The Role of Environmental Taxation in Spurring Technological Change[1]

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1. Introduction

Do environmental taxes change the use and even invention of new technologies? This simple question has not generated much interest in the literature until recently. For a long time the focus in most contributions, in particular by economists, has been on the (static) cost effectiveness or efficiency of such taxes since the seminal contribution by Baumol and Oates (1971). So called Pigovian taxes guarantee cost efficiency because agents, like consumers or firms, select the lowest cost options when they are confronted with a price on environmental pollution.[2] For this simple theorem to hold, variety in cost of different *existing* abatement options is enough and *new* technological options are not at all necessary.

Despite this focus on the cost effectiveness potential, dynamic impacts have always generated some interest. Kneese and Schulze, for instance, pointed out long ago that ‘over the long haul, perhaps the most important single criterion on which to judge environmental policies is the extent to which they spur new technology toward the efficient conservation of environmental quality’ (Kneese and Schulze, 1975, p.38). Indeed, it is hardly disputed nowadays that environmental taxes can be of critical importance to the inducement and diffusion of *new* technologies or ‘technological change’ for short. Imposing an environmental tax on a polluting activity is likely to increase effort to generate new ideas about abatement

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2 The necessary condition for static efficiency is that marginal abatement costs are equalized across firms, and in this respect instruments like emission taxes or tradable emission permits are generally preferred to quotas, performance standards and investment subsidies (Baumol and Oates, 1988).

options, subsequent filings of new patents, pilots of new technologies, changes in process and product characteristics, and, finally, a reduction in emissions at lower cost.

In the early days the focus in environmental regulation was almost entirely on standard-setting such as uniform reduction percentages across pollution sources, input restrictions, product requirements and technology-specific prescriptions (Downing and Hanf, 1983; Opschoor and Vos, 1989). Much has changed since. Clearly the tide has turned for market based environmental policy instruments, such as environmental taxes (see Stavins, 2003). Whereas these market based instruments usually address specific pollution problems, like water or air pollutants, the growing attention for climate change even calls attention to economy wide taxes such as energy or carbon taxes.

Interestingly, this change in perception of pollution as a problem at the periphery (water pollution) to a problem that may affect the economy as a whole (climate change) has also induced more interest in the link between environmental taxes and technological change. In particular when environmental quality is perceived as an indispensible input for production, it also makes sense to consider shifts in the production possibility curve and how environmental policies, like environmental taxes, affect these shifts. Moreover, if technological change becomes part of the solution to address environmental problems, it is also important to consider the incentive structures that affect this change (e.g. Jaffe et al., 2003 and Popp et al., 2009). Moreover, environmental tax expenditures may have a role on their own because they specifically address well-known (positive) externalities in the decision making processes that drive technological change.[3]

To discuss technological change without understanding its driving role in capitalism is impossible. Following the famous work by Schumpeter (1934 and 1942), the literature on technological change typically distinguishes between three main phases. The first phase is invention and initial development of new ideas usually embodied in new technology and/or product design. This phase not only includes research and development (R&D) in large firms, but also lonely inventors. Only in the second or innovation phase is it that (some of those) new ideas are elaborated into new technologies or products to be applied in the world. In this phase new inventions and ideas are tested and screened for their market potential. Only in the

[3] Note, however, that subsidies (including environmental tax expenditures) have received relatively little attention in the environmental economics literature. Indeed, from recent surveys of the adoption literature (Requate, 2005) and market based instruments (Stavins, 2003), it is clear that the economics profession has focussed predominantly on the analysis of pollution taxes, tradable pollution permits and quotas.

third phase new ideas reach firm ground. In this phase they typically diffuse across society and become widely implemented.[4]

The relatively recent and new economic literature on these effects is the subject of this chapter. I discuss what is currently known about the impact of environmental taxation as well as environmental tax expenditures on technological change. In framing the main subject this way I stay away from at least three related topics. First of all, I do not review the literature that compares environmental taxes relative to other instruments in a dynamic perspective.[5] Second, no attention is paid to the effectiveness of both tax instruments as emission reducing devices. Third, what we know about resource taxation, i.e. taxes on (nonrenewable) minerals or fossil fuel extraction, is not reviewed either.[6]

2. Dynamic incentives of environmental taxes

As noted in the introduction, the main criterion by which the economic profession has evaluated tax instruments is that of static efficiency, i.e. the extent to which these instruments can achieve a specified environmental objective at minimum cost. However, static efficiency is just one of many criteria for instrument choice, and it is not necessarily the most important one (Jaffe and Stavins, 1995; Jaffe et al., 2003). Accordingly, one would expect the introduction of environmental taxes and tax expenditures to also be fundamental drivers of an increase in research and development (R&D) investment in abatement technologies, subsequent filings of new patents and, finally, a reduction in emissions.

To assess the likely impacts of tax measures on innovation, it is useful to distinguish, first of all, explicitly between the incentive mechanisms induced in a static setting, i.e. with *given technologies*, before considering generalizations to a dynamic setting. As a starting point, consider the following substitution channels to evaluate different taxes from a regulatory perspective (Smulders and Vollebergh, 2001; Fullerton, 2002):[7]

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4 This distinction associates learning with diffusion of technology and/or knowledge across agents (firms, households).

5 Magat (1978) compares effluent taxes and standards using an innovation possibilities frontier model of induced innovation. Interestingly follow ups are Fischer et al 2003 and Requate and Unold (2003). Requate (2005) and Vollebergh (2007) review the theoretical respectively empirical literature from this perspective.

6 Newbery (2005) shows that this restriction may be far from innocent. The dynamics involved here justify a wholly separate discussion, however. See also Smulders (2005) for a discussion of insights obtained from the analysis of nonrenewable resources and endogenous technological change.

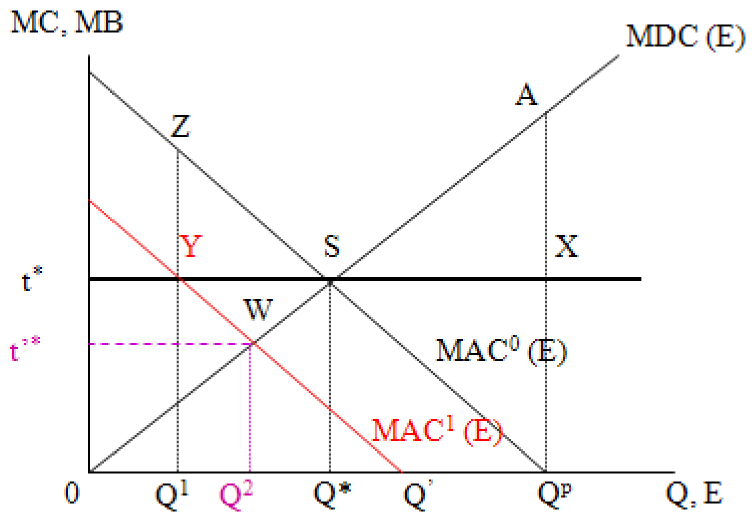
7 These channels also apply to policies that aim to dispose of or even reduce waste. See, for instance, Fullerton and Kinnaman (1995) and Aalbers and Vollebergh (2008).

- First, end-of-pipe *emission abatement* separates emissions from input use and output;
- Second, *input substitution* implies the substitution of emission-intensive for emission-extensive inputs, like switches in composition in fuels;
- Third, *factor substitution* involves the replacement of dirty by clean inputs, such as for labor for fossil fuel energy;
- Fourth, *output substitution* accounts for the substitution between dirty and clean products, and also includes what could be called *output characteristics substitution,* applying to changes in the characteristics of products.

Taxes typically differ as to what and how these different mechanisms are triggered. [8] Note that the prototype Pigouvian emission tax exploits all four mechanisms at the same time which explains its efficacy (and, by implication, its emission reduction efficiency). The alternative of an *input* tax does not exploit the emission abatement channel of reducing emissions. With input taxation the firm can no longer reduce tax payments directly by reducing emissions if this would require the same (or more) inputs. An *output* tax can also be exploited as an alternative for an emission tax. For instance, an *ad valorem* output tax is a very indirect and therefore costly instrument to reduce emissions. A firm facing such an output tax has no incentive to abate emissions directly because that does not reduce its tax burden. The classification of these substitution mechanisms in a static setting identifies options for firms to react to different types of tax policy measures. The static analysis typically classifies substitution channels along a *given* technology frontier, however, which implies – conceptually – that these substitution mechanisms only exploit already known and available products or technologies. Accordingly, the focus in such an analysis is on the promotion of their diffusion. In other words, these mechanisms represent shifts *along* the technology frontier, but they do not describe shifts *of* the frontier. Long run dynamic incentives induce entirely new technologies that may or may not be implemented in practice.

Figure 1. Dynamic incentives from environmental regulation

[8] See Vollebergh (2008) for an application to Dutch energy and climate taxation.



The dynamic impact of an environmental tax on technological change can be represented as an *inward shift of* the marginal abatement cost curve (MAC) and represents a shift *of* the (abatement) technology frontier.[9] The idea behind this shift is as follows. Assume a profit maximizing firm produces output Q^p in the *status quo* and faces the introduction of a tax t* on its emissions to internalize the marginal damage associated with its production (MDC).[10] As is well-known the 'classic' social optimum in a world without changes in technology or ecology is point Q*. Starting in a polluted world with output Q^p and associated marginal damage A, welfare increases after introducing a Pigovian tax on pollution equal to t* in order to guarantee the optimal social level of pollution at point Q*. The reason that this optimum will be 'produced' by firms and consumers in this market is simple. With such a tax in force (rational) firms avoid paying the full *initial* tax amount $0t^*XQ^p$ by reducing waste or adopting *currently available* and relatively inexpensive add-on technologies. The marginal abatement cost curve MAC^0(E) describes these options.

With an environmental tax firms face, apart from their abatement costs, additional payments equal to 0t*SQ*. To avoid paying for the *remaining* emissions, the firm could also

9 Note that the inward shift of the marginal abatement curve is exactly similar to the shift in the technology frontier as described by Newell *et al.* (1999). Less elastic abatement in the status quo corresponds with few options to reduce emissions without reducing output. New inventions are likely to make abatement more elastic whereas learning is typically more linked to diffusion processes rather than new inventions. See also OECD (2010, p.123ff) for a useful discussion of the relevant mechanisms involved and how this might be related to the design of a tax (or rebate).

10 Figure 1 is based on the assumption that each unit of output yields one unit of emission.

invest in invention or innovation to develop new abatement equipment with lower remaining emissions and therefore lower tax payments. If successful, the production possibility set is shifted outwards (higher emissions abatement for a given input), which 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 Ot^*YQ^1. So it would always be beneficial for the firms to invest in creating a new invention, as long as the expected (average) costs of the additional investment (including the cost of any capital equipment the technology requires) is lower than the (average) tax savings Q^1YSQ^*.[11]

Note, that these incentives for invention and innovation of a (new) environmental tax do not exist if a firm expects future command and control regulations to remain similar. If firms comply with current standards and abatement costs $MAC^0(E)$ are 'sunk', no additional benefits can be expected from investing in new abatement equipment labelled $MAC^1(E)$. However, if not all cost are sunk, e.g. because of maintenance and operating cost or the firm expects future regulations to be stricter, incentives remain to invest in the development of new technologies.[12] For instance, the firm would save $Q^1ZSQ^* – Q^1YWQ^2$) from the new technology under this new regulation, which could even be more than savings under a tax (or auctioned tradeable permit scheme)**.**

3. Environmental taxes internalizing positive externalities

Interestingly some (environmental) taxes, or more specifically tax *expenditures*, can be evaluated in a similar way. Tax expenditures may (re)establish a social optimum in the context of technology spillovers. Instead of paying some 'fine' for generating pollution, such tax expenditures in fact provide a bonus to do more of a 'good' activity because it has positive 'spillovers'. A key issue in the economics of innovation, however, is that agents' willingness to invest time or money in research or learning is fraught with public good aspects, i.e. the problematic appropriation of its social value. Since the seminal paper of Arrow (1962), the standard view here is that the inventor 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 less likely to be

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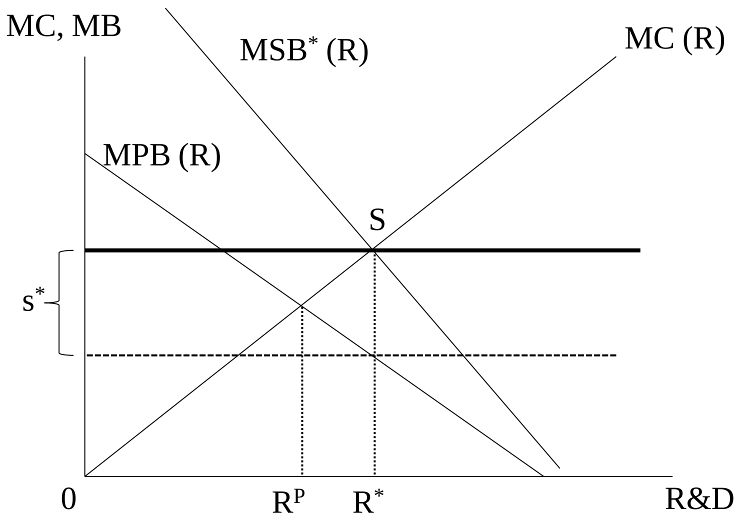
11 Note that the graph disregards dynamic aspects of investment decisions as well as the potential benefit of selling the technology to other firms in a similar situation.

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

instantaneous across a heterogeneous population because of all sorts of information failures (see also Popp et al, 2009).

Due to the inability to fully exploit new knowledge privately, (rational) firms are likely to under-invest in this type of investment. Without stimulus a firm would invest in R&D up to where his private return MPB(R) would be equal to his private cost MC(R) which is at the level R^p (see Figure 2). This level is below what is socially optimal. The reason is that the knowledge generated by the firm's activity may easily spill over to other firms. For instance, inventors may leave the firm while knowledge protection, e.g. through patents, cannot prevent the inventor to take his knowledge with him. Accordingly a firm cannot fully appropriate its returns privately and therefore is likely to under-invest in this R&D activity. An optimal response from a social welfare perspective would be to stimulate the market for new knowledge by using a subsidy or, what is equivalent, a tax expenditure to guarantee a social optimal amount of R&D spending R* or diffusion by firms (see Figure 2). Ideally this tax expenditure or subsidy should be equal to the difference between the social and private return to R&D in the social optimum, which is equal to s*.

Figure 2. Tax expenditures for positive R&D spillovers



Similar reasoning applies to adoption decisions. Adoption decisions are typically firm or household specific choices and usually require new knowledge for the adopter. Indeed, re-schooling of existing staff or hiring new people is but one example of the additional cost involved. Moreover, if one firm invests in a specific technology, this might induce learning effects which, in turn, may benefit all firms that have not yet adopted the new technology. [13] Such investment externalities may provide justification for regulators to stimulate adoption of new technologies with subsidies as well. It is not uncommon to design such incentives as (environmental) tax expenditures. Examples of such incentives are an investment subsidy, but in particular tax deductibility schemes are very common. The latter include investment credits, accelerated depreciation, partial expensing, and exemptions.

Note that these spillover considerations apply to *all* R&D and adoption investment decisions and not only to environmental R&D decisions. Thus no specific *environmental* tax expenditure for R&D or adoption seems to be required. This conclusion is preliminary, however. Viewed from a different angle, R&D or adoption are input neutral only under very exceptional circumstances and usually depend on relative prices of inputs (see also section 5). Both types of investment decisions apply to *specific* technologies and products. Technologies and products usually differ in terms of their characteristics, e.g. in the use of energy or the amount of pollution (e.g. Newell et all, 1999). Some technologies and products therefore have beneficial characteristics relative to others. Due to information or other market failures firms or households may not always be aware of such differences and their associated positive (external) benefits. This provides justification for regulators to stimulate R&D activity and adoption of cleaner technologies and products with additional subsidy as well. Thus *environmental* tax expenditures come on top of subsidy that already compensates for the general spillover (see also section 6). Indeed many of such expenditures actually exist in practice (Jenkins and Lamech, 1992; Price et al., 2005; OECD, 2006).

The theoretical literature on the dynamic impact of the tax expenditure instrument has been remarkably limited, however. Only a small literature focuses on the *adoption* decisions of technologies with beneficial characteristics from the environmental perspective and how the government could stimulate its penetration (e.g. Wirl, 2000; Van Soest, 2006). In this analysis a decision maker adopts a new technology or product after comparing the (future) benefits and investment costs of the available options.[14] In this framework the (predicted) effect of a tax expenditure is straightforward. Defining the net adoption costs as the actual

[13] If firms are heterogeneous, for instance with respect to the technology currently in use or with respect to capital (or borrowing) constraints, the adoption of a particular technology is likely to follow a gradual pattern over time or a so-called penetration curve.

[14] This method is the Net Present Value (*NPV*) framework and simply computes the discounted net benefit streams of a typical investment option by subtracting the (discounted) investment cost from the (discounted) benefits associated with the (economic) life time of the option at a given discount rate (e.g. market interest rate).

adoption costs minus the investment subsidy provided, technologies with lower net adoption costs are likely to obtain a higher ordering in the ranking of available alternative technologies. Therefore the subsidized technology will be adopted more readily than in its absence. If firms are heterogeneous, for instance due to technology currently in use or capital (or borrowing) constraints, the adoption of a particular technology follows a gradual pattern over time. A subsidy will shift this pattern whereas the overall penetration will be lifted somewhat due to lower net cost of this particular technology.[15]

So the idea behind additional incentives for environmentally friendly technologies is to reduce the net R&D and adoption costs to stimulate a higher ordering in the (financial) ranking of potential research avenues or available alternative technologies among firms or households. Therefore the subsidy may direct R&D in specific directions and environmentally more productive technologies and products will be adopted more readily than in the absence of the environmental expenditure. These expenditures stimulate inventions as well as earlier adoption due to lower net cost of the subsidized options. Note that this analysis applies to both firms and household decisions. Basically, household investment decisions, such as buying a new refrigerator or other electric or energy consuming appliances, are also adoption decisions of new technology already available at the market. So the diffusion phase typically also includes the penetration of new technologies or products to households.

4. Environmental taxes shifting technological change

For a long time the analysis of pollution mainly focused on the first of the substitution channels mentioned before, i.e. emission abatement. Specifically the whole concept of 'abatement technology' reflects the idea that emissions are 'additional' ('separable') to the production process. Examples of such add-on technologies are water purification installations and scrubbers. Figure 1 clearly reflects this idea with its focus on an environmental tax that regulates a specific emission in a specific market ('partial equilibrium').

Two main developments have changed this perspective. First, both firms and governments realized at some point that environmental policy would be irreversible and in several areas would become more and more stringent. After an initial phase of retrofitting and the development of add-on technologies, firms started to engage in the development of entirely new (add-on) technologies, including what is sometimes called 'integrated

15 Note that this line of reasoning holds even if firms belong to different risk classes, that is, if they differ with respect to the discount rate they apply to their investment decision (DeCanio and Watkins, 1998).

technology' (Kemp, 1997). This process can be observed in many areas of environmental control, such as water sanitation and purification, air pollution control (smog, acid rain particles, etc.) and waste management. Second, the growing concern about climate change and other energy related issues contributed to the acknowledgement that some pollution problems are more fundamentally rooted in our economic system. Indeed, many problems relate to production processes that are both directly and indirectly responsible for emissions, such as electricity generating technologies or energy consuming technologies and products.

Around the same time economists started to pay more attention to a better understanding of the role of technological change as the engine of economic growth. For instance, Nelson and Winter (1982, p. 275ff) built on the fundamental contributions of Schumpeter in their effort to better understand the dynamics of capitalism through the role of technological change. However, it took until the end of the 1980s when these and other complaints shifted attention of mainstream economists to more explicitly investigate or 'endogenize' the dynamics of technological change (Romer, 1990; Aghion and Howitt, 1992). Application of these new mechanisms to environmental issues started, for instance, with Gradus and Smulders (1993).

Instead of exogenous technological change which arrives as 'manna from heaven', the endogenous growth literature acknowledges that technological change is a complex process that is dependent on more than just the passage of time. The key modelling assumption is to include a knowledge stock in the production function of the economy. As a consequence a society that is willing to spend enough on R&D can realize a steady state of technological change sufficiently strong to offset the diminishing returns from capital-resource substitution. Accordingly sustainable long-run growth is now possible in this framework. Opportunities and incentives for R&D are determined by costs and benefits to innovation. Investment in R&D, for instance, competes with investments in physical assets or consumption, whereas the return equals the required rate of return for the other assets.

It is one thing to show that R&D is key to understand the dynamics and economic growth in capitalism. Quite another thing is whether this dynamics also benefits the environment.[16] Smulders (2005) explains why this is not obvious at all. Without regulation new technology only improves environmental quality under two conditions. First, the new technology should decrease the unit production cost (which excludes the environmental cost if

16 Note the fundamental difference between (non-renewable) resource scarcity which is more or less properly marketed versus environmental scarcity which is prone to fundamental market failures. See Smulders (2005) for a clear distinction between those two scarcity issues.

the environment is not priced). Second, the new technology must substantially reduce the marginal productivity of polluting inputs.[17] If this reduction is not strong enough, it is unlikely that compensation can be found for the expansion in the scale of output induced by the new technology. So an improvement may only happen by coincidence in this case.

Environmental policy, such as environmental taxes, can shift the balance towards better environmental quality. With such a policy, firms have an explicit incentive to avoid pollution not only by reducing output or emissions per unit of output, but also by shifting their R&D investments to change the technology frontier. For instance, Goulder and Schneider (1999) use a small partial equilibrium model to study the cost and benefits of endogenous technological change modeled as investments to lower the cost of abatement. They show for the case of an emission tax that the net social benefits rise once technological change is endogenized. Compared to the case of exogenous abatement technology both optimal pollution and output is lower. Thus the possibility of reducing costs in abatement may improve the trade-off between environmental quality and production in favor of the environment in this model.

The study by Goulder and Schneider (1999) shows that the dynamic impact of an environmental tax is not only to lower the cost of abatement, but also to affect the optimal stringency of the tax. This is illustrated in Figure 1 where the ex post social optimum, i.e. after the new (abatement) technology becomes available, is Q^2. Because the new technology reduces the opportunity cost of environmental regulation, also a *lower* optimal tax t'* ex post is justified! Note that this feedback still reflects the fundamental insight that technological change improves cost efficiency of environmental policy: emission reduction is cheaper along the whole new abatement technology frontier.

These results are not obtained in an endogenous growth approach proper, however. In the paper by Goulder and Schneider (1999) technological change is reduced to improvements in abatement technology and no interactions with other markets are taken into consideration. The endogenous growth literature studies also allow the production technology for the whole economy to adapt. Indeed, one could reach the opposite conclusion using a general-equilibrium model where R&D reduces production costs (Smulders, 2005). In such a model the effect of endogenous technological change is to *lower* optimal abatement because

[17] If the first condition is not met the firm is better off using the old technology and would not adopt the new one. If the second condition is not met either firms increase pollution per unit of output, or they decrease pollution per unit of output, but due to the expansion of the scale of output, total pollution still increases (rebound effect).

spending resources on abatement crowds out investment in total factor productivity improvements. In other words, endogenous technological change also allows for increases in the opportunity cost of abatement itself.

Nowadays quite a large literature has explored the role of technological change in theoretical as well as applied general equilibrium models, in particular in the area of climate change. These models not only focus on R&D, but also consider learning-by-doing, learning-by-using, the role of vintages in current physical capital, and lock-in in existing technological paradigms (see also next section). The interested reader could consult several older and more recent reviews of this literature (e.g. Clark et al., 2006; Popp et al., 2009;).[18]

One key issue in this literature is the role of the knowledge stock that governs the overall level and direction (i.e., input-bias) of technological change. As noted by Popp et al. (2009, p.7), the difficulty lies in determining how this stock accumulates and affects future input use and emissions. In particular, Acemoglu (2002) has shown how the trade-off between innovation in different directions inherent in the innovation possibility approach results endogenously from a firm's dynamic optimization. In deciding how much to invest where in the generation of new ideas ('R&D') firms also consider changes in the relative (input) prices. So higher prices for certain inputs directly affect the (expected) returns of a specific invention which is likely to generate a bias of new inventions away from the more expensive input.[19]

This so called induced innovation hypothesis has been applied to environmental externalities recently by Sue Wing (2006), Gerlach et al., (2009) and Acemoglu et al. (2009). This literature explicitly combines the two previously mentioned market failures.[20] First, pollution creates a negative environmental externality which requires an environmental tax to induce polluters to abate emissions up to the social optimum. Second, knowledge spillovers characterize endogenous technological change and a subsidy could compensate for potential social loss of underinvestment in R&D. Sue Wing (2006), for instance, finds that environmental taxes indeed bias production away from the dirty good towards the clean good. To what extent research will be biased towards the clean good, however, depends on the

[18] There are also a number of special issues of journals like Ecological Economics, Environmental and Resource Economics and Energy Journal specifically devoted to this literature.

[19] The overall direction of technological changes balances market size and price effects. Market size encourages innovation towards the larger input sector, while the price effect directs innovation towards the sector with the higher price. The overall effect is determined by input substitutability and elasticity between the dirty and clean sector.

[20] Note, however, that other market failures like monopolistic competition play a role too.

substitutability of the clean and dirty input. Only if the environmental tax is large enough innovators tend to compensate for the hump-shaped profile of the dirty R&D.

I conclude from this literature that judging environmental taxes from a cost efficiency point of view is limited. Environmental taxes not only exploit the available substitution mechanisms at a given production possibilities frontier, but also induce changes of this frontier itself. This, in turn, contributes to lower abatement costs for a given reduction commitment, but also has indirect effects on the optimal reduction level itself as well as on R&D effort and its direction. As for the interaction between environmental taxes and R&D subsidies for the 'clean sector', the analysis with endogenous technology confirm results obtained from partial equilibrium analysis. As Jaffe et al. (2005, p.169) argue, the rate of investment in the clean technology is usually below the socially optimal level in cases where environmental externalities have not been fully internalized. Therefore they maintain that it is unlikely that environmental policy alone creates sufficient incentives for first-best levels of adoption. So investment subsidies should be used not as a substitute, but as a complement to environmental policy.

5. Empirical analysis of environmental taxes

Studies of the actual impact of (Pigovian) tax instruments on technological change are still very limited. Much of our early knowledge comes from some typical case studies and anecdotal evidence (Opschoor and Vos, 1989; Skou Andersen, 1994). Moreover, the early studies also focus on short run and less on long run (dynamic) impacts. One of the oldest examples to date is Bressers (1988) analysis of the impact of an earmarked water charge implemented in the Netherlands in 1970.[21] The original purpose of this charge was a full-cost recovery scheme to finance public sewage treatment measures. Its design was such that 'polluters had to pay': firms and households had to pay a fee roughly in relation to the amount of (organic) pollution created by them. Incidentally, a remarkable drop in oxygen-consuming industrial pollution in industrial wastewater relative to the amount of industrial production could be observed in the Netherlands. Based on a small sample of regions, Bressers (1988) found that the water levy, and in particular the increase in its rate between 1975 and 1980, contributed strongly to this change in the level of pollution. However, this study does not make the effect of the charge on technological change explicit at all.

[21] For an update of this case see http://economicinstruments.com/index.php/water/article/165-.

Kemp (1998) more closely focuses on this dynamic impact. Specifically, he studied whether the average tax rate of this water charge in the Netherlands had an impact on the diffusion of biological effluent treatment plants in the Dutch food and beverage industry between 1974 and 1991. His empirical estimation fits diffusion equations to the average tax rate at each period in time and finds that the adoption of this technology is strongly influenced by the effluent tax rate.[22] His 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, such as the use of investment selection criteria which cannot be directly controlled by the regulator. Note, however, that also the study by Kemp does not study whether this charge has also contributed to the rise of *new* knowledge.

Another well-known measure of a potential dynamic impact are shifts in abatement cost functions over time. Höglund Isaksson (2005), for instance, studied changes in Swedish nitrogen oxides (NO_x) abatement cost functions in response to the Swedish NO_x charge implemented in 1992. The revenues from this charge were refunded net of transaction costs and firms receive output-based instead of emissions-based refunds. The drawback of output-based refunding, however, is that diffusion of abatement technology is hampered because firms may strategically prevent information disclosure to other firms. Looking at pollution abatement cost (PAC) changes for 162 NO_x abatement measures implemented in 114 firms during the period 1990-96, Höglund Isaksson (2005) observes that firms were very active to comply with the charge on emissions of NO_x announced in 1991 and introduced in 1992. She observes that many of the analyzed plants had options for reduction at a very low or even zero cost. Furthermore, she also finds that learning and technological development in abatement are present because this range tends to widen over the analyzed period.

Clearly these studies tend to focus on short run impacts of the use of environmental taxes and analyze impacts on new knowledge indirectly at best. For instance, declining abatement cost over time may be due to learning effects associated with diffusion of an already existing technology, but could also be the result of new knowledge. Identification of this impact, however, is quite complex due to data limitations as well as the limited use of such taxes in practice. One approach taken in the literature is to explore variation in *energy prices* as a proxy of variation in the stringency of tax instruments. Indeed, the theoretical literature suggest that higher (tax inclusive) energy prices are likely to shift technological

22 This result is also confirmed by specification of diffusion based on the epidemic model of technological diffusion.

change towards less energy-intensive technologies, which, in turn, reduces emissions as long as energy and emissions are complements. An early example that followed this approach is Greene (1990). He studied the practical experiment provided by the CAFE standards imposed on the fuel efficiency of cars in the U.S. while controlling for energy price variation. Greene finds that the CAFE standards had perhaps twice as much influence as gasoline prices. Accordingly, this suggests that the responsiveness of fuel efficiency to prices is significant, but also that binding standards are an important driver behind changes in the car market. Also recent advances in the literature that report evidence for dynamic shifts in the car market still do not explicit control for a potential difference between energy prices and taxes (e.g. Knittel, 2009).

A major step forward in identifying long run dynamic impacts of policy is to use explicit measures of new knowledge, like patents. In particular Popp (2002) is the first paper to date that contains clear econometric evidence that the filing of US patents is sensitive to changes in relative prices, in particular between 1970 and 1994. Specifically, Popp shows that rising fossil fuel prices, in particular oil and gas prices, raise the cost of this type of energy use (and its associated emissions) and induce patents (and citations) for energy-saving technologies. Technology groups such as fuel cells, use of waste as fuel or for heat production, and coal gasification have clearly benefited from the changes in energy prices over time.

Another, recent study is Johnstone et al. (2009) who evaluate the impact of different environmental policy instruments on patents in an international context. Using country data for a panel of OECD countries they evaluate which instruments have the strongest impact on the number of renewable energy patents for wind, sun, ocean, biomass and waste for 25 countries between 1978 and 2003. Again environmental taxes are studied only indirectly through changes in energy prices in this paper. These authors find a positive effect only for waste covenants, while taxes, standards and tradable permits stimulate patents for all renewables.

Energy prices are not the same as energy or environmental taxes, however. Firms and households may react differently to market prices or taxes while tax-to-price ratios differ enormously across products. Studies that explicitly analyze the impact of such taxes on new knowledge are not yet published so far. Only a very recent report by the OECD (2010) contains some interesting recent material based on some underlying studies that have tried to identify this role explicitly. One of these studies is Martin and Wagner (2009) who evaluate whether the UK climate levy in connection to a tax rebate for those firms that participate in a so called Climate Change Agreement (CCA) has stimulated new invention as measured by patents. They report that participating firms started to patent less after the introduction of this policy. This suggest that a tax incentive by its own would provide stronger incentives to engage in innovative activity than negotiated targets under CCA.

6. The empirical analysis of environmental expenditures

The available empirical evidence on the impact of environmental tax expenditures on technological change is also rather bleak. Again the available studies focus on short run behavioral responses and typically neglect the impact on new knowledge. Much of our insight is derived from the Demand Side Management (DSM) program operated by US electric utilities in the 1990s. This program aimed to entice households to the adoption of high-efficiency appliances. The typical incentive employed under the DSM approach was a tax rebate to induce households to adopt these appliances. Empirical evidence from this program seems to support the belief that such subsidies are ineffective and inefficient. For instance, some studies report that the behavior of many agents was not affected by the subsidy (e.g. Malm, 1996, Wirl, 2000).

In a somewhat neglected study, however, Hassett and Metcalf (1995) provide some counterevidence, showing that those energy-conservation credits have actually been effective in stimulating the penetration of modern energy-saving technologies. Using much better (panel) data at the household level, they first reproduced previous results showing no, or even adverse effects. But when they included (unobservable) individual characteristics, such as 'taste' for conservation, they actually found that US households invested in energy-saving technologies, such as insulation and replacing furnace burners, and therefore respond in a rational way to the energy-conservation incentives of the tax credit.

That the design of a tax credit matters a lot for its impact has been shown in a study by Revelt and Train (1998). They studied the relative importance of rebates or loans for the adoption of those high-efficiency appliances by households in the US. To study the potential effect of loans, stated-preference data were collected to estimate the effect of loans relative to the effect of rebates. Using 6,081 choice experiments of 401 customers, they also concluded that DSM is effective but that loans have a larger impact than rebates. This is surprising because a rational individual would prefer the rebate over a loan (of equivalent money) if upfront costs were the basic problem. As explained by Revelt and Train (1998, p. 652) individuals may not be indifferent and see the subsidy as a signal. It is clear for a loan that the lender makes money from it, but a rebate is a 'giveaway' and customers may wonder what its motivation is. If individuals start wondering about its motivation, their behavior is likely to be affected. For instance, if an individual is suspicious about the benefactor, he or she might not buy the appliance, just for that reason.

Further and recent evidence that a rebate on an energy efficient technology actually changes adoption behavior by firms is provided by Aalbers et al., (2009). They analyze the impact of technology adoption subsidies on investment behavior in an individual choice experiment with managers of real firms as participants.[23] The authors construct the decision environment of agents in such a way that they all essentially face the same investment decision. Moreover, to mimic decision situations in small and medium enterprises decision-makers also face binding time constraints. The findings are remarkable. 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 realize much higher energy savings in the treatment with subsidy compared to the treatment without subsidy. Furthermore, the subsidies seem to induce more radical choice behavior: either managers adopt (very) early or they do not purchase a technology at all.

Clearly all these studies focus on adoption behaviour of existing technologies that are not yet widely used or not used at all. Despite the fact that the use of tax expenditures, like investment credits, accelerated depreciation, partial expensing, and exemptions, is widespread, we know little or nothing about their long run impact. Whether and how these subsidies have had a an impact on, for instance, R&D expenditures or the availability of entirely new knowledge as measured by patents, has only been studied in some of the background studies as reported in OECD (2010).

7. Research Agenda

Recent advantages in both theory and applied general equilibrium analysis illustrate that environmental taxes are likely to have an impact in all stages of technological change, i.e. invention, innovation and diffusion of new products and technology. Some of this literature is also a warning against simple, sometimes too positive receptions of this dynamic impact. Cheaper abatement also has an opportunity cost and may justify adaptations of the regulator

23 Note this paper does not study tax expenditures proper (saving on tax payments or a rebate), but investment subsidies instead (a reduction on the investment costs).

and induce rebound effects as well. Directed clean technology may also crowd out other R&D activities that could be helpful to other areas of human life.

Empirical studies of the link between environmental taxes on technological change are remarkably scarce. Studies that pass the test of modern identification requirements usually exploit proxies of taxes using energy price changes. Others are restricted to case studies and do not always account for (econometric) pitfalls such as the identification of proper controls, including the use of multiple instruments at the same time. Further efforts should be made to exploit the much better data sets that have become available recently, such as patent data, and to collect new ones. Typical promising areas of research are energy and waste. One example is the impact energy taxes may have had on new ideas or the adoption of new technology relative to the role of energy prices and other instruments. Similar questions apply to water and waste charges.

Some other topics deserve wider study as well. One example is the role of tax design, i.e. the choice of the tax (expenditure) rate and base, on new ideas or adoption of existing, but not yet applied technology. Keen (1998), for instance, has shown the different impacts that ad valorem or specific taxes may have in the context of monopolies. Also selection effects should be studied more systematically to better understand the (dynamic) effectiveness of taxes and tax expenditures (including expenditures). The study by OECD (2010) is a good example of how to proceed and contains a lot material that deservers further scrutiny. Furthermore, current empirical assessments have the tendency to be biased towards observable information, like changes in abatement costs, number of patents (citations), physical characteristics of technologies, etc (so we may miss affects on organization design, changes in attitudes, etc). How taxes affect soft practices, like the use of internal monitoring systems, also deserves further attention (e.g. Frondel et al., 2008). There is also some evidence that decisions of households, apart from the scale of the investment, are quite different from those of firms (DeCanio and Watkins, 1998). Finally, behavioral economics may also be a promising area for future studies. The findings in this literature are a warning against simple conjectures based on theoretical propositions even if they come from the ‘enlightened’ endogenous technological change literature.

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