, 2000; Jaffe and Trajtenberg, 2002). Also invention of new *products* is hardly to be observed directly, but usually only through indicators for innovation. Citations of patents account for relative importance of the different patents or can be used to show knowledge flows among inventors.

8. There is a growing literature trying to empirically investigate these linkages as well. See, in particular, Labonne and Johnstone (2006) and Rennings, Ziegler, Ankele and Hoffmann (2006).

9. In the current theoretical literature on environmental policy, it is crucial to distinguish between the possible timing and commitment strategies of the regulator and the firm, where each of them can be assumed to move first.

26. If it appears that environmental stringency is not a casual exercise, and perhaps even cycles of increasing regulatory stringency might be expected, one is also likely to see more of the inventions being commercialized. *Innovation* is an activity that uses inventions as a starting point where often R&D staff is no longer involved. The outcome is usually implementation of new technologies in the production process or new marketable products. So innovation proxies for new technologies and products are:

- measures of inputs, like marketing staff using available stock of patents;
- measures of output, like entirely new technologies or products, changes in physical characteristics of already existing technologies or products, and changes in cost per unit of abated emission.

27. Note that output measures of innovation could be typically observed by looking both at production processes of firms using new technologies as well as at typical products sold to consumers, because innovation is typically a marketed invention that could be sold either to firms (new technologies) as to consumers (new products).

28. Finally, environmental regulation is also likely to play a role when it comes to the diffusion of these innovations. Diffusion of a new technology or product reflects the ultimate impact of a particular invention and its subsequent innovation. In particular the size of the market for a new technology or product is likely to depend on the number of regulated firms. If, for instance, the government provides a tax credit for specific investments, one is likely to observe a faster and stronger penetration of those investments. Proxies to measure this impact are:

- measures of scale, like the number of firms or households that typically use this new technology or product, but also exit of firms that do not innovate
- measures of cost improvements, like changing (overall) abatement costs.

29. Note also that market exit is an indicator of innovation.[10] One would not expect a random selection of firms to leave a regulated market, but typically those firms that have substantial problems to adapt to the new (regulatory) environment. This process might be difficult to observe, however, because new regulatory regimes typically phase-in gradually, applying first to new "entrants" and then to the incumbent firms if they switch to new vintages (Levinson, 1999). Abatement cost changes are another indicator that account for the adoption of new technology. Lower abatement cost for a given emission reduction activity is likely to reflect the arrival of either new technologies ("innovation") or cost savings from the use of a given technology on a wider scale ("diffusion" or "learning"). As economists typically expect abatement cost to rise for a given emission-output production possibility set, reductions in abatement cost are often seen as an indicator of dynamic effects.

3. Environmental Policy and Induced Technological Change

30. This section reviews the empirical literature on the impact of environmental policy on technological change at a general level. The papers that focus on this linkage are summarized in Table 1. These papers show that indicators, like R&D expenditures and patents, are sensitive to environmental policy regulation. From the theory we know that innovation and diffusion respond to changes in relative prices (Aghion and Howitt, 1992; Acemoglu, 2002). Hence, changes in the rate and direction of technological change can also be induced by purposive changes in relative prices, for instance by a

10. One might call this the 'inverted' Porter hypothesis. According to the Porter hypothesis (certain) innovative firms could gain from regulation and, in addition, could even have a positive effect on overall economic growth.

regulator who introduces emission taxes. Note that also CAC regulation would have such an impact because this raises the (implicit) price of emissions (*e.g.* Copeland and Taylor, 2004; Fullerton, 2002). Moreover, technology choice (including investment in invention) is also likely to be affected by indirect mechanisms that may have a beneficial effect on the environment. For instance, a rise in the energy price would shift technological change towards less energy-intensive technologies which, in turn, also reduces emissions as long as energy and emissions are complements.

31. To identify the link between environmental regulation and technological change, one would like to look at the consequences of (changes in) the stringency of regulation for existing firms or sectors as measured by its implied (changes in) shadow price. For instance, if regulation is currently not binding the shadow price for the environment (or emissions) as an input is zero, and no effects are to be expected. If (expected) regulation becomes binding, however, the (expected) price becomes positive and firms start to exploit several mechanisms to reduce emissions or the cost of abatement, like output reduction, substitution of inputs or direct abatement (see Smulders and Vollebergh, 2001). Future (expected) cost can be reduced by investing in ("environmental") R&D that, if successful, is likely to reduce future abatement costs.

32. The available empirical papers, however, follow a somewhat different path. Because shadow prices are usually unavailable, stringency is measured through proxies. The most important proxy is measures of pollution abatement cost (PAC). This indicator has the obvious advantage that it captures cost consequences of different types of regulation at the firm or sector level, and therefore aggregates implications across different policy dimensions. A set of studies in the late 1990s used PAC to demonstrate that there is some association between higher abatement cost and the propensity to invest in productive R&D and its likely output, filed patents for environmental technologies. Lanjouw and Mody (1996) were the first to show that this association can be measured across the world. Using patent data at the country level between 1971 and 1988, they explored the number and distribution of environmentally related patents and their diffusion across the world. They found a substantial rate of concentration of such patents, in particular in Germany, Japan and the USA. Environmental regulation as measured through PAC as a percentage of GDP also correlates with the share of environmental patents in the total number of patents for these countries. Lanjouw and Mody also observed that innovators in developing countries obtained a nontrivial number of patents and that substantial imports of foreign patents occurred.

33. Jaffe and Palmer (1997) explore the association between environmental policy and technological change at the industry level for the US. Using patents as well as measures of R&D between 1974 and 1991, they found that there is a significant correlation within industries over time between the rate of (lagged) expenditure on pollution abatement and the level of R&D spending, although the magnitude of this effect is small. Furthermore, no such correlation could be observed with overall patenting. In contrast to the latter finding, Brunnermeier and Cohen (2003) report a positive correlation when also including the number of inspections as a measure for the intensity of regulation. In their study of the US manufacturing sector between 1982-1992 patents respond to increases in PAC, but not to increased enforcement. Also industries that are internationally competitive are more likely to innovate.

Table 1. Empirical studies of the effect of environmental policy on technological change

Authors	Main focus	Policy Driver and Indicator	Data set	Main result
Lanjouw and Mody (1996)	Innovation	Environmental regulation (PAC) on share of environmental/ total number of patents	Country data 1971-1988	Share between 0.6 and 3% in Germany, Japan and USA; patents correlate with PAC for these countries; imports of foreign patents substantial in developing countries
Jaffe and Palmer (1997)	Invention and innovation	Environmental regulation (PAC) on R&D expenditure and patents	US manufacturing sector panel data 1974-1991	Lagged PAC has a positive effect on R&D expenditure, but little effect on patents
Becker and Henderson (2000)	Diffusion	Environmental regulation (CAA - attainment or not) on plant births	Large plant data set 4 manufacturing sectors 1967-1992	Differential in county air quality attainment status favors attainment areas reducing births for polluting industries in non-attainment areas. Large preregulation plants benefit from grandfathering.
Brunnermeier and Cohen (2003)	Innovation	Environmental regulation (PACE and inspections) on patents	146 US manufacturing sector panel data 1982-1992	Patents respond to increase in PAC, but not to increased enforcement; industries that are internationally competitive more likely to innovate
Popp (2002)	Innovation	Energy price on patents of energy-supply and demand technologies and citations	US energy patent data 1970-1994 and productivity estimates using citations	Energy prices and quality of existing (stock of) knowledge strongly effect innovation
Snyder, Miller and Stavins (2003)	Innovation and Diffusion	Environmental regulation (dummies) on adoption of membrane cell technology and exit of firms	51 US chlorine manufacturing plants 1976-2001	Regulation increases price of chlorine and as a result exit of facilities using environmental inferior options; adoption of technology was not directly affected (hazard model)
Gray and Shadbegian (1998)		Environmental regulation (PAC) on firm investment	116 US paper mills 1972-1990	New mills respond to stricter regulation; leads to Crowding-out effects
Shadbegian and Gray (2005)		Environmental regulation (PAC) on productivity	68 US paper mills, 55 oil refineries and 27 steel mills 1979-1990	Abatement expenditures contribute little or nothing to production, but also do not affect productivity of non-abatement either

PAC = Pollution Abatement Costs
PACE = Pollution Abatement and Control Expenditures
CAA = Clean Air Act

34. Two papers of particular interest are Becker and Henderson (2000) and Greenstone (2002). These papers focus on the role of entry and exit of firms in response to environmental regulation, which is an indicator of Schumpeterian dynamics.[11] Both papers use *attainment status* of US counties as a proxy for differences in environmental regulation. Becker and Henderson (200) examine unintended effects of air quality regulation using US plant data for 1963-1992. They use the differential in regulatory stringency as revealed by the annual designation of country air quality attainment status, which has been applied since 1978. The regulator uses this tool as an incentive mechanism with greater regulatory oversight, including specific equipment requirements, on plants in non-attainment areas and more favourable regulation in attainment areas. As a consequence plant births are reduced in non-attainment areas by 26-45 percent, with bigger (polluting) industries and sectors being affected the most. The industrial structure also shifts toward less regulated single-plant firms in these areas, whereas large pre-regulation plants do benefit from grandfathered provisions, but at the expense of environmental degradation.

35. Similar evidence is reported by Greenstone (2002) who looked at these effects at an even more detailed level. Not only does his study operationalise environmental stringency through a simultaneous evaluation of all air regulation, he also studies effects on employment, capital stock and shipments as well for existing and newly opened plants. He also reports a substantial decline in manufacturing activity in non-attainment counties, although it has been modest compared to the entire manufacturing sector. Accordingly both papers nicely document the decline of polluting industries.

36. These findings seem to provide little support for the idea that environmental regulation might trigger "win-win" situations at an aggregated level (Porter and Van der Linde, 1995). However, this might still hide potential "win-win" effects *within* the polluting industry if the cleaner firms have gained relatively to the polluting firms within that industry (*ceteris paribus* the overall decline of that industry). The likely existence of a first "win" has been demonstrated by Snyder *et al.* (2003) when studying the effect of environmental regulation (dummies) on the adoption of membrane cell technology and the exit of firms within US chlorine manufacturing plants 1976-2001. They report that regulation increases the price of chlorine and leads to the exit of facilities using environmentally inferior options. Interestingly, adoption of this technology was not found to be directly affected by this regulation. In other words, without switching to the more beneficial technology firms have a larger chance to exit the industry. Whether this has left the remaining firms to actually gain from this regulation (the second "win") is still unclear, however.

37. Economists typically ask whether environmental regulation might have a drawback on aggregate productivity, for instance because of crowding-out effects on R&D (see Nordhaus, 2002; Smulders and De Nooij, 2003). A given dollar of investment can be spent only once. When this dollar is spent on (research in) pollution reduction, other perhaps more productivity-enhancing options are no longer possible. To assess to what extent crowding-out effects might be present at the sectoral level Shadbegian and Gray (2005) focus on abatement cost for sectors where these cost are relatively large, in particular for paper mills, oil refineries and steel mills. These pollution abatement costs (PAC) are defined as the capital expenditures and operating cost, including labour, materials and depreciation, to reduce emissions to air, water or ground (including waste reduction).[12] Shadbegian and Gray allow their measure of productivity to distinguish explicitly between traditional output and "environmental output", to account for what they call the "mismeasurement effect", *i.e.* productivity measures that do not differentiate between these different goals of input use. Using a micro dataset for plants in the three sectors mentioned, they find that abatement

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11. Attainment status captures – at least implicitly – also what is called New Source Bias of regulations, *i.e.* the fact that the phase-in of new regulation is often a gradual process with the new plants or firms facing the strictest regulations (compare also Levinson, 1999 and a recent paper by Bushnell and Wolfram, 2006).

12. PACs in most industrial sectors are well below 1,0% of total production costs, but for the sectors studied by Shadbegian and Gray these costs are much higher.

expenditures contribute little or nothing to production, but also have no statistical significant effects on the productivity of non-abatement expenditures. Moreover, further decompositions to allow for heterogeneity in production technologies within these sectors provide little evidence for differences across these groups. Note, however, that if environmental technologies become integrated over time, it will be more difficult to measure abatement cost and underreporting may become more likely. These productivity effects require analysis that allows for other potential mechanisms as well.

38. In conclusion, environmental regulation has a serious impact on technological change in general. Not only does this regulation make life more difficult for existing firms by increasing the (implicit) price of pollution, there is also a clear positive impact on invention and innovation of new technologies. Moreover, indirect evidence suggests that an increase in the implicit price of some emissions also boosts patents in complementary areas. In particular, rising energy prices (costs) implicitly raise the cost of emissions responsible for air quality and its inducement of patents (and citations) for energy technologies that are (or become) substitutes (in the future) is also beneficial in reducing emissions as long as these substitutes are also closely correlated with fewer emissions. The use of pollution abatement cost as a proxy to measure the stringency of environmental policy may also have drawbacks. For example, one reason is that the way in which PAC is measured does not account for technological change in abatement (Iovanna, Maguire and McGartland, 2003), which might also explain why its level appears rather constant (as a percentage of GDP) over time (see Brock and Taylor, 2004).[13] A final note is that almost all studies exclusively deal with US environmental policy. Therefore little is known about peculiarities of circumstances affecting results in other countries.

4. Policy instruments and Induced Technological Change

39. A somewhat different approach to explore the linkage between environmental policy and technological change is to study the likely effects of specific instruments on invention, innovation or diffusion of specific technologies. The set of studies discussed in this section identify this linkage for one specific environmental policy instrument. The studies that explicitly consider comparisons between instruments are reviewed in the next section. The papers in this section have been ordered in relation to whether CAC or market-based instruments are analyzed, and they are summarized in Table 2. Note that we do not include studies that deal with technological change only implicitly, for instance studies that measure the effectiveness of policy instruments without explicitly considering their implications on either abatement technologies or cost.[14]

40. The finding that environmental policy does affect technological change is basically confirmed in all studies, with some exceptions. Bellas, for instance, reports no technological progress from standards on Flue Gas Desulphurisation (FGD) units at coal burning plants. Looking at changes in present value FGD expenditures over the life time of (old and new) units as the dependent variable, using installation year as a proxy for vintage, he finds only weak evidence for some cost advantages of new units over older ones. At least as important, however, is his finding that the operating costs of an existing unit decrease over time. During his observation period, *i.e.* 1970-1991, stringency of regulation of new units is determined, in part, by state of the art pollution abatement technology. So any potential rent for the firm due to cost reduction of installing a new and better unit is subsumed by the regulator (by increasing stringency). Existing units are likely to be governed by standards that existed when the unit began operation. Because any cost saving

13. Note that PACs may provide a measure of external regulatory pressures that help induce technological change, and that some PACs are difficult to measure (*e.g.* the PAC component of a new investment project that makes a plant both cleaner and more productive).

14. Examples of these studies are Berkhout, Ferrer-i-Carbonell and Muskens (2003) on the effect of energy taxes on household consumption of energy and studies of the effect of waste taxes on level and composition of household waste (*e.g.* Fullertion and Kinnaman, 1996).

from such a unit would be retained by the firm itself, the firm has a strong incentive to improve operation – which is exactly what has been observed.

41. Popp (2006a) also explicitly considers the effect of a specific type of regulation, in particular standards for NOx- and SO2-emissions for technological change in three countries, the US, Germany and Japan, between 1970 and 2000. Like in his other studies, he measures this change through the filing of patents and, in this case of citations as well. As this regulation was explicitly focused on abatement of NO_x- and SO_2-emissions, it is interesting to see patents of air pollution control equipment respond so strongly. Popp reports that inventors respond to environmental regulatory pressure in their own country, but not to foreign environmental regulations. Citations of existing patents show that domestic inventors are building on earlier Japanese technology. The latter finding suggests that technology transfers mainly appear indirectly, and firms adapt foreign inventions to local circumstances.

42. In his other study, Popp (2006b) looks at the interaction between invention and innovation on the one hand, and the diffusion of knowledge through embodied abatement technology by a specific set of regulated firms, *i.e.* US coal-fired power plants on the other. The narrow focus on patents and adoption of NO_x-pollution control equipment provides an excellent opportunity to explore the interaction of supply and demand of new (abatement) technology in response to emission regulation, in this case NO_x-standards in the US. Popp considers the creation of a patent data knowledge stock between 1970 and 2002, and abatement technology adoption of the very same technologies by 996 US coal-fired power plants 1990-2002. He finds that technological advances, in particular abroad, are important for adoption of newer post-combustion treatment technologies. Again, however, adaptive R&D by US firms can be observed before foreign inventions are adopted. He also finds that expectations of future technological advances delay adoption.

43. Clearly, both studies by Popp confirm the finding in the previous section that CAC policy does affect technological change. The somewhat anomalous finding by Bellas might be due to the different indicator used and the period observed to measure this change. Popp (2005, p.217) has argued that measuring technological change through variations in the time trend might not be a proper way to measure inducement because it "only captures the *overall* effect of technological change" (his emphasis). Technological change in these empirical models is typically measured as a time-related change in (energy or environmental) productivity, after having controlled for changes in labour, capital and energy inputs. This does not tell anything about likely changes in the nature ("direction") of the technologies used. Patent data can be used to measure such changes directly.

44. Three papers have looked explicitly at the effect of earmarked taxes, *i.e.* tax-cum-rebate schemes, on innovation or diffusion in three different European countries.[15] Kemp (1998) shows that diffusion of biological effluent treatment plants in the Dutch food and beverage industry between 1974 and 1991 has been sensitive to the Dutch water effluent charge. In particular, he reports that the timing of the adoption of such plants has been influenced strongly.[16] This result confirms the idea that prospective adopters trade-off the costs of effluent treatment against the savings on effluent tax payments. Kemp also finds that adoption strongly depends on firm specific characteristics, like the use of investment selection criteria which cannot directly be controlled by the regulator. Unfortunately, this study does not explicitly control for the CAC regulation that affected these firms also at the same time.

15. Tax-cum-rebate schemes are an example of the two-part instrument found to be an optimal incentive scheme when pollution or emissions are considered as inputs (see Fullerton, 2005). According to this scheme, the polluter pays a deposit for using the environment as an input and receives a rebate when he abates emissions. Accordingly only *net* emissions are taxed under this scheme.

16. This finding is supported also by older Dutch research on the effect of this tax-subsidy scheme in reducing water effluents.

Table 2. Empirical studies of impact of specific environmental policy instruments

Authors	*Main focus*	*Policy Driver and Indicator*	*Data set*	*Main result*
Command and Control Instruments				
Bellas (1998)	Innovation	Standards on Flue Gas Desulphurisation (FGD) on design, performance and abatement cost	144 FGD units in US power plants 1970-1991	No significant technological progress reported (time trend!), but operating costs decrease over time
Popp (2006a)	Invention and innovation	NO_x- and SO_2-regulation on air pollution control equipment	Patent and citations data US, Germany and Japan 1970-2000	Inventors respond to environmental regulatory pressure in their own country, but not to foreign environmental regulations; any technology transfer appears indirect.
Popp (2006b)	Invention, innovation and diffusion	NO_x-regulation on patents and adoption of NO_x-pollution control equipment	Patent data knowledge stock 1970-2002 and 996 US coal-fired power plants 1990-2002	Technological .advances, in particular abroad, are important for adoption of newer post-combustion treatment technologies; adaptive R&D by US firms necessary before foreign innovations are adopted
Market-based Instruments				
Kemp (1998)	Diffusion	Water effluent charge on diffusion pattern of biological effluent treatment plants	77 Dutch food and beverage plants 1974-1991	Water charge stimulated early adoption of biological effluent treatment plants
Höglund Isaksson (2005)	Innovation	NO_x-charge on abatement cost (PAC) changes	162 energy abatement measures of 114 Swedish combustion plants 1990-1996	Extensive reduction at low cost; learning and technological development in abatement would be present
Millock and Nauges (2006)	Diffusion	Tax on SO_2, NO_x, and HCl emissions, with subsidy for emission abatement	226 French plants from three industrial sectors 1995-1998	Tax reduces emissions of SO_2, NO_x and HCl, but the abatement elasticity with regard to the tax is quite small.
Hassett and Metcalf (1995)	Diffusion	Energy tax credit on residential conservation investment	37,658 US households 1979-1981	Energy tax credits increase probability of investment in energy-efficient capital
Klaassen *et al.* (2005)	Innovation and diffusion	R&D and adoption subsidy on cost reducing innovation	Wind turbine farms Denmark, Germany and DNK	Estimation supports two-factor learning curve (Lbd & LbS) and homogeneous learning curves for the three countries
Aalbers *et al.* (2007)	Diffusion	Adoption subsidy on investment in expensive innovative technology	Students and managers in experiment	Strong behavioural impact of a subsidy in experimental setting for both managers & students
DeCanio and Watkins (1998)	Diffusion	Voluntary green lights program on energy saving investments decisions by firms	9548 US companies with 268 participants	Firm characteristics matter for participation to join and commit to program

45. The study by Millock and Nauges (2006) evaluates the effect of a tax-cum-rebate scheme in France using observations for 226 plants from three industrial sectors between 1995 and 1998. Under this scheme SO2, NOx, and HCl-emissions are taxed and the revenue is returned to this sector. They report that this instrument has contributed to the reduction of emissions of SO2, NOx and HCl, but the abatement elasticity with regard to the tax is quite small.

46. Finally, Höglund Isaksson (2005) studied the effect of the Swedish NOx-charge implemented in 1992. The revenues from this charge are refunded net of transaction costs and firms receive output based instead of emission based refunds. The drawback of output-based refunding is that diffusion of abatement technology is hampered, because firms may strategically prevent information disclosure to other firms (see also Sterner and Isaksson, 2006). Looking at abatement cost (PAC) changes of 162 energy abatement measures implemented in 114 combustion plants, this study estimates that extensive emission reduction has taken place at very low cost. She also finds learning and technological development in abatement to be present. Note that the remarkable differences in abatement elasticities for both studies might be explained by the fact that the Swedish charge is a 100 times higher than the French NO_x tax studied by Millock and Nauges (2006).[17]

47. Subsidies have always met scepticism among economists (see Baumol and Oates, 1988). Indeed, from recent surveys of the adoption literature (Requate, 2005) and market-based instruments (Stavins 2003), it is clear that the economics profession has focused predominantly on pollution taxes, tradable pollution permits and quotas. Despite the fact that the subsidy instrument is not popular among economists, it is actually quite often used in practice. Subsidies appear in many forms: not just explicit investment subsidies are widely used, but also tax deductibility schemes are very common – including investment credits, accelerated depreciation, partial expensing, and exemptions (Jenkins and Lamech 1992; Price et al. 2005; OECD, 2006).

48. One widely studied subsidy program has been the Demand Side Management (DSM) program by electric utilities in the US in the 1990s. The empirical evidence on the effectiveness and efficiency of this program seems to support the economists' belief that subsidies are ineffective and inefficient. However, Hassett and Metcalf (1995) show that energy–conservation credits given to households have been effective in stimulating the penetration of modern energy–saving technologies. Using much better (panel) data at the household level than previous studies, their estimated coefficients suggest that subsidies have been effective after all. Hassett and Metcalf (1995, p.213) reproduce previous results, like Walsh (1989), showing no, or even adverse effects when not controlling for these unobservable characteristics. When including unobservable individual characteristics, like "taste" for conservation, they find that US households invested in energy–saving technologies, like insulation and replacing furnace burners. With these proper controls they find that consumers do respond in a rational way to energy-conservation incentives of a tax credit.[18]

49. In what is perhaps the first experimental study on the behavioural impact of environmental policy instruments, Aalbers *et al.* (2007) analyze the impact of technology adoption subsidies on investment behaviour in an individual choice experiment where managers from firms participated. By using an economic experiment, the authors are able to construct the decision environment of agents in such a way that they all essentially face the same investment decision under slightly different circumstances.

17. The French tax is EUR 0.04573 per kg NO_x whereas the Swedish charge is EUR 4.4 per kg.

18. Nonetheless, Hassett and Metcalf admit that their result adds little to the knowledge of the deadweight loss attached to this subsidy scheme due to so called "free riders", *i.e.* those agents that also in the absence of the subsidy would have invested in energy saving. Some studies report that the numbers of agents whose behaviour is not affected by the subsidy would be high (for example Malm, 1996, Wirl and Orasch 1998, Wirl 2000).

Moreover, the experimental setting is such that the decision-makers also face binding time constraints, to mimic the decision situations that managers in small and medium enterprises find themselves in. In these smaller firms, there is insufficient managerial time available to both search for the best available technology, and, at the same time, follow the output market sufficiently close to maximize profits (see DeCanio 1998). This study finds that subsidies are highly effective as an incentive mechanism even if only a small (expensive) subset of available technologies is subsidized and the subsidy does not make these technologies profitable. The managers realise much higher savings in the treatment with subsidy, compared to the treatment without subsidy. Furthermore, the subsidies seem to induce more radical choice behaviour: managers either adopt (very) early or they do not purchase a technology at all.

50. The importance of firm characteristics for the effectiveness of environmental policy in general and diffusion of new technology in particular has also nicely been demonstrated by DeCanio and Watkins (1998). They report that self-selection of firms participating in the voluntary Green Lights program of the US EPA is evident. Even when controlling for firm-specific differences in risk-classes, firms tend to differ systematically instead of randomly, when participating in the program. It appears that Green Lights membership is positively associated with good performance by firms, and with sectoral and regional characteristics that suggest the importance of informational diffusion.

51. A final study of interest is the case study by Klaassen, Miketa, Larsen and Sundqvist (2005) on the support for wind turbines in Germany, Denmark and the United Kingdom. As explained in this paper, progress in wind turbine technology as well as the accumulated experience in producing wind turbines, is likely to be affected by initial R&D subsidies and a gradual shift towards adoption subsidies to increase demand in a later stage.[19] The findings of Klaassen et al. (2005) suggest similar learning curves for the different countries. Import indicators for the UK (80%) as well as Germany (40%) reflect a leading role for Denmark, which is hardly surprising because Denmark supported investment in innovation for windmills much earlier than the other countries. Accordingly, this case study provides casual evidence for the Porter hypothesis, although it remains unclear whether environmental policy is beneficial in this case even beyond the environmental dividend itself. Moreover, a case study can never generate a general confirmation of any hypothesis, but it does seem to give some indication that at some specific place and time, environmental policy might be favourable to growth in particular sectors.

52. The studies reviewed in this section all explicitly deal with specific environmental instruments and their likely effect on invention, innovation or diffusion. These studies often claim that such effects exist, but its identification is not always convincing. Moreover, the studies are often difficult to compare. First of all, instruments have specific design features that determine their incentives which, in turn, is likely to have an impact on their effectiveness. Second, local circumstances tend to differ and isolation of policy effects is usually very difficult. Third, specific indicators used to measure technological change may differ. The overall impression though is that environmental policy instruments, whether they are CAC or market-based, have a clear impact on technological change. To find out more about the differences in their dynamic impacts, we now turn to studies that take this perspective explicitly into account.

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19. The innovation and diffusion mechanism is studied here using the so called two-factor learning curve (see Kouvaritakes et al., 2000), which is a typical bottom-up perspective on the development and spread of new technologies. According to this concept cost reductions for particular technologies arise out of two kinds of learning. The first mechanisms is called ‘searching’ and typically arises because of investment in the stock of R&D (and its lagged effect). The second mechanism is labelled ‘learning by doing’ but this concept is somewhat more general here, because it not only allows for improvements in (on the spot) applications of such technologies and their uses, but for the development of ‘new’ technology as well. The typical empirical indicator is cumulative capacity as it is assumed that this type of learning grows the more of the technology is applied.

5. Differences in Dynamic Impacts of Policy Instruments

53. This section reviews studies that explicitly analyze the differential impacts from different types of environmental policy instruments on technological change. For a long time, comparisons have only used indirect evidence given the lack of market-based instruments in practice and/or the availability of data to evaluate them. In particular, several studies looked at CAC versus energy price effects. Only recently have some papers become available that compare the effects of CAC instruments versus market-based instruments for some interesting cases. The papers are summarized in Table 3.

54. The first set of studies uses variation in energy prices as a proxy for variation in the stringency of market-based instruments and compares their effects with those of CAC instruments. Note that a rise in the energy price is also likely to shift technological change towards less energy-intensive technologies which, in turn, also reduces emissions as long as energy and emissions are complements. In particular, several studies used hedonic price functions to examine the effects of public policy in the context of home appliances and energy-efficiency of automobiles. Such cases are used to study the differential impact of instruments on variation in different indicators of technological change.

55. The interesting study by Newell, Jaffe and Stavins (1999) used a product-characteristics approach to evaluate the relative impact of energy prices and changes in energy-efficiency standards. This approach captures the important effect of invention creating new “models” with characteristics that were not previously feasible and innovation commercializing models that were not previously offered for sale.[20] They apply their approach to the changing energy characteristics of models of air conditioners and gas water heaters between 1958 and 1993. The evidence suggests that the rate of innovation was independent of energy prices and regulations, whereas its direction is induced for some products. Energy price changes also had a considerable effect on the subset of technically feasible models offered for sale, and this responsiveness increased substantially after product labelling was required. Regulations worked largely through energy-inefficient models being dropped (“exit”), which is in fact the intended effect of energy-efficiency standards.

56. Two other, somewhat older studies, studied indirect effects of changes of implicit emission prices, like changing fuel prices. The study of Greene (1990), for instance, looked at the interesting practical experiment provided by standards imposed on fuel efficiency of automobiles. Older studies report that the fuel efficiency of new cars in the US responds more than proportionally to changes in (expected) fuel prices (see Jaffe *et al.* (2002), p.60-61). Greene showed that the CAFE standards introduced by the US government also had an effect, in particular for US automobile manufacturing firms. He estimates that the CAFE constraint was binding for US based firms and not for foreign (European and Japanese) firms. Specifically, CAFE standards had perhaps twice as much influence as gasoline prices. Accordingly, the experiment in the car market suggests that the responsiveness of technological change to prices is significant, but also that binding standards could be exploited as an important vehicle for technological change.

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20. According to this approach induced innovation is the movement in the frontier of feasible models that reduce the cost of energy efficiency in terms of other attributes (see Newell *et al.,* 1999, p. 943ff).

Table 3. Empirical studies of differential impacts of environmental policy instrument

Authors	*Main focus*	*Policy Driver and Indicator*	*Data set*	*Main result*
Indirect Instruments				
Greene (1990)	Diffusion	Gasoline prices vs. CAFE standards on increasing fuel economy	15 sets of manufacturer CAFE data for 1978-89	CAFE standards were a significant constraint for many manufacturers, and were perhaps twice as important an influence as gasoline prices.
Jaffe and Stavins (1995)	Diffusion	Energy price vs. building codes on adoption of thermal insulation technologies in new residential construction	US State level data on thermal insulation 1979-1988	Mean energy efficiency increases with higher energy prices (adoption decisions are more sensitive to up-front cost than to longer-term operation expenses)
Newell, Jaffe and Stavins (1999)	Invention and Innovation	Energy price vs. regulation on new models offered for sale	Energy characteristics of air conditioners and gas water heaters 1958-1993	Rate of overall innovation independent of, but direction responsive to energy prices and regulations; in particular subset of technologically feasible models offered for sale
Direct Instruments				
Revelt and Train (1998)	Diffusion	Rebates or loans on high-efficiency appliances households in the US	6,081 choice experiments of 401 customers	Demand Side Management is effective, but loans have larger impact than rebates (plus more profitable for firm)
Kerr and Newell (2003)	Diffusion	CAC and TDP under US lead phase down	378 US refineries 1971-1995	Increased stringency encouraged greater adoption of new technology; differential between adoption propensity of expected permit sellers relative to expected permit buyers higher under TDP than under CAC
Carlson, Burtraw, Cropper and Palmer (2000)	Diffusion	CAAA with CAC and TDP-SO_2 on marginal abatement costs	734 units of US power plants 1985-1994	Declining marginal abatement cost for both CAC and TDP due to fuel switching and technological change (time trend!), cost savings are (relatively) larger under TDP
Popp (2003)	Invention and Innovation	CAAA with CAC and TDP-SO_2 on patents of scrubbers	180 FGD units in US power plants 1972-1997	Little evidence that new patents before 1990 improved ability of scrubber technology, but patents granted during TDP system during 1990s improve removal efficiency of scrubbers
Lange and Bellas (2005)	Innovation and Diffusion	CAAA with CAC and TDP-SO_2 on scrubber cost	Comparison of 157 pre- and 40 post CAAA boilers US power plants 1985-2002.	More recent scrubbers are cheaper to purchase and operate than older scrubbers, but these cost reductions seem to be a one-time drop rather than a continual decline

PAC = Pollution Abatement Costs
PACE = Pollution Abatement and Control Expenditures
CAA = Clean Air Act
CAAA = Clean Air Act Amendments 1990
CAFE = Corporate Average Fuel Economy
TDP = Tradable Permits

57. The study by Jaffe and Stavins (1995) also looked at the relative importance of CAC versus market-based instruments for the diffusion of new technology. In particular, they evaluate the role that (changes in) energy prices and building codes had on adoption of thermal insulation technologies in new residential construction in the US between 1979 and 1988. They find that the mean energy efficiency increases with higher energy prices and rising adoption cost. Using an economic model to explain the relative magnitudes, their estimates suggest that ad valorem energy taxes in the 10 to 25% range have noticeable impacts on the energy efficiency of new homes, and that this impact would be felt rather quickly. Adoption subsidies of similar magnitude would have an even larger impact because adoption decisions are found to be more sensitive to up-front cost than to longer-term operation expenses (Jaffe and Stavins, 1995, p. S 59). As far as direct regulation is concerned, they also did not find any discernable effects on building practices. This might provide some evidence that if (new) standards are set below existing standards they will have no effect on the margin, whereas energy taxes (and subsidies) always do.

58. Further evidence that reducing up-front cost (or postponing cost) do have considerable impact on adoption decisions is provided by the paper of Revelt and Train (1998). They studied the relative importance of rebates or loans on the adoption of high-efficiency appliances by households in the US. The typical subsidy employed under the Demand Side Management approach by the US electric utilities is a rebate to induce households to adopt these appliances. To study the potential effect of loans, Revelt and Train used stated-preference data to estimate its relative effect to rebates. Using 6,081 choice experiments of 401 customers, they concluded that Demand Side Management is effective, but that loans have larger impact than rebates. Moreover, these loans are more profitable for the household. This is surprising because if up-front costs were the basic problem, the individual would prefer the rebate over a loan (of equivalent money). As explained by Revelt and Train (1998, p.652), however, individuals may not be indifferent and they see the subsidy as a signal. A rebate is a "giveaway" over which customers may wonder what its motivation is, whereas it is clear for a loan that the lender makes money from it. If individuals start wondering about its motivation their behaviour is likely to be affected. For instance, if the individual is suspicious about the benefactor he might not buy the appliance, just for that reason.

59. Finally, at least four recent studies have analysed CAC instruments against the use of tradable permits. I start with a recent study by Kerr and Newell (2003) on the relative effectiveness of CAC and tradable permits in the US lead phase-down in the 1980s. This was the first case where TDP were applied in practice, in particular in controlling the lead in leaded gasoline between 1983 and 1987. Kerr and Newell employ a unique panel on 378 US petroleum refineries between 1971 and 1995 to study adoption decisions by refineries of lead-reducing technology under different regulatory regimes.[21] Diffusion is considerably different under the two regulatory regimes. In particular, the positive differential in the adoption propensity of expected permit sellers (*i.e.* low-cost refineries) relative to expected permit buyers (*i.e.* high-cost refineries) was greater under the market-based regime than under individually-binding, but non-tradable, performance standards.

60. The remaining three studies to be discussed all focus on the differential dynamic impact of TDP and CAC in the case of the US Clean Air Act Amendments (CAAA) that allowed emissions trading since 1990. These case studies clarify why it is so difficult to identify such impacts and therefore provide further evidence of the importance of proper comparison between policy regimes applied in practice. First of all, Carlson, Burtraw, Cropper and Palmer (2000) make clear why simple correlations between the introduction of an instrument, like allowance trading in the case of CAAA, and abatement cost reductions should be

21. Kerr and Newell's (2003) evaluation is based on a theoretical model of technology adoption. According to this model firms adopt gradually if costs fall and increased stringency increases the value of adoption. Firms with lower benefits or higher costs will adopt more slowly. Divergence in adoption propensity between low versus high compliance cost plants is also expected under different regulatory regimes, in particular under a TDP system and an individually binding performance standard.

treated with care. As they explain in detail, some officials suggest that the introduction of allowance trading of SO_2 was the main reason for the strong decline in abatement cost of SO2 as measured by the permit price. Indeed, *ex ante* estimates of marginal abatement costs produced at the time that the CAAA were written, were as high as $ 1,500, whereas the allowance price, which is an *ex post* signal of marginal abatement costs, was only around $ 100 in 1997. Instead of making inferences about the causality of the introduction of the allowance scheme, one might equally well see this as evidence that the (*ex ante*) estimate was simply wrong. Similarly, it would be false to attribute this effect to the trading mechanism per se as well as to dynamic effects that would have been raised by this scheme.

61. Carlson *et al.* (2000) aim to carefully separate between reduction in abatement cost due to trading on the one hand and other reasons, like fuel substitution or the instalment of new technology, on the other hand. They estimate marginal SO2 abatement costs for 734 units of US power plants between 1985 and 1994. Their estimates suggest that the decline in marginal abatement costs could be attributed to technical improvements (as measured through the time effect), including advances in the ability to burn low-sulphur coal at existing generators, as well as improvements in overall generating efficiency, but mostly to a decline of fuel costs. Further estimations to identify the potential gains from trade under the TDP regime suggest that under both CAC (phase I) and the allowance regime (phase II) marginal abatement costs have fallen.[22] Finally, this study provides estimates of potential cost savings of trade and show that they are (and will be) considerable for the TDP regime.

62. The paper by Lange and Bellas (2005) focuses on the effects of the policy differential on advancement in scrubber technology only. As discussed before, Bellas (1998) found little evidence for cost advances of new technologies as employed by power plants in the pre CAAA period from 1970 and 1991. Bellas only found learning effects over the use of existing technologies. In their paper, Lange and Bellas estimate the effects of allowance trading on scrubber costs using a hedonic model. The model does not focus on the reduction in compliance cost, but on the scrubbing costs instead, in order to isolate a potential dynamic (technology) effect. Like the paper by Newell *et al.* (1999), this paper identifies technological change by adjusting cost changes for design and operating parameters. They find more recent scrubbers to be cheaper to purchase and operate than older scrubbers, but also that these cost reductions are a one-time drop, rather than a continual decline.

63. Popp (2003) also looked at advances in scrubber technology, in particular at the invention stage. He combines the filing of new patents for scrubbing technology with the actual instalment of this technology in 180 FGD units in US power plants between 1972 and 1997 to study the effect of these patents on pollution control. He finds that the level of innovation for FGD units, measured by the number of successful patent applications by year, was actually higher before permits were introduced in 1990. However, the new patents from before 1990 have not improved removal efficiency of scrubbers. Innovation focused only on reducing operating costs, which is basically in line with the finding by Lange and Bellas (2005) for the same period.[23] After the allowance trading system was introduced, innovation not only lowered scrubber costs but also improved removal efficiency. Accordingly, the change to market-based environmental regulation did not induce more innovation, but lead to more environmentally friendly innovation.

64. Clearly, the case of introducing allowance trading of SO2 in the US for electric utilities has had an impact on the direction of technological change in this area. This impact, however, very much depends on how it is identified. In particular, as also noted by Popp (2005, p. 219), the type of policy affects the nature of innovation, and this nature remains hidden in overall abatement cost estimates with a time trend

22. Note that as a consequence, the gains from trade should fall as well (See Carlson *et al.*, 2000, p.1295).

23. There remains a difference, however, as to whether operating costs did fall prior to CAAA of 1990 (Popp, 2003) or did not (Bellas, 1998).

measuring technological change. These insights illustrate that the effect of environmental policy on technological change may not always be properly identified by looking at abatement cost changes alone. Together the studies reviewed in this section illustrate how difficult it is to identify dynamic impacts of policy instruments, in particular their differential impact. One serious drawback is again that these studies are all for the US only and it would be interesting to see whether the use of market-based regulation in other countries might be location or culture specific or not.

6. Conclusions

65. The papers reviewed here clearly observe changes in invention, innovation and diffusion of technologies, although the direct causal link with environmental policy is not always clear in specific cases. The overall conclusion seems justified that environmental policy in general has an impact on at least the direction of technological change. This conclusion holds, regardless of the type of instrument applied, *i.e.* whether CAC or market-based instruments are used. Indeed, in the early days of environmental regulation the focus was almost entirely on standard-setting through technology prescriptions (*e.g.* prescriptions of "Best Available Technologies"). Such prescriptions are almost by definition technology-forcing and binding because these prescriptions imply emission constraints that reduce the number of options in the emission-output possibility set. The most important effect of this (standard-setting) policy (also corroborated by several of the studies reviewed here) is that they induce exit of the dirtiest firms operating in the market.

66. Equally impressive are the strong correlations between specific type of regulations and the R&D process as measured through patenting behaviour. One telling example is Popp's (2003) finding that the nature of inventions and innovations shifted from new models of SO_2 removal technologies towards further improvements of existing FGD models when the CAA allowed firms to exploit rents from (emission) permits trading. Apparently, and in line with what economists suggest, innovators look carefully for rent opportunities which, in turn, depend on the specific incentives signalled by the type of (environmental) policy. This is also precisely what could be learned from cases providing indirect evidence of price incentives, like the rise (and decline) in fossil fuel prices (*e.g.* Newell *et al*., 1999). Emission reductions clearly benefit from taking a free ride on higher *implicit* emission prices due to rising energy prices, because most fossil fuel use is closely linked to air quality emissions. Changes in energy prices have had strong impacts on invention, innovation and diffusion of more energy-efficient technologies which, in turn, has lowered emission levels as well.

67. If incentives are so important and technological change is so sensitive to the type of regulation being applied, the old adage of economists that market-based instruments have stronger dynamic impacts deserves some nuancing. The evidence here is somewhat different from what one might have expected based on the early environmental economics literature on instruments, but less so if we take the recent advances in the theory into account (see also Section 2.2.2). In particular, the papers suggest that also standards imposed under CAC provide clear signals as to what physical properties of production processes are undesirable, which in turn could be targeted by inventors. The greater flexibility provided by TDP systems seems to direct both R&D and innovation efforts away from fundamental research on entirely new opportunities, and towards using the flexibility opportunities provided by this type of regulation of existing technology. This suggests crowding out effects are also triggered by the type of signals provided by the regulator. One explanation could be that standard-driven technological change is directed by the physical signal given by the standard. For instance, if the standard is in gram emission per unit of time, inventors are likely to focus on new technologies that reduce this particular target.

68. Given that the design of signals is crucial, future research of the dynamic impact of environmental instruments should take this issue more serious (*e.g.* Laffont and Tirole, 1996). First of all, more empirical research on the timing and commitment by the *regulator* is important. Currently, little or

nothing is known about the role of the regulator itself. Second, we already know that an *ad valorem* and a specific tax are equivalent in terms of their *economic* incidence only under specific circumstances (like the absence of monopoly power or quality differentials of goods (Keen, 1998)). For environmental externalities it is quality and direction that matter, and the relevant incidence – from a social perspective – is in terms of the tax's contribution to the internalisation of a specific externality. Learning more about the dynamic effects of specific design of a given instrument, like taxes, subsidies, standards or TDP systems., is important For instance, subsidies are usually targeted to specific technologies (a firm is only eligible to a subsidy if it invests in technology X). Therefore, the choice of the technology being subsidized is essential for its dynamic impact. Also, signalling by taxes depends on the choice of the tax base: the stronger the linkage to specific emissions, the more directed the search for new technologies will be. With low levels of tax, however, this responsiveness is likely to be small anyway. So it is also important to compare instruments from an effectiveness perspective: to what extent are the different policy instruments (and their design!) politically feasible and/or object of rent-seeking behaviour by the regulated agents. This is a topic beyond the scope of this review, however.

69. The main conclusion is that proper design of instruments is extremely important. The common (and rather broad) distinction between CAC and market-based instruments may sometimes be too general, and may require modification. It would be recommendable to pay much more attention to the implication of choosing proper signals. In choosing between both sets of instruments it is still important to note that financial incentives are usually stronger under market based instruments, like a tax. Moreover, technology-related information requirements for public authorities are much lower when using a tax compared to when using technology standards. This reduces the space for rent-seeking and the potential to misdirect innovation. In addition, taxes allow for more flexibility from the part of the regulated agent, reducing adjustment costs and optimising entry/exit and capital turnover rates. As noted before, however, introducing taxes is not devoid of design problems either (Vollebergh, 2004). From a political economy perspective it is important to announce it early to help with capital stock adjustment, if a refund is applied it should be lump sum or in a manner which is exogenous to the abatement decision, and the tax should be levied as close to the externality as possible to avoid misdirection (OECD, 2006b).

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