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Environmental policy and technology diffusion under imperfect competition

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Chapter 4

Pollution control and diffusion incentives

4.1 Introduction

How and to what extent do the various instruments of environmental policy support a firm's decision to adopt innovative and environmentally benign technologies? The general opinion is that market-based instruments provide a stronger incentive than command-and-control policies. Does this also imply a general consensus about the extent to which the various market-based instruments stimulate the diffusion of energy-efficient technologies? The answer to this is, unfortunately, negative. As we shall see, the theoretical literature does not yield consistent results with respect to the ranking of instruments. The purpose of this chapter is to present an overview of the literature on the adoption and diffusion incentives of various instruments of environmental policy, as well as to give an interpretive assessment of underlying assumptions and consistency of the analyses.

Usually, the environmentally benign technology is defined as the pollution control technology applied to limit emissions, effluents and waste. The new technology basically differs from existing technology by having lower marginal costs of emission reduction. The majority of the literature abstracts from the impact of lower pollution control costs on prices as well as output, i.e., the output market and associated market structure remain undiscussed. Only in a few recent publications the output market is included in the analysis, following a market structure of perfect competition.

Since this thesis focuses on the adoption and, in particular, the diffusion aspect of technology, we restrict ourselves to a review of the literature related to the technology adoption and the diffusion incentives. This implies the exclusion of the R&D oriented literature, which mainly focuses on the preceding stage of creating a new environmental technology and making it available for its potential users. Two interesting references in this area are e.g. Carraro *et al.* (1996) and, more recently, Montero (2002). Furthermore, we will only scantily discuss the literature that concentrates on the efficiency of policy instruments. For some influential papers on this issue see e.g. Biglaiser and Horowitz (1995), Biglaiser *et al.* (1995), Parry (1998) and Fischer *et al.* (1998).

In section 4.2 we review the literature that deals with environmental policy instruments as a stimulus for adoption and diffusion of pollution abatement technologies. Section 4.3 discusses the literature that takes the output market into account, followed by a brief examination of some relevant empirical studies in section 4.4. The chapter ends with conclusions in section 4.5.

4.2 Partial theories, disregarding the product market

In the 1970s, the seminal articles of Zerbe (1970) and Orr (1976) already revealed a preference for market-based instruments for creating continuous incentives to reduce emissions. This continuous incentive is missing when direct regulation is applied. However, given the superiority of market-based instruments, there is little consensus on which instrument in this class serves best for stimulating the adoption and diffusion of pollution abatement technology.

The debate on this issue ignited in the mid 1980s with the contribution of Downing and White (1986). They compared the incentive effects of effluent fees, subsidies, marketable permits and direct regulation on the technology adoption of a single profit-maximizing polluter. The new innovative technology is characterized by lower marginal abatement costs, and so by adopting it the firm can increase its profits. Their main conclusion is that direct regulation performs worst in providing adoption incentives since it has the lowest score on the ‘increasing profits’ criterion. Effluent fees are superior to direct regulation in this respect and are basically similar to the incentive generated by (grandfathered) tradable permits.

The approach is to compare the firm equilibrium *before* and *after* adoption of the new technology and to see how the instruments perform on the criterion of potential cost savings from adoption. The methodology is illustrated graphically in figure 4.1. MC_0 and MC_1 depict the marginal emission control costs of a firm when it applies the old or new technology respectively. Suppose the emission target is to reduce emissions up to 60% of uncontrolled emissions (index 100) and that direct regulation orders 40% of emission reduction. Assuming that both technologies have the same fixed costs, the increase in profits from adopting the clean technology is then visualized by the surface *abcd*. If an emission tax had been applied in order to reduce emissions up to 40% before the new technology was available, a tax rate p_0 would have to be imposed. Now adoption of the new technology goes hand in hand with higher emission control, yielding profits equal to area *aecd*. Compared to direct regulation, the extra profits *bec* consist of savings on emission tax expenditure due to lower residual emissions after adoption. Since the adoption of the clean technology increases profits more under taxes than under direct regulation, diffusion of clean technology will proceed faster if taxes are implemented. Anticipating on discussions that will follow, we want to point out that the preceding argument rests upon the assumption that the tax rate p_0 remains unchanged *after* adoption of the new technology. It implies that the authority accepts the higher level of emission control under the tax regime compared to direct regulation. Basically, the same approach is followed by other authors on the subject. They come down to comparative static analyses of firm equilibria *before* and *after* adoption of clean technology. As we shall see, some authors focus on industry equilibria and may also include the output market equilibria.

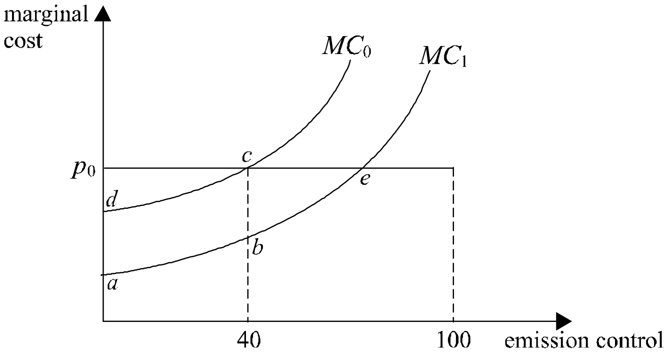

Figure 4.1: *Firm choice of control technology: direct regulation versus taxes.*

The intuition of the analysis is that market-based instruments allow the polluter flexibility to adjust its pollution control level in order to maximize the profits to be reaped from lower (marginal) abatement costs. If marginal costs are lower, it is efficient to increase the level of pollution control in order to save fee expenditures or purchase of permits. Direct regulation fixes the level of pollution control by command and residual emissions are for free. Therefore, the firm cannot increase its profits by a higher level of pollution control. In order to realize the same level of emission control, the similarity between emission taxes and tradable permits is based on the assumption that the permit price and emission tax are equal.

Like Downing and White (1986), who focused on the firm level incentives of different policy measures, Milliman and Prince (1989) compared the incentive effects of emission taxes, emission subsidies, direct controls, freely allocated permits and auctioned permits. They are aiming at establishing a relative ranking of these pollution control instruments to the extent they promote technological change, measured by the reduction in abatement costs. Regarding the permit schemes, they explicitly assume a negative relationship between technology diffusion and the permit price. This is plausible because a lowering of marginal control costs will lower the market demand for tradable permits. Given an unchanged and fixed (total) supply of permits (equal to the emission ceiling for the group of polluters), the equilibrium price in the permit market must be lower *after* adoption of the new technology. Ordering the firm-level incentives of the regulatory controls from high to low, Milliman and Prince (1989) obtain an intuitively rather odd ranking of: (1) auctioned permits, (2) emission taxes and subsidies, (3) freely allocated permits and (4) direct controls.

Taxes and subsidies have the same impact because their different effects on the marginal and average production costs, and consequently on output and potential (uncontrolled) emissions, are neglected. Given this assumption, a subsidy per unit of emission reduction which is equal to the tax per unit of emission (p_0 in figure 4.1), lead to the same adjustment in emission control and to equal profits from adopting the new technology. Crucial here is the assumption that both the tax and subsidy rate do not change after the abatement technology has been adopted. Then, the surface *bec* in figure 4.1 represents the net savings on emission tax expenditure and the net revenue from emission control subsidies in case of taxes and subsidies respectively.

Milliman and Prince (1989) find that auctioned permits provide a stronger adoption incentive than grandfathered permits. The reasoning here is that permits allocated by auctioning cause higher costs because firms have to buy permits to cover all their residual emissions, instead of having a basic quantity of permits for free as in case of grandfathering. Therefore, potential cost savings are higher under auctioned permits. However, this assumption is not correct. Free permits have an opportunity cost. If a firm causes residual emissions, it has to use its free permits to cover the emissions. But by doing so, it surrenders the opportunity to sell permits and make profits in that way. So, the permit price reflects the opportunity costs of using permits to cover emissions. The permit revenue foregone by using them as an input to produce output is as much a part of total costs as the permit expenditures for buying permits in an auction. That is why one intuitively would expect an equal ranking of auctioned and grandfathered permits.

Milliman and Prince (1989) go even a step further and argue that grandfathered permits can be as bad as direct regulation. Marin (1991) suggests that Milliman and Prince's peculiar conclusion is the result of the assumption of firms being identical. In a reply to Marin, Milliman and Prince (1992) show that even with heterogenous abatement costs their established instrument ranking still holds in a comparative static analysis. Their argument basically relies on the fact that under grandfathered permits the permit expenditures of firms buying extra permits equals the revenue of permit sellers. Consequently, no additional expenditure or revenue is involved for the total group of firms; only savings on abatement costs remain as fruit of adoption, similar as to direct regulation. In itself, they have a point here. However, the discussion implicitly reveals that not homogeneity or heterogeneity of firms is the weak spot, but the assumption of grandfathered permits having no opportunity cost. If homogeneous firms all get the same quantity of permits they do not have to trade. For instance, suppose again an emission ceiling of 60% of uncontrolled emissions. This is presented by the vertical line intersecting *bc* in figure 4.1. After adopting the clean technology, the firm would hold the same quantity of permits for free and acquire cost savings *abcd*, which equals the cost savings under direct regulation. The error here is that grandfathered permits are not without a cost, but have a price - if not a market price than a shadow price - and cost savings from higher emission control with the abatement technology are therefore potentially available. So, the ranking is false when we incorporate opportunity costs for grandfathered permits.

Where Milliman and Prince (1989) compare the firm-level incentives, Jung *et al.* (1996) shift their attention to the incentive effects at the industry level by defining a so-called 'Market Level Incentive' (MLI), reflecting the changes in aggregate profits in consequence of various pollution control policies. The

MLI-measure actually represents the changes in producer surplus or the industry's cost savings from technology adoption. To aggregate, they impose some restricting assumptions. First, there is a fixed number of firms which all adopt the new technology and thus face identical abatement costs. Moreover, the adoption of the new technology does not affect the market price of output, implying that the impact of output adjustment on the adoption incentive is neglected. Finally, the permit price falls when the marginal costs of firms in the industry decrease due to the increase in diffusion of clean technology. Given this structure, they find the same ranking as Milliman and Prince (1989), i.e., auctioned permits achieve the highest incentive, followed by emission taxes and subsidies, freely allocated permits and finally direct controls. However, as indicated by Keohane (1999) and Requate and Unold (2003), there are some flaws in the identical firm-level and industry-level ranking of Milliman and Prince and Jung *et al.* respectively. By considering a competitive industry, both Keohane and Requate and Unold find no distinction in adoption incentive between auctioned and grandfathered permits. Moreover, both studies find that taxes or abatement subsidies are superior to direct regulation in its incentive to invest in pollution control technology and that the comparison between direct regulation and permits (either free or auctioned) is ambiguous.

Based on Requate and Unold (2003), we may infer a fundamental criticism with respect to the difference between grandfathered and auctioned permits as obtained by Milliman and Prince (1989) and Jung *et al.* (1996). They do not mention it explicitly, but they actually presume that grandfathered permits are not costless, but have opportunity costs. Therefore, the marginal costs of auctioned and grandfathered permits are identical and so are the adoption incentives. Keohane (1999) states that irrespective of how a firm acquires its permits, i.e., either for free or by auction, the opportunity costs (and permit expenditure) will be equal and hence also the adoption incentives will be equivalent under auctioned and grandfathered permits. Furthermore, given that the permit price is decreasing in the degree of diffusion, both Keohane (1999) and Requate and Unold (2003) show that *every* firm can free ride on this lower permit price. What is important here is the distinction between the *individual* firm-level incentive and the gains from *aggregate* behavior. As a result, a lower permit price simply implies lower costs and subsequently a lower adoption incentive[1].

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[1] Note that one of the differences in approach between Requate and Unold (2003) on the one hand and Milliman and Prince (1989) and Jung *et al.* (1996) on the other hand, is that the latter two studies presume in advance that *all* the firms will eventually adopt the new

By modifying figure 4.1, we can show why Jung *et al.* (1996) obtain a flawed inequivalent nature of grandfathered and auctioned permits. Figure 4.2 can be used to illustrate the consequences of including the costs of grandfathered permits. To do so adequately, we have to bring the analysis up from the firm to the industry level.

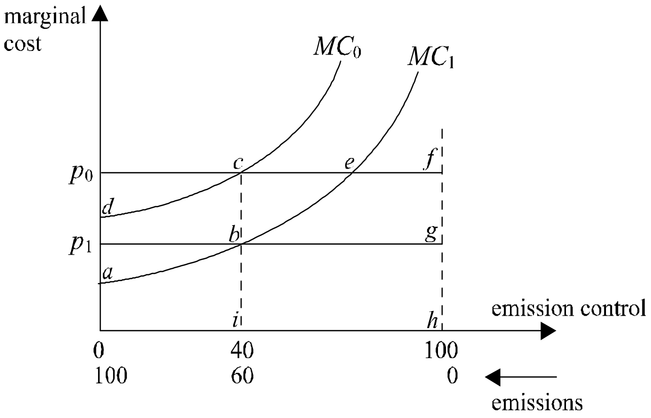

Figure 4.2: *Industry choice of control technology: tradable permits.*

Suppose there are, let's say, a thousand firms with identical marginal abatement costs of the old and new pollution control technology respectively. Firm emission control multiplied by thousand is shown on the x-axis in figure 4.2 and represents now the industry's emission control. An emission control index of 100 implies zero emissions and therefore zero demand for permits. Moving from right to left, permit demand increases. The marginal cost control curves of the industry can now be interpreted as the market demand for permits. Industry marginal cost curve MC_0 shows the high demand for permits when all firms use the old technology and MC_1 represents permit demand when all firms have switched to the new technology. The emission ceiling of 60 represents the fixed supply of permits. Before the new technology is available, permit demand equals permit supply at price p_0. The cost of permits is $cfhi$: as opportunity costs in case of grandfathering or as permit expenditure in case of auctioning. Once the new technology is available, all firms will adopt it and the equilibrium

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technology, whereas the number of firms that choose to adopt the abatement technology is endogenous in Requate and Unold's study.

permit price drops to p_1. What are the cost savings under tradable permits? The answer to this depends on whether the reduction in permit cost, equal to the surface $bcfg$ and which is the consequence of the drop in permit price from p_0 to p_1, is an adoption incentive/disincentive. Jung *et al.* (1996) interpret the lower permit expenditures under auctioning as cost savings for adopters, whereas they assess it as a loss under a system of freely allocated permits because of the associated fall in permit value. However, as Requate and Unold (2003) and Keohane (1999) rightly argue, both the permit cost advantage under auctioned permits and permit value loss under grandfathered permits also hold for the non-adopters and therefore the reduction in permit expenditures or permit revenue does not affect the adoption decision.

In the paper by Requate and Unold (2003) the firms are assumed to be identical. This assumption is relaxed in Requate and Unold (2001). They subsequently investigate the long-run adoption incentive under taxes and tradable permits and find also with heterogeneous firms that freely allocated permits and auctioned permits provide equal adoption incentives. Let's spotlight the debate on the appropriate ranking order of these incentives.

The comparative statics analysis is in our view not an entirely satisfying framework to tackle the problem adequately. One needs a dynamic approach which identifies the changes in adoption incentives during the diffusion process of the pollution control technology. The importance of a dynamic analysis, in particular to identify the role played by the fall in the permit price, has already been recognized by Keohane (1999) and Requate and Unold (2003). To get a clear picture of the adoption incentives during the transition period, one has to determine how the decrease in the permit price affects expected rents (or gains) of individual firms: for adopters as well as non-adopters. This is illustrated in figure 4.3.

Consider again a thousand identical firms. The very first firm adopting MC_1 will face the permit price p_0 (from figure 4.2) since the market permit price will be determined by the 999 (1000-1) firms sticking to their MC_0. Therefore, the first adopter will control r_0r_e and gain from adoption $aecd$, which is larger than the gain $abcd$ in case of direct regulation. If more firms choose MC_1, and the permit price starts to fall, both adopters and non-adopters will reduce their emission control levels. When 50% of the firms have switched to the clean technology and the permit price equals $p_{\frac{1}{2}}$, non-adopters will control r_0r_m and adopters control r_0r_k, making an adoption gain $akmd$. Compared to direct regulation, this is lkb more, but lcm less. In the end, when all firms face MC_1 and the permit price equals p_1, the adoption gain abp_1 is evidently below the adoption gain under direct regulation, which constantly promises a reduction in control cost *abcd* to adopters from the beginning to the end of the diffusion process. The conclusion is then that in the first stage of the diffusion process tradable permits promises the highest adoption gain and speed of diffusion compared to direct regulation, whereas in the later stage the adoption gain and adjustment speed under permits slows down and falls below the adoption incentive and diffusion speed under direct regulation. A generalization about which of the two instruments performs best appears to be impossible. Evolutionary game theory could offer a type of model suitable to analyze the dynamic process of price adjustment and diffusion (De Vries and Nentjes, 2003).

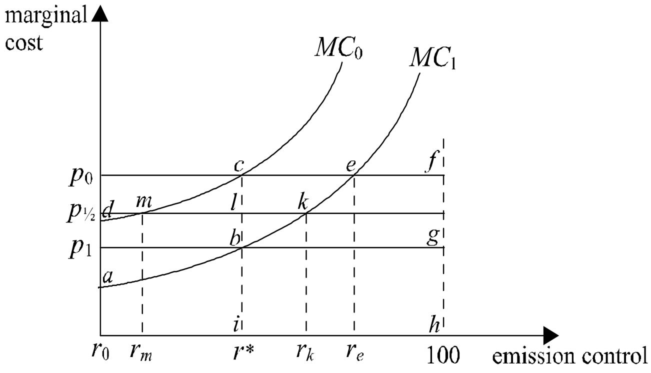

Figure 4.3: *Firm choice of control technology: tradable permits.*

What has been said here about auctioned and grandfathered permits can be used as a benchmark to assess the impact of emission taxation as well as emission control subsidies on technology diffusion. If the environmental authority would be willing and able to mimic the permit price adjustment by initially setting the tax rate and subsidy rate respectively at p_0 and then gradually decrease the tax or subsidy rate as diffusion progresses until it has reached p_1. When these conditions are fulfilled, subsidies, taxes and tradable permits all provide the same adoption incentive. However, it is more probable that the regulator will not react, or if he does, only with considerable delays. For example, why change the tax rate if firms abate more after adoption of the new technology than they did before? It would mean that, implicitly, the regulator uses the innovation and its diffusion to set a more stringent emission target.

But even if the regulator does not intend to set the tax level higher than the emission target requires, he first has to observe lower emissions before he can adjust the tax rate. Such observations can only be made after adoption and normally with some delay. Also calculating, discussing and introducing a new tax or subsidy rate will take time. Taking these complexities of regulation into account, it seems plausible that the rates will decrease slower than a permit price will do as technology diffusion increases. Consequently, taxes and subsidies would in practice provide stronger diffusion incentives than a tradable permit scheme.

Figures 4.2 and 4.3 can be used to show how the ranking order of Downing and White (1986), Milliman and Prince (1989) and Jung *et al.* (1996) would have been if logical errors had been avoided. In making the ranking, Downing and White evaluate at the old permit price p_0 and the tax level is also set at p_0. Given this assumption, the conclusion that market-based instruments have a superior adoption incentive compared to direct regulation is correct. Milliman and Prince (1989) also evaluate at price p_0 and they should have come to the same ranking order as Downing and White with the addition that grandfathered permits and auctioned permits provide equal adoption incentives. Jung *et al.* (1996) evaluate at p_1. The conclusion then is that direct regulation is superior to the market-based instruments, which perform equally well. This is quite different from what they actually find.

Apart from the analytical flaws, the main weakness of the above three studies is the comparative static nature. Since the adoption incentives change during the diffusion process, conclusions that make economic sense can only be drawn by using a dynamic approach. We already mentioned the studies of Requate and Unold (2003) and Keohane (1999), who also point to the relevance of such an approach. Fragments of a dynamic analysis can also be found in Malueg (1989) and Marin (1991). They did draw the attention to certain dynamic features of the adjustment process. In his criticism on Milliman and Prince (1989), Marin has noted that even with homogeneous firms at the *start* of the diffusion process, ‘different costs only occur in their intermediate stage where one firm has innovated but others have not yet followed the innovation. Before the innovation has diffused, the formerly identical firms now have different schedules for the costs of abatement and, as expected, the innovator with lower marginal cost abates less with direct controls than with marketable permits or taxes/subsidies, as well as having less gain from reducing its own cost schedule below that of other firms’ (Marin, 1991, p.297). Although Marin is on the right track, it follows from our illustration in figure 4.3 that his argument is only valid for the early stage of the diffusion process. In the later stage it is just the other way around; then the innovator has higher gains under direct regulation relative to marketable permits.

Malueg (1989) also indicated that the adoption incentive might be reversed in the later stage of diffusion. He argued that the incentive under tradable permits is not merely a positive one[2]. The rationale behind his reasoning lies in the specific role of the firm at the timing of investment in the pollution control technology. What he seems to point out is that when the permit price is lower (as will happen as diffusion increases), the cost savings under a permit system will also be lower compared to direct regulation. This is quite correct as we have seen. However, it is not only relevant for the buyer of permits. The figures mimicking a dynamic analysis at the industry and permit market level (figure 4.2) and the firm-level (figure 4.3) suggest that grandfathered and auctioned permits have an equivalent adoption incentive, but cannot unequivocally be ranked compared to direct regulation. The same is true for emission taxes and emission reduction subsidies compared to tradable permits and direct regulation.

We come to the end of this section. A salient feature of the above mentioned studies is that the output market, both at the firm and industry level, was out of sight. In the next section we will examine some important contributions that do, however, take this into account. Although we did not plan to present systematically the literature that deals with the welfare implications in relation to the implementation of environmental policy, some of the following studies do include this aspect.

4.3 Partial theories including the product market

Spulber (1985) was the first who explicitly considered the role of the market for final outputs. Assuming identical firms, he found that an emission tax is equivalent to auctioned permits in that they are both efficient in the long-run in terms of entry. More precisely, by allowing free entry both instruments provide the optimal number of firms to enter the market, provided the effluent tax and permit price being equal to marginal social damages. Following Spulber's (1985) output market approach, Requate (1995) asks whether this result also

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[2] Malueg uses the term tradable credits, but his credit system is purely a permit market in the classic sense.

holds if the set of available technologies not just contains a single technology, but that firms can choose among different ones. He distinguishes two types of technology: one with low and one with high marginal abatement costs. The latter technology also incurs higher fixed costs. Requate (1995) models a perfect competitive industry where the industry size is endogenous thus allowing free entry. He particularly examines whether emission taxation and auctioned permits yield the degree of adoption that is socially optimal. His conclusion is that an emission tax basically always generates an incentive that leads to complete adoption or no adoption at all, i.e., emission taxes yield complete specialization in one of the two technologies. Furthermore, under a tradable permit regime he finds the existence of a unique competitive equilibrium in which both types of technologies coexist for various permit allocation policies.

This welfare result is also found by Requate (1998). The main difference with Requate (1995) is that now the ranking between an effluent tax and auctioned permits for a wide range of damage parameters is analyzed. He shows that the associated incentive depends highly on the social damage function and so finds no unique ranking. For both sufficiently low and high damage parameters, taxes generate a higher incentive relative to auctioned permits, whereas permits perform better for an intermediate range of parameters. With respect to welfare, Requate finds that permits are always welfare increasing since they yield an efficient allocation of emissions[3] after the introduction of a new technology. On the other hand, an emission tax may generate a welfare reduction. The intuition is that 'if an innovative firm has a cost advantage under taxes, it will serve the whole market, while it may be socially optimal for the conventional firms and the innovating firm to share the market' (Requate 1998, p.141).

The output market is also modelled explicitly in the literature that examines the interrelationship between environmental policy and the internalization of social damages as a result of pollution. This literature differs in two ways from the work mentioned above. First, the market for outputs features imperfect competition and second, it does not so much address the issue of technology diffusion, but rather focuses on whether the implementation of environmental policy within such markets may internalize pollution damages *optimally*. Nevertheless, it may be important to realize how pollution control policies affect behavior on imperfect output markets and therefore we do point out the existence of this literature despite that it is lacking a diffusion item. Because these

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[3] Under the assumption that the permit market is perfectly competitive.

types of markets are at the core of this thesis, it may yield some background insight.

The main lesson concerning the internalization of negative externalities from pollution in perfect competitive markets hinges on equating the emission tax to marginal social damage. This first-best Pigouvian tax rule results in a complete internalization of the external damages (e.g. Baumol and Oates, 1988). The relevant question now is: will first-best Pigouvian taxation also fully internalize damages if the output market is imperfectly competitive? The answer to this lies in the main difference between a perfect and imperfect competitive output market as such. It is commonly known that the latter market structure inflicts a distortion on output, i.e., firms supply less than would normally be optimal under perfect competition. Hence, production under imperfect competition results in lower emissions than would normally be the case when the firms engage in a perfectly competitive market. It is therefore inadequate to impose a tax at the level of marginal social damage. This was first pointed out by Buchanan (1969). In such a case, Pigouvian emission taxation is second-best and the optimal emission fee falls short of marginal social damage in general. Studies revealing a similar conclusion are Barnett (1980), Levin (1985), Ebert (1992) and Requate (1993a, 1993b). The intuition is that by lowering the emission tax below the Pigouvian level, the welfare loss due to a higher pollution level is more than compensated by the welfare gain due to higher output.

Except Barnett (1980), who considers Pigouvian taxation under monopoly, all studies examine an oligopolistic market structure with firms competing in outputs. More specifically, Levin (1985) considers a general symmetric homogeneous Cournot oligopoly. Ebert (1992) too considers a homogeneous symmetric Cournot oligopoly, but distinguishes several cases. In one case he analyzes a system of emission taxes where firms reduce emissions by reducing output. In another case production is held constant, but with the option to reduce emissions by choosing an abatement technology. The abatement technology embodies decreasing returns to scale, but at the same time does not depend on the level of production. As a general result, the internalization is complete if the tax rate falls short of marginal social damage.

Requate (1993a) includes emission taxes and marketable permits in his analysis. He compares Pigouvian taxation with a system of marketable permits within an asymmetric Cournot duopoly. The model includes two linear technologies and the firms produce a homogeneous good. The firms have different constant marginal costs and different emissions per unit of production. He shows that implementation of the optimal policy, i.e., the optimal tax and optimal number of permits, does not result in a first-best social welfare optimum. The reason why a tax is not first-best is due to its uniformity; when firms are asymmetric, an individual tax rate would be necessary in order to reach the first-best solution. Permits are not first-best because permit trading may stimulate collusion between firms. The optimal individual tax and optimal individual number of permits are dependent on the technologies and the slope of the social damage function.

The oligopolistic firms in the above reviewed studies are all of the quantity setting type. Instead, two papers that focus on price setting games are Requate (1993b) and Lange and Requate (1998). In Requate (1993b) a Bertrand duopoly is analyzed and a similar framework as in Requate (1993a) is adopted in order to make a comparison possible. That is, linear technologies and asymmetry are assumed; only now the players are two price setting firms. One of the findings is that after the introduction of the new technology taxation increases welfare for a wide range of parameters and not permits. So, the result is the opposite of Requate (1993a). Furthermore, he shows that the social optimum can be reached by combining marketable permits with a subsidy on output. The research topic in Lange and Requate (1998) is second-best taxation within a differentiated product market in which two firms act as price setters. Again, the common result of the Pigouvian tax falling short of marginal social damage holds, given there is not too much asymmetry. The result holds under both a situation of goods being complements or substitutes. Furthermore, they demonstrate that the second-best tax is always below marginal social damage in case of monopolistic competition.

A more recent contribution related to the central model in this thesis is Moraga-González and Padrón-Fumero (2002). They analyze a differentiated duopoly where the firms can choose to produce either a clean or dirty product variant. Each variant requires a fixed setup cost, which is lower for the clean one. Competition between the two firms is modelled as a two-stage game; in the first stage firms simultaneously decide in which product to invest, whereas in the second stage they compete in prices, i.e., by setting the profit maximizing price given the price set by the competitor. They find a unique subgame perfect equilibrium in which both the clean and dirty product variant coexist.

They subsequently investigate the impact of emission standards, product charges and subsidies on the aggregate volume of emissions and social welfare in this equilibrium and compare them with a no-regulation benchmark case. Compared to the no-regulation benchmark, one of their main lessons is that industrial pollution (aggregate emissions) may rise under some instruments.

This is due to tougher price competition, which induces a higher sales level (and thus more production). Moreover, they find that a subsidy to reduce abatement costs does not change the aggregate emission volume in the equilibrium and is welfare increasing. Table 4.1 contains a summary of their results[4].

Table 4.1: *Instrument effects on welfare and aggregate emissions compared to no-regulation of Moraga-González and Padrón-Fumero (2002).*

Instrument	Welfare	Aggregate emissions
Emission standard	+/-	+
Uniform product charge	-	0
Non-uniform product charge		
on dirty product	+/-	-
on clean product	-	+
Technology subsidy	+	0

The main objective of Moraga-González and Padrón-Fumero (2002) was to illustrate the effects of environmental policy on aggregate industry emissions and social welfare. In this thesis we will rather focus on the diffusion dynamics, the general market dynamics and the long-run diffusion incentives of various environmental policy instruments. Instead of adopting an equilibrium approach in advance, the analysis in this thesis will be of a dynamic nature and aims at exploring the evolutionary path that leads towards possible diffusion equilibria.

4.4 Empirical studies

All the studies mentioned above are of a theoretical nature. The empirical literature on the effects of environmental policy on technology diffusion is rather limited. Exceptions are Jaffe and Stavins (1995), Kemp (1997), Kerr and Newell (2001) and Keohane (2002).

Jaffe and Stavins (1995) evaluate the diffusion effects of Pigouvian taxation, adoption subsidies and technology standards. Based on U.S. state-level field data on the diffusion of thermal insulation in new home construction,

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[4] A '+' refers to an increase, '-' to a decrease and '0' stands for no effect.

they find support for market-based instruments outperforming command-and-control strategies. Their econometric analysis reveals that the magnitude of the subsidy effect on the increased use of thermal insulation is bigger than the effect resulting from Pigouvian taxation.

Part II of Kemp (1997) is completely dedicated to empirical diffusion studies of environmental benign technologies using Dutch industry data. In one chapter he applies a threshold and epidemic model to analyze the spreading of biological waste-water treatment plants in the Dutch food and beverage industry. As a general conclusion, he finds that emission taxation and economic variables play an important role in the adoption and diffusion of these treatment plants. Another result Kemp obtains is that both the epidemic and threshold model do not properly fit the actual diffusion patterns, implying that other factors seem to be essential in driving the diffusion as well, as Kemp argues. He suggests that these might have to do with, for instance, learning or temporary financial constraints.

Where Jaffe and Stavins (1995) study diffusion of thermal home insulation in the U.S., in chapter 7 of Kemp (1997) this type of technology diffusion in the Netherlands was investigated again by applying the threshold and epidemic model[5]. Contrary to the epidemic model, which produced a reasonable fit of the actual diffusion pattern, the threshold model did not seem to be able to explain this adequately. Furthermore, like Jaffe and Stavins (1995), Kemp has investigated the effect of subsidies on the diffusion of thermal home insulation and finds that subsidies for double glazing have a small but positive effect on the adoption decision. With respect to cavity wall insulation the effect of subsidies is also small and positive[6].

Kerr and Newell (2001) conduct an extensive empirical analysis of the U.S. petroleum industry. They investigate the adoption incentives of different environmental regulations in this industry. Their model is based on detailed data on refineries over 25 years (1971-1995). First of all, their dynamic analysis shows that market-based instruments induce the cost-effective adoption of new technologies. Moreover, they find a positive relationship between environmental stringency and the incentive to adopt lead reducing technologies.

Keohane (2002) empirically tests the theoretical prediction that the response of a firm is more sensitive to the implementation of a tradable permit scheme than to command-and-control in terms of an emission standard. Using

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[5] He particularly focuses on double glazing and cavity wall insulation.

[6] In both cases the measure of the effectiveness of subsidies is statistically *in*significant at the 5% significance level.

data from coal-fired power plants, he endorses the theoretical result of tradable permits yielding greater cost savings from applying a new pollution control technology than would be under direct regulation.

4.5 Concluding remarks

Up to now, the theoretical literature dealing with the diffusion of environmentally benign technologies induced by environmental policy has mainly followed a partial and comparative static analysis, comparing equilibria before and after the introduction of a pollution abatement technology. The focal point in these analyses are the equilibria itself rather than investigating the qualitative behavior of the adjustment path that may lead to the equilibria. This branch of work can basically be divided into two parts: one focusing exclusively on pollution control disregarding the output market[7] and the other taking an explicit notion of such markets. The bulk of literature is in the first category.

We have identified big differences between authors in their ranking orders of different environmental policy instruments, given the effects on the adoption and diffusion of clean technology. The analysis underlying the established ranking orders is frequently based upon flawed assumptions such as not taking into account the opportunity costs of grandfathered tradable emission permits, or as incorrect reasoning like imputing the effects of a lower permit price only to the adopters of the pollution control technology.

Within a comparative static framework, our first conclusion is that the ranking order depends on the assumed price or tax level, given the emission target the industry faces. If the 'old' price (*before* the introduction of the clean technology) is used and output effects are neglected, then all four market-based instruments (auctioned and grandfathered emission permits, emission taxes and emission reduction subsidies) perform equally well and their adoption incentive exceeds the incentive emanating from direct regulation. The alternative approach is to assume that adjustment (diffusion included) is immediate, that firms have perfect foresight of the 'new' price of emissions (*after* the introduction of the clean technology) and that the environmental authority (also equipped with perfect foresight) sets the tax or subsidy at the new levels. Then the ranking order is reversed: direct regulation provides a higher adoption incentive than the market-based instruments.

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[7] Sometimes this is also referred to as a 'partial-partial' analysis.

The second conclusion is that a purely comparative static analysis is not a very enlightening approach in order to provide adequate policy advise on which instrument performs best in stimulating the diffusion of clean technology. A dynamic analysis is needed in order to determine what happens between start and finish of diffusion and how the adoption incentive and actual diffusion evolves during the adjustment period from the old to the new equilibrium. This pertains in particular to the tradable permit instrument since permit prices will change during the process of diffusion of clean technology. Consequently, the adoption incentives develop differently than the impact of emission taxes or emission reduction subsidies. It illustrates that without a dynamic analysis less well-founded predictions can be made on which instrument will be the ultimate winner of the race.

The final conclusion is that the diffusion analysis should not only investigate the pollution control decisions of firms and industry, but also its repercussions on output markets and its feedback to pollution control. This applies to both perfect as well as imperfect competitive output markets. So, the interaction between technology choice and the decisions on output and prices in the product market should not be neglected.