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SURVEY

Dynamic incentives by environmental policy instruments—a survey

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Abstract

In this paper I survey and discuss recent developments on the incentives provided by environmental policy instruments for both adoption and development of advanced abatement technology. A main conclusion to be drawn from the literature is that under competitive conditions market based instruments usually perform better than command and control. Moreover, taxes may provide stronger long term incentives than tradable permits if the regulator is myopic. If the government can anticipate new technology or is able to react on it optimally, regulatory policies by virtue of administered prices (taxes) and policies by setting quantities (issuing tradable permits) are (almost) equivalent. The literature also shows that under competitive conditions there is no difference between auctioning permits and grandfathering. Moreover, timing and commitment of environmental policy is not crucial for adoption under competitive conditions. Commitment has positive incentive effects, however, if an R&D sector has market power. In the presence of market imperfections the ranking of the different policy instruments is ambiguous.

Keywords: Emission taxes; Auctioned permits; Grandfathering; Emission standards; Technology adoption; R&D

JEL classification: L5; Q2; Q28

1. Introduction

This paper addresses recent developments on the incentives provided by environmental policy instruments to spur both R&D and the adoption of emission reducing or energy saving technology. It is well known that among the wide array of pollution control instruments, economists prefer those which provide incentives through prices rather than through command and control. The main advantage of market-based instruments such as emission taxes, subsidies on abatement, and different regimes of tradable permits (notably free and auctioned permits) is their (static) cost efficiency. The theoretical prediction that firms will take advantage of the efficiency gains of those instruments has been well confirmed by

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empirical observations, in particular on markets for tradable permits. Meanwhile those instruments are much better understood and more widely accepted by both the public and by policy makers, as can be seen from a growing number of countries which employ these instruments. Notably, Norway, Sweden, Finland, the Netherlands, France, Slovenia, and even Russia have implemented emission taxes for various pollutants, in particular SO_2 and NO_x (although the variation of tax rates is quite large, ranging from a few cents in some countries up to about 2000 EURO per ton of NO_x in Sweden). Targeting CO_2-emissions, notably Denmark, Germany, and the Netherlands charge taxes on energy. By contrast, the United States were the first to introduce markets for pollution permits on a large scale, notably for SO_2 and NO_x. Other countries such as Australia use permit markets for local and regional pollutants such as salt effluents into rivers. New Zealand issues land development permits whereas Iceland uses tradable permits to allocate fishing quotas. Very recently the European Union has launched a directive for CO_2 permit trading in Europe to be started in January 2005. This will then be the world's largest market for pollution allowances.

Kneese and Schulze (1975) have pointed out early that, besides the issue of static efficiency, the extent to which policy instruments "spur new technology toward the efficient conservation of the environment" is one of the most important criteria on which to judge the performance of environmental policy instruments. It took quite a while, however, until researchers started to inquire those long run incentives and to point out the differences between the different policies. By several reasons there is still little that we know empirically to which extent those instruments perform differently. Firstly there is hardly any chance to make experiments and empirical comparisons of instruments under similar economic conditions. Secondly, several countries regulate the same externality by several instruments.[1] Hence this paper concentrates on the theoretical inquiries on adoption and innovation incentives of environmental policy. For an excellent survey on the empirical literature I refer to Jaffe et al. (2002).

With respect to theoretical studies it is expedient to distinguish between adoption of new, though yet existing technology, on the one hand, and research and development of new technology, on the other.[2] Downing and White (1986), Malueg (1989), Milliman and Prince (1989) and more recently Jung et al. (1996) made the first attempts to rank environmental policy instruments, in particular, taxes, subsidies, auctioned permits, free permits, and emission standards with respect to their incentives to adopt less polluting technology. Their results, to be summarized below, have later been challenged by different authors who made the point that those authors mainly compare aggregate cost savings of a whole industry and that these cost savings are not equivalent to incentives of a single firm to adopt new technology in equilibrium.

More recently other authors have included R&D into the analysis of environmental policy incentives. Their contributions can once more be divided into two strands of literature. One road goes along the methodology of microeconomics, in particular industrial organization, using concepts of game theory in order to analyze strategic behavior in equilibrium. Most of these models are partial equilibrium models which are static or quasi-dynamic in the sense that they allow for sequential decisions taken by a regulator, by an innovating sector, and by the firms which adopt new technology. Except for Parry et al. (2003) the vast majority of authors do not explicitly capture the aspect of time. A second road follows the methodology of endogenous growth theory. Since it would burst this survey to treat both approaches, I will concentrate on the partial equilibrium microeconomic contributions, and I will not pursue the growth approach in this paper.

Hence this paper is organized as follows. Section 2 starts with introducing some basic con-

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[1] For example Germany, uses energy taxes, feed in subsidies for electricity generated by wind and solar power, and from 2005 on also tradable permits to regulate the emissions from fossil fuels.

[2] This terminological distinction is not always sharp in the literature. For example pioneers in this area such as Downing and White (1986) talk about "innovation" whereas Milliman and Prince (1989) use the notion of "technical change" in their studies although it is mainly incentives for "adoption" of existing technology which is the subject of both contributions.

cepts, such as abatement cost functions, a listing of different regulatory pollution control instruments, the question of how to compare incentives for adoption, diffusion and R&D, and finally a classification of different forms of timings and commitment strategies. In Section 3 I survey the results on incentives of adoption whereas in Section 4 I deal with the literature on environmental R&D and the interplay between technology adoption, on the one hand, and incentives to engage in research and development of advanced abatement technology, on the other. In Section 5 I draw some conclusions and give some outlook for further research.

2. Some basic concepts

2.1. Definitions and model frameworks

For a polluting firm there are basically two strategies to reduce pollutants: one is to reduce gross emissions by reducing output, another one is to keep output constant and to reduce emissions by employing an abatement technology. In general, a mix of both will be optimal. Experts usually distinguish between two types of abatement technologies, end-of-pipe technologies, on the one hand, and process integrated technologies, on the other. The latter leads to a decline in gross emissions whereas, with the former, gross emissions remain unchanged and are subsequently decreased, for example by using a filter. In both cases a firm's abatement cost is nothing else than its forgone profit incurred by reducing emissions. A firm's abatement cost function $C_i(e_i)$ represents the cost to reduce emissions from the laissez-faire emission level $e_i^{\max}$ to some lower level $e_i<e_i^{\max}$ and satisfies the following properties: $C_i(e_i)>0$, $-C_i'(e_i)>0$ and $C_i''(e_i)>0$ for $e_i<e_i^{\max}$, and $C_i(e_i)=0$ for $e_i \geq e_i^{\max}$. If the product market is competitive, decisions on output are optimal. In this case, the abatement cost functions account for the optimal output adjustment. It is straightforward to show that such an abatement cost function can be derived from a firm's joint cost function which may incorporate both cost of production and cost of abatement. Note further that if firms are small and thus cannot influence the output prices, there is no need to explicitly pay attention to the output market.[3]

Pollution-reducing technological progress can now be defined by declining abatement costs for any level of emissions. Before investment, a typical firms' technology is represented by its abatement cost curve C_0. Adoption of new technology leads to a lower marginal abatement cost curve C_I (see Fig. 1) with

$$-C_I'(e) < -C_0'(e) \quad \text{for all } e<e_0^{\max}.$$

In addition, buying and installing the new technology involves a fixed cost $F>0$. If, by contrast, pollution is proportional to output and if there is no further short run abatement technology, pollution-reducing technological progress can be modelled by decreasing emission coefficients (i.e. reducing the emission–output ratio). In this case, lower emission coefficients do not necessarily lead to declining marginal abatement costs if emission levels are already low.

2.2. Pollution control instruments

Unregulated market forces do not necessarily induce adoption of pollution reducing technology, a feature which calls for regulation. Economists distinguish mainly between two types of pollution control instruments: command and control and market based instruments. The most common instruments of command and control are technological standards (a regulatory authority might prescribe the firms to adopt the best available technology),

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[3] To become a bit more formal we denote by $C(q,e)$ the joint costs which a typical firm incurs to produce q units of output with no more than e units of emissions. For this definition it is not relevant, whether the firm has an end-of-pipe or an integrated technology. The firm's profit is then given by $\pi(q,e)=pq-C(q,e)$. In the absence of regulation the competitive firm chooses q and e such that $p=C_q(q,e)$ and $-C_e(q,e)=0$ providing a maximal profit $\pi^{\max}$ and an emission level $e_{\max}$. It is plausible to assume $C_q>0$ and $C_{qq}\geq 0$. Further, $-C_e(q,e)>0$, $C_{ee}>0$, and $-C_{eq}(q,e)>0$ for $e<e_{\max}$. We refer to $-C_e(q,e)$ as the marginal abatement costs. If now the firm is constrained to emit no more than e units of the pollutant, the rule induces output $q(e)$ and a reduced profit $\pi(e)=\pi(q(e),e)$. The full abatement cost can then be defined as $\tilde{C}(e)=\pi^{\max}-\pi(e)$, which is the forgone profit resulting from reducing emissions from $e_{\max}$ to e. It is easy to show that the reduced abatement cost function $\tilde{C}(e)$ has the same properties as $C(q,e)$ with respect to e.

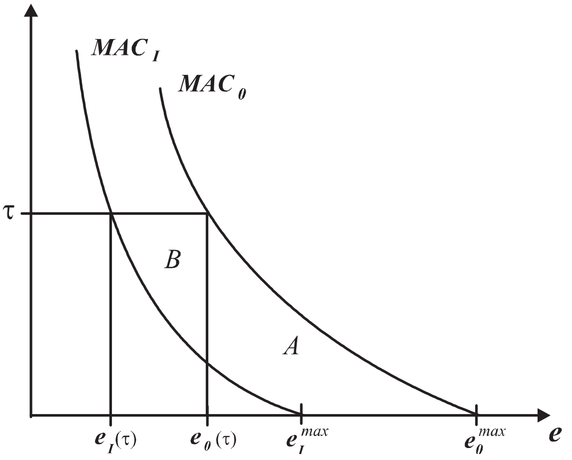

Fig. 1. Single firm's investment incentive under taxes.

emission standards (firms are constrained by an absolute upper emission level), and finally, so-called generation performance standards, sometimes referred to as relative standards. The latter means that firms' face a cap on the ratio of emissions per output. This sort of standard is most commonly applied in reality. Market based instruments, by contrast, provide incentives to reduce emissions through prices, and firms are free to decide how much they want to emit or to abate. The most commonly used market based instruments are emission taxes, subsidies on abatement of emissions, and tradable permits. Under emission taxes and abatement subsidies the prices for emissions are administrated by a regulator. If she levies a linear tax per unit of a pollutant or pays a subsidy per unit of abated emissions, then each firm has to pay (gets) the same marginal price for each unit of pollution it emits (abates). Under permits, by contrast, a firm must hold one permit for each unit of pollution it wants to emit. Usually firms can trade those permits with other firms. There are two allocation schemes for permits: free allocation according to historical emission or output levels (often referred to as grandfathering or benchmarking, respectively) or auctioning off the permits in which case the firms have to pay for each unit of the pollutant they are going to emit. In contrast to the tax rate, the market price of permits is determined endogenously by the market mechanism. Economists usually prefer market based over command and control instruments by virtue of their static efficiency. For, under competitive conditions, market based instruments lead to equalization of marginal abatement costs across firms, a necessary condition for achieving an aggregate emission target at least costs. Moreover, it is easy to see that regulation by prices (taxes or subsidies) and regulation by quantities (tradable permits) is equivalent if markets are competitive and the number of firms is fixed. Under free entry, taxes and permits are also equivalent, as Spulber (1985) has shown, whereas subsidies will usually induce excess entry. The dynamic properties, in particular the innovation incentives of these instruments are much more complex and, therefore, are subject to discussion below.

2.3. How to compare incentives for adoption, diffusion and innovation

When comparing the incentives for adoption, diffusion, and innovation of different policy instruments, it is natural to begin with the incentives for adoption. In a first step this can at best be analyzed from the perspective of a single firm. The incentive for adoption is simply given by the firm's additional total profit from switching to the new, exogenously given technology. Let us study this incentive in particular for market based instruments like an emission tax or a system of tradable permits, and let p denote a tax rate or a permit price, respectively. Assuming interior solutions, firms' cost minimization requires marginal abatement cost to equal the price of emissions for both technologies:

$$-C_0'(e_0) = p \tag{1}$$

$$-C_0'(e_I) = p \tag{2}$$

which yields emission levels $e_0(p)$ and $e_I(p)$. Then a typical firm decides to adopt the new technology if and only if

$$C_0\big(e_0(p)\big) + pe_0(p) - C_I\big(e_i(p)\big) - pe_I(p) - F > 0 \tag{3}$$

whereas firms are indifferent about adopting the new technology if

$$C_0(e_0(p)) + pe_0(p) = C_I(e_I(p)) + pe_I(p) + F \tag{4}$$

Inequality (3) and Eq. (4) are the driving forces for the analysis.[4] Eq. (4) determines the number of firms which adopt the new technology in equilibrium. The rate of diffusion refers to the percentage of firms adopting the new technology. The incentives for adoption and the rate of diffusion are interrelated. In particular in the case of tradable permits the market price of permits depends on the number of firms which adopt the new technology.

The incentive for innovation refers to the benefit a firm enjoys from developing and inventing a new technology. Firms engaging in research and development of pollution-reducing technologies are either part of the polluting industry itself, or they engage in R&D exclusively in order to sell or license their new technology to a different polluting sector. In the first case, the innovator's benefit is determined by the change of her compliance costs (including short run abatement cost, revenues from emission subsidies or permit sales, or expenditures for emission taxes or permit purchases, respectively) and the change of her profit on the output market. In addition, the innovator's benefit might increase by accruing license fees, and it may be reduced by other firms which imitate his technology. If the innovator's objective is mainly to sell or license his new technology, his profit depends on the polluting firms' willingness to pay for the new technology, which in turn is determined by the adoption costs, by the change of compliance costs, and by the profits those firms accrue from adopting the new technology. Again, the possibility of imitation has a diminishing effect on the innovator's profit. Fig. 1 illustrates the change of an adopting firm's compliance costs under an emission tax. Depending on the kind of regulation, a potential innovator will put a certain effort into R&D. A higher effort may either lead to a higher degree of innovation (for example a more radical shift of both the abatement and the marginal abatement cost curves), or induce either an increased probability or an earlier date of success. A profit maximizing innovator chooses an effort level such that the marginal (expected) benefit equals the marginal cost of R&D. Denicolo (1999, p. 186) points out that the innovation incentive of the different instruments can be correctly measured by the innovator's respective profits if her "R&D investment cannot affect the nature of the innovation and hence the reduction in effluent emissions that it entails." Otherwise, "it is the marginal profit that matters to determine the innovator's incentive to invest."

It is important to note that the distinction between investment into adoption and into innovation is not always sharp. Some authors such as Phaneuf and Requate (2002), Petrakis and Xepapadeas (2003), or Gersbach and Requate (2004) assume cost functions of the form $C(e,k)$ where e denotes emissions and k can be interpreted as both investment into abatement equipment or R&D effort. In the literature survey following below, we subsume a paper under a model of innovation (in contrast to a model of adoption) when the respective model contains at least one of the following aspects. Either, there is a stochastic element, i.e. the size of innovation, its date, or the R&D success is uncertain, or secondly, a patent is granted on the innovation, or thirdly, spillovers occur, or finally, imitation is possible.

2.4. Possible timing and commitment strategies of the regulator

When analyzing diffusion, innovation, and technological progress, it is important to distinguish the possible timing and commitment strategies of the regulator. This basically boils down to the question about who is the first to move, the regulator or the firms. If the regulator moves first and is able to make a commitment to the level of her policy instrument, we refer to ex ante regulation or ex ante commitment. A myopic regulator does not anticipate a new technology and therefore commits ex ante to a level of her policy instrument which is optimal with respect to the conventional technology. If, by contrast, the firms move first by engaging in R&D or by adopting a new technology and the regulator moves second by adapting the level of her policy instrument to the respective R&D outcome or to the rate of adoption of new technology, we talk about ex post regulation. If the regulator has no incentive to change her behavior after firms have moved, her policy is called time

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[4] It is important to note that we assume that each adopting firm is small and can neither influence the tax rate nor the price for permits. Otherwise, we could not assume to have the same price for emissions before and after adoption of the new technology. Amacher and Malik (2002), by contrast, (see below) consider regulation of a single firm. There, the rationale is a bit different.

consistent. The adjustment of her policy in case of a time inconsistent policy is sometimes called ratcheting. Note, that ex post regulation is always time consistent. The early literature usually considers the regulator as the natural first mover whereas more recent contributions emphasize the importance to also study the regulator's reaction on innovation and technology adoption.

3. Results of models on adoption and diffusion

In this section we focus on theoretical microeconomic partial equilibrium models which serve to analyze the incentives for adoption and diffusion of the environmental policy instruments. The models summarized in this section differ, on the one hand, with respect to the behavior of the regulator who is assumed to either act myopically or to engage in ex ante or ex post regulation. On the other hand, they differ with respect to whether or not they pay attention to the output market, or whether or not they include uncertainty. We begin to discuss the models of myopic regulation.[5] Table 1 summarizes the different features of the models described below including the policy rankings as far as those are available.

3.1. Myopic regulation

The first contributions dealing with adoption of a new abatement technology are those by Downing and White (1986), Milliman and Prince (1989), and Malueg (1989). For different types of pollution control instruments the authors compare the aggregate cost savings incurred by industry when adopting a new technology. By ex ante assuming an industry wide adoption of the new technology, Milliman and Prince arrive at the following (descending) ranking of policy instruments with respect to those cost savings: (1) auctioned permits, (2) emission taxes and abatement subsidies, (3) free permits and emission standards. Jung et al. (1996) come to a similar ranking employing a more formal analysis. They find, however, that free permits outperform (absolute) emission standards.

3.1.1. The alleged argument

The basic argument set out by Milliman and Prince (1989) and Jung et al. (1996) is outlined in Fig. 1. MAC_0 denotes the marginal abatement cost curve of a representative firm running a conventional abatement technology whereas MAC_I is the marginal abatement cost curve after adoption of some advanced abatement technology.

Let us first look at the investment incentives provided by an emission tax. If a particular firm switches from conventional to advanced technology, its savings in variable abatement cost plus tax payments are represented by the area $A+B$ depicted in Fig. 1. If installing a new technology causes a fixed set-up cost $F>0$, it will be profitable for the firm to invest in the new technology if and only if $F<A+B$.

Now consider pollution control by auctioning off permits. Let σ_0 denote the original price for permits (see Fig. 2) before the advanced technology was available. Let us assume for a moment that only one small firm, which is not able to manipulate the permit price, has access to the new technology. Then the incentive for this single firm to install the new technology is the same as in case where the firm is regulated by a tax. If, however, a considerable number of firms adopt the new technology, the equilibrium price for permits must go down. Jung et al. assume such a price, say σ_I, to be exogenously given (see again Fig. 2). Then indeed, each firm that has adopted the new technology has lower variable costs than in a situation where no other firm has adopted the new technology. The cost difference is equal to the area $A+B+C$ depicted in Fig. 2. This cost difference, however, is not equivalent to a single firm's incentive to adopt the new technology. In other words, the criterion for whether or not to adopt the new technology is not determined by the inequality $F<A+B+C$. Rather, this incentive is given by the marginal firm's cost saving if it adopts the technology given that other firms have already decided to adopt, i.e. if the price has already fallen to σ_I . This cost saving of the marginal firm is displayed by area $A_1<A+B$ in Fig. 3. Hence the incentive to invest under permits must be lower than under taxes.

Note that if $A_1 \ll F \ll A+B$ holds, some but not all the firms will adopt the new technology in equilibrium. Assuming that all the firms will adopt the new technology–as some authors do–is tantamount to

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[5] This ranking refers to adoption of new technology. Milliman and Prince also study other scenarios which yield different rankings.

Table 1
Models of adoption and diffusion

Authors	Policy instruments	Timing of game/behavior of regulator	Special attention to output market	Marginal damage	Policy ranking
Amacher and Malik (2002)	Emission taxes	Ex ante, ex post	No	Increasing	1. Ex post 2. Ex ante
Carraro and Soubeyran (1996)	Adoption subsidies and discriminatory emission taxes	Ex ante	Yes	Constant	Ambiguous
Downing and White (1986)	Emission taxes, abatement subsidies, emission standards, free permits	Myopic	No	Increasing	No welfare ranking
Jung et al. (1996)	Emission taxes, abatement subsidies, emission standards, auctioned permits, free permits	Myopic	No	Increasing	1. Auctioned permits 2. Taxes, subsidies 3. Free permits 4. Standards
Gersbach and Glazer (1999)	Free permits	Ex post	Yes	Constant, increasing	–
Kennedy (1999)	Free/auctioned permits and different adjustment rules	Ex ante	No	Constant	Both adjustment rules efficient
Kennedy and Laplante (1999)	Emission taxes, permits	Ex ante, ex post	No	Constant, increasing	Taxes and permits are efficient if there are many firms
Laffont and Tirole (1996a)	Permits, permits and futures, permits and price support policy/options	Ex ante	No	Increasing	1. Options 2. Permits and futures 3. Permits
Milliman and Prince (1989)	Emission taxes, abatement subsidies, auctioned permits, free permits, emission standards	Myopic	No	Increasing	1. Auctioned permits 2. Taxes, subsidies 3. Free permits, standards
Malueg (1989)	Permits	Myopic	No	No damage function	–
Montero (2002a)	Auctioned permits, free permits, emission standards, performance standards	Exogenous emission target	Yes	Emission cap	For competitive output markets, and uniform permit allocation: 1. Free permits, auctioned permits 2. Absolute standards 3. Relative standards Ambiguous otherwise
Petrakis and Xepapadeas (1999)	Emission taxes	Ex ante, ex post	Yes	Increasing	1. Ex ante commitment 2. Ex post taxation
Phaneuf and Requate (2002)	Permits and banking of permits	Ex ante	No	Increasing	Ambiguous
Requate and Unold (2001)	Emission taxes, abatement subsidies auctioned permits, free permits	Myopic, ex ante, ex post	No	Increasing	1. Free permits, auctioned permits, taxes 2. Standards
Requate and Unold (2003)	Emission taxes, abatement subsidies, auctioned permits, free permits, emission standards	Myopic, ex ante, ex post	No	Increasing	1. Free permits, auctioned permits 2. Taxes 3. Standards
van Soest (in press)	Emission taxes, emission standards	Ex ante	Yes	No damage function	Ambiguous
van Soest and Bulte (2001)	–	–	Yes	No damage function	–

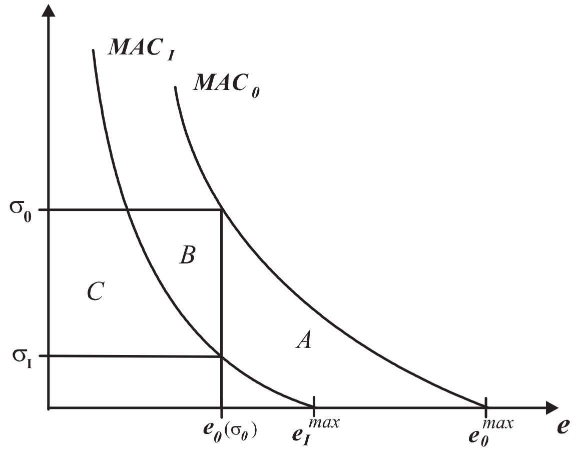

Fig. 2. Single firm's total cost reduction if all firms invest under permits.

assuming the fixed set-up cost to be sufficiently low, i.e. $F \ll A_1$. If one assumes, however, that ex ante all the firms will adopt the new technology, it is of little interest to ask the question which policy instrument will provide a higher incentive to adopt the new technology.

3.1.2. Adoption incentives in equilibrium

Both Kennedy and Laplante (1999) and Requate and Unold (2003) challenge the approach by those authors by pointing out that equilibrium considerations must be taken into account when studying the incentives to adopt new technology and, therefore, the number of firms which adopt the new technology must be determined endogenously. Requate and Unold (2003) study several scenarios: The first one corresponds to those studied by both, Milliman and Prince (1989) and Jung et al. (1996) who both assume the regulator to be myopic.

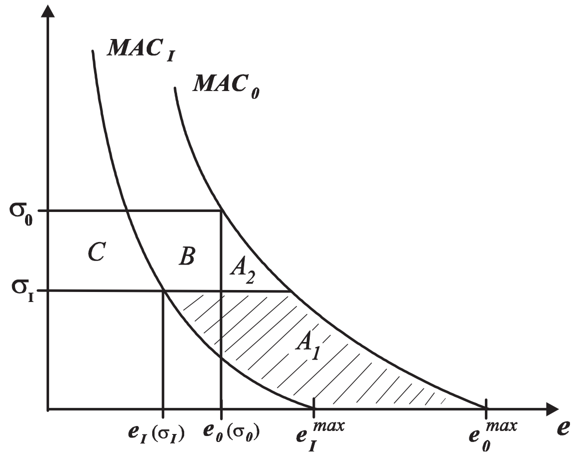

Fig. 3. Single firm's investment incentive under permits.

We now briefly summarize the incentives provided by the different policy instruments in case of a naive regulator. Both the socially optimal outcome and the firms' performance depends on the fixed set-up costs: If this fixed cost is sufficiently high, it will be socially optimal that no firm invests, and indeed no firm will invest under either policy. If the fixed cost is zero or sufficiently low, all firms should invest and they will invest even under moderate environmental policy. For intermediate values of fixed costs, however, –i.e. for the interval $(\underline{F},\overline{F})$ displayed in Fig. 4–the outcomes resulting from decentralized decision making under the different policy instruments and the socially optimal allocation are all different. This result is displayed in Fig. 4 where the number of firms which adopt the new technology in social optimum and under the different policy instruments is plotted as a function of the fixed set-up costs: Curve A denotes the socially optimal number of firms whereas the curves B, C, and D denote the number of firms that invest under permits, taxes, and a standard, respectively.

The result is formally derived in Requate and Unold (2003), but the intuition is simple: In social optimum, the lower the fixed costs, the more firms should adopt the new technology. For intermediate values of fixed costs partial adoption is optimal. Moreover, the lower F, the lower the marginal damage, and the lower the optimal emission level.

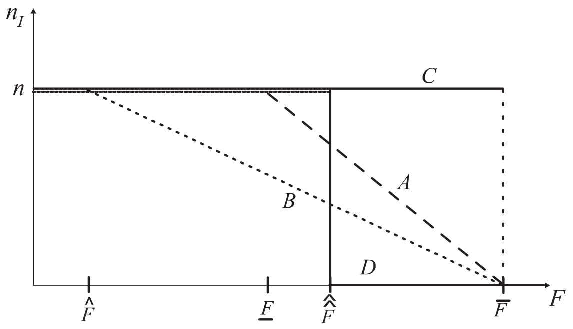

Fig. 4. Number of firms investing in the advanced abatement technology.

The formerly optimal tax, however, is sufficiently high to induce all firms to adopt the new technology even for those cases where partial adoption is optimal. Under permits, by contrast, the permit price falls when more firms adopt the new technology. Since the regulator does not change the total supply of permits, the permit price falls below the socially optimal level and makes non-adopting firms free ride on those firms which adopt the new technology. Under an absolute emission standard, either all or no firms adopt the new technology, depending on how sharp the standard is set. We see that taxes (or equivalently subsidies on abated emissions) provide the strongest incentives to adopt new technology, whereas, depending on the parameters either permits or standards provide the lowest incentives. Note that for a considerable range of parameters both taxes and standards induce more firms to adopt new technology than permits. Although environmentalists may prefer taxes and standards for this reason, from a broader economic point of view we cannot say that taxes and standards are generally better than permits. It depends on parameters which of those instruments leads to the lowest welfare loss compared to the first best allocation.

3.1.3. Grandfathering

According to Malueg, Milliman and Prince, and Jung et al., free permits provide lower incentives to adopt new technology than auctioned permits. The argument they propose is that innovation leads to depreciation of the firms' permits. However, innovating depreciates the firms' permits anyway, irrespective of whether these permits are auctioned off or distributed for free. In contrast to what Jung et al. claim, the original permit price is completely irrelevant with regard to the incentive to adopt a new technology in equilibrium. To see this, let $\tilde{e}$ be the firm's (identical) initial endowment of permits. As the firms are alike before innovation, there will be no trade before the new technology is available. Since the advanced technology leads to lower marginal abatement costs for each emission level, the investors must be sellers and the non-investors must be buyers of permits. In an equilibrium with partial adoption, firms must be indifferent about adopting the new technology or not, i.e.

$$C_0(e_0) + \sigma[e_0 - \hat{e}] = C_I(e_I) - \sigma[\hat{e} - e_I] + F. \tag{5}$$

We see that $\sigma \cdot \hat{e}$ cancels out. Thus Eq. (5) is equivalent to Eq. (4) and we immediately see that the incentive to adopt a new technology is the same for free (grandfathered) and for auctioned permits.

Matters are slightly different if an innovator has market power as is assumed by Montero (2002a) and Fisher et al. (2003). In that case there is an endowment effect, and the choice of the regime may affect the incentive to innovate.

3.1.4. Uniform emission standards

Finally, consider a uniform emission standard $\bar{e}$, sometimes referred to as "command and control policy". In this case a firm will be indifferent between staying with the conventional technology and adopting the advanced technology if

$$C_0(\bar{e}) - C_I(\bar{e}) - F = 0 \tag{6}$$

Since $-C_0'(\bar{e}) > -C_I'(\bar{e})$, the LHS of Eq. (6) decreases in $\bar{e}$. This means that the cost advantage of the new technology decreases as the emission standard is relaxed. This implies, however, that there exists a standard $\bar{\bar{e}}$ (depending on F) such that no firm will adopt the new technology if $\bar{e} > \bar{\bar{e}}$, but all firms will adopt the new technology if $\bar{e} < \bar{\bar{e}}$. As a consequence a uniform standard does not necessarily have the lowest adoption incentives, in contrast to what has often been claimed in the literature (e.g. Milliman and Prince, 1989; Jung et al., 1996).

3.2. Anticipating new technology, timing, and commitment

We now turn our attention to scenarios where the regulator anticipates the evolution of a new technology. We focus on the issue of timing and commitment and the difference between ex post and ex ante regulation. Kennedy and Laplante (1999) analyze a similar model as Requate (1995) where symmetric firms behave as price takers on the output market and choose whether or not to adopt a new abatement technology that lowers their marginal abatement costs but incurs fixed investment costs. Considering a scenario where the regulator anticipates the new technology and makes an ex ante commitment to the level of her policy instrument, the authors study the time consistency of emission tax and permit policies. They find that, if the environmental damage function is linear, ex ante commitment is time consistent for both instruments, no matter how many polluting firms are operating in the market. If, instead, the damage function is convex, time inconsistencies arise if the number of firms is relatively small. Ex post regulation, by contrast, referred to as "ratcheting", is time consistent by definition. However, firms then tend to underinvest in the new technology under permits (too little adoption) and to overinvest under taxes (too much adoption).[6]

For a continuum of firms no inconsistencies arise even when the damage function is convex. In a model with many (a continuum) of asymmetric firms, Requate and Unold (2001) come to a similar result. They even show that both, optimal ex ante and optimal ex post regulation lead to first-best allocations for all of the following environmental policy instruments: emissions taxes, subsidies on abatement, auctioned permits and free permits. Uniform standards, of course, cannot induce the optimal rate of adoption due to their static inefficiency. In the symmetric version of the model Requate and Unold (2003) confirm the optimality of ex ante and ex post regulation for the case of permits. Under taxes, however, a first best allocation can only be obtained for the case of ex post regulation. For the case of ex ante regulation, taxes may induce many equilibria, some of them inefficient in case that partial adoption is socially optimal.[7]

Amacher and Malik (2002) analyze the incentive for adoption for a single firm under an emission tax only. The firm can choose between a "cleaner" abatement technology that incurs high fixed but low marginal cost and a "dirtier" technology which incurs low fixed but high marginal cost. A first best is achieved if the firm adopts the "cleaner" technology and emits the respective socially optimal emission level. The second best outcome is defined as the firm adopting the "dirtier" technology and emitting the corresponding socially optimal amount of emissions. If the regulator commits ex ante to an emission tax rate and if the damage function is strictly convex, then it is possible that neither the first nor the second best outcome will be achieved: The Pigouvian tax, optimal with respect to one technology, may prompt the firm to adopt the other technology, and the emission level would not be socially optimal. With ex post regulation, by contrast, i.e. when the firm moves first, the first or the second best outcome are the only possible equilibria. The authors further show that the firm is always better off under ex post regulation, whereas the regulator, depending on parameters, may either prefer ex ante or ex post regulation.

3.3. Imperfect competition

In all the models discussed so far, the authors have either explicitly or implicitly assumed that the output markets are perfectly competitive. A couple of models pay explicit attention to imperfect competition on the output market and its consequences for adoption and regulation. Requate (1997) reconfirms the phenomenon of multiple equilibria for ex ante commitment to a tax policy, in particular if there is free entry.

Petrakis and Xepapadeas (1999) investigate regulation of a single monopolistic polluting firm that can choose among a menu of new technologies where the emission-per-output-coefficient is lower than the one of the conventional technology, and where the cost is the higher the smaller this coefficient. Assuming specific functional forms, in particular linear damage, and focusing on emission taxes only, the authors compare ex ante commitment to ex post regulation with respect to the optimal level of investment, the optimal emission tax, and welfare. Since the monopolist can influence the tax rate under ex post regulation, she will always invest more than in the case of ex ante commitment. Therefore, both the emission tax and welfare are always lower under ex post regulation compared to the case of ex ante commitment.

Montero (2002a) is mainly interested in the investment incentives of tradable permits and two kinds of standards, emission and performance standards, but rules out the possibility of taxation. Besides allowing for perfect and imperfect competition on the

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[6] The fact that the slope of the damage function is crucial may be reminiscent of Weitzman's (1974) seminal paper, as a referee suggested. In fact, there is little in common: Weitzman found that the ratio of the slopes of the marginal abatement cost function and of the marginal damage functions may be crucial for instrument choice. Here the question of whether or not the slope of the marginal damage function is positive is crucial for whether or not there is a problem of time consistency.

[7] Feess and Gleaves (2000) independently found similar results.

output market, he is one of the very few researchers who also models imperfect competition on the permit market. In his model ex ante symmetric firms produce a homogenous good and emit a pollutant. The firms can choose among different abatement technologies that are associated with lower marginal abatement costs than the conventional one. In contrast to the other approaches, however, there is no damage function, and thus optimal pollution levels are not considered. Rather, the regulator aims at enforcing an exogenously given aggregate emission standard. The R&D incentives are compared by means of the respective marginal profits. The total effect of a typical firm's investment decision consists of a direct cost effect and, in case of imperfect competition, of strategic effects on both the output and the permit market. The direct effect, always prompting the firms to invest, is the same for permits and for an absolute emission standard. Under performance (or relative) standards it is lower. The strategic effect with respect to the output market causes the firms to invest more under standards, but less under permits. In the former case the investment lowers whereas in the latter case it raises the competitors' output. The strategic effect on the permits market is in particular relevant under auctioned permits: since all firms are permit buyers, they benefit from a lower permit price due to higher investment. Hence, for imperfect competition on both markets Montero finds the following (partial) ranking: Both, an emission standard and a regime of auctioned permits provide a higher incentive to invest than free permits whereas a performance standard may provide a higher, a lower, or the same investment incentive than both free permits and the emission standard. Finally, both types of standards may provide a higher, a lower, or the same incentive to invest than auctioned permits. If there is perfect competition on both markets, only the direct effect matters. Thus an emission standard, free and auctioned permits provide the same incentives whereas the incentive provided by the performance standard is lower. Interestingly, the results are qualitatively the same as in the case where there is imperfect competition only on the permit market. For imperfect competition on the output market only, Montero finds that the incentives for tradable and auctioned permits are equivalent whereas an emission standard may provide a higher incentive than permits. These findings are in line with those of Requate and Unold (2003) who implicitly assume perfect competition on the output market.

In a recent comment on Montero (2002a), Bruneau (in press) holds the view that performance standards generate a greater incentive to innovate than permits even under perfect competition. Moreover, he extends Montero's analysis to the case of increasing marginal costs and argues that in this case both auctioned and free permits dominate performance standards. Bruneau, however, neither carries out a complete equilibrium analysis nor a welfare comparison, and thus does not rank the instruments with respect to total social costs or welfare. Since performance standards lead to inefficient abatement levels in the static case, it cannot be ruled out that they lead to inefficiently high investment.

3.4. Including uncertainty

A couple of contributions take into account different kinds of ex ante uncertainty in dynamic models with two or three periods where the uncertainty will usually be resolved in the second period: Laffont and Tirole (1996a) assume uncertainty about the benefits accrued by the firms from emitting pollutants. Kennedy (1999) considers uncertainty about environmental damage, whereas in Phaneuf and Requate (2002) the abatement cost is subject to uncertainty. van Soest and Bulte (2001) and van Soest (in press) take into account the uncertainty about technological progress. The approach by Bulte and van Soest is an important step in the direction to model ever ongoing R&D effort, for, R&D is usually not once and for all, and R&D failure may be just temporary.

Laffont and Tirole (1996a) analyze optimal regulation of many (a continuum of) (potentially) polluting asymmetric firms in a two period model where in both periods, firms can either emit one unit or nothing. Firms are regulated by emission permits. In the first period full abatement requires the firms to cease production whereas in the second period they can use an abatement technology which they had to purchase in the first one. In the first period firms know their benefit from pollution in period 1 but not that of period 2. Only the probability distribution of those benefits is known. This uncertainty is resolved in the second period. A novelty of this model is that the shadow cost of public funds is taken into account.

Thus the regulator chooses the optimal Ramsey permit price (respectively the corresponding amount of permits) in period 1. The authors show that if the permit market is a pure spot market, i.e. if the regulator issues permits in each period and in the first period is not able to make a commitment about the second-period permit price, then excessive investment incentives are created. A too high permit price prompts the firms to bypass the permit market via adoption of the abatement technology. By committing to a lower second-period permit price, especially by introducing a futures market, the regulator can enhance welfare by discouraging unwanted investment. However, committing to a lower second-period price in the first period is not time consistent. For, a marginal increase in the number of permits in the second period increases welfare. A price support policy or options to pollute, issued in period 1, allow the regulator to solve this problem of time inconsistency. It is important to note, however, that the over-investment result hinges on the assumption that the regulator wants to collect money form auctioning off permits in order to mitigate the social costs of public funds. In other words, the regulator wants to slow down diffusion of advanced technology because this erodes his tax base!

Kennedy (1999) sets up a two period model where in the first period the (constant) marginal damage may be high or low. Given this uncertainty, a large number of polluting firms have to decide whether or not to adopt an improved abatement technology which incurs fixed costs and lower marginal abatement costs. Kennedy assumes a very special scheme of permit trading, rarely used in real existing policy frameworks: one permit allows the emission of one unit of pollution in each period of time (rather than just for one period). When uncertainty about the marginal damage is resolved in the second period, the regulator can adjust the number of permits. Kennedy considers two kinds of adjustment rules which both implement the social optimum if announced in period 1; firstly, open market operations, i.e. buying back permits if the marginal damage turns out to be high and auctioning off more permits if the damage is low, and secondly, a proportional adjustment rule, where firms lose a fraction of their permit endowment if the damage is high, or get more permits proportional to their initial endowment if damage is low. Kennedy argues that the first rule is unlikely to be implemented since firms will be rewarded if the expected damage turns out to be higher than expected. I think, however, that expropriating permits from firms is as least as difficult since it violates the firms' property rights.

Phaneuf and Requate (2002) examine the effects of banking permits on the incentives to invest in advanced abatement technology if there is aggregate uncertainty about the abatement cost. To this end they set up a three period model where in the pre-regulation period 0, firms can invest in an abatement technology. In the periods 1 and 2, respectively, the uncertainty about the abatement cost is resolved. Banking allows firms to postpone investment until more information on the abatement costs is revealed. The authors find that, if the discount factor is sufficiently small, and if period 1 costs are revealed to be low, there will be positive banking but no first period investment. If instead period 1 costs are revealed to be high, there will be no banking but positive first period investment. The analysis of the constrained socially optimal response of the firms to the resolution of uncertainty (i.e. total endowment of permits is fixed) shows that the regulator would like some banking, but that private and social optimal responses to the resolution of uncertainty are not identical. This can lead to sub-optimal levels of investment in improved technology. A unique conclusion concerning the savings of social cost through banking is not possible, though. For a quadratic cost and damage function the authors show that banking leads to lower costs for society if the damage function is relatively flat. Otherwise non-banking is preferred.

van Soest and Bulte (2001) study the problem of technology adoption for the case that future technological advances are uncertain. For this purpose they apply the option value approach developed by Dixit and Pindyck (1994), which has been applied to the problem of technology adoption by Farzin et al. (1998) and improved by Doraszelski (2001). Van Soest and Bulte show that even if adoption of new technology pays according to the criterion of net present value comparisons, it may not be profitable if further improvements are likely to occur. Hence the firm is better off by postponing the adoption decision to the point of time when an even better technology is available. Using this calculus they offer an explanation why firms do not invest, although it seems favorable to do so. In a companion paper van Soest (in press) uses this approach in order to compare policy instruments with respect to the incentive to adopt improved energy-efficient technologies. Surprisingly, he finds that firms tend to postpone the adoption of improved technology if environmental policy is more stringent. Moreover, comparing energy taxes to absolute energy use standards, he finds that there is no unambiguous ranking of the two instruments when it comes to stimulate early adoption of new technology.

3.5. Regulation and hold up

Gersbach and Glazer (1999) identify incentives for firms to hold up innovation. In their model the regulator aims at prompting all (ex ante symmetric) firms of an oligopolistic, polluting industry to adopt a certain abatement technology at a fixed cost and to abate the corresponding optimal amount of emissions. If a firm does not invest, it can only abate emissions by reducing its output. A crucial but most unusual assumption is that the social benefit of the last unit of output exceeds its social cost of pollution. Hence, the regulator will never force a non-investing firm to abate emissions. Anticipating this, firms have an incentive to not invest into the new technology. Gersbach and Glazer show that this hold-up problem can be overcome by ex post issuing free permits, assuming a competitive equilibrium on the permit market. In equilibrium all firms invest if the number of firms in the market is as least two.

Although entering the realm of R&D, which we will deal with more properly in the next section, Cadot and Sinclair-Desgagne (1996) tackle a similar problem. They look at a situation where the regulator wants to implement a stricter emission standard. Without regulation firms have no incentive to adopt new technology or to engage in R&D whereas immediate regulation constitutes too high a burden for the firms and is thus not credible. Thus, the firms can again hold up the regulator by doing nothing. To solve this problem, the authors construct a dynamic incentive scheme that can be implemented as a Markov perfect equilibrium. In equilibrium both the regulator and the firms can use mixed strategies. The regulation scheme is characterized by a decreasing probability of setting a stricter standard as firms reach a certain stage of technology development.

4. Innovation, R&D, and adoption

So far we have considered scenarios where the new technology was given and firms had only to decide whether or not to adopt it. In this section we will study innovation and R&D before firms adopt the new technology. The question about how to model innovation depends on whether innovation is a private or a public good. If innovation is mainly firm specific and thus a private good, it can be modelled in a stylized way by letting production and cost functions depend on some investment level k. To adapt this to our previous model we would write $C(e,k)$ with $C_k<0$ and $-C_{ek}<0$, i.e. both abatement and marginal abatement costs are decreasing with more innovative investment. One can show easily that the results from the last section carry over to this model.

Matters are different if from the social perspective innovation is a public good, and once it has been invented, other firms could in principle use it without incurring considerable costs.[8] In these kinds of models authors either assume that ex ante there is only one innovator (e.g. Denicolo, 1999; Fisher et al., 2003, or Requate, in press), or that several — usually identical R&D firms — engage in a patent race, but ex post one innovator, the winner of the race, prevails in the market. Then this innovator can either sell or license the technology to other firms which decide whether or not to adopt it. Since in that case the innovator usually can exercise some market power, commitment and timing of the regulation game are crucial concerning both the incentives to engage in R&D and the incentives to adopt new technology.

The various models summarized in this subsection differ, firstly, with respect to which policy instruments are subject to investigation, secondly, which timing and commitment strategies are feasible for the regulator and which strategy she is assumed to pursue,

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[8] Innovators can, of course, exclude other firms from using it, and they can charge license fees to rent it out.

thirdly, whether R&D success is stochastic or deterministic, forth, whether the marginal damage is constant or increasing, or finally whether or not special attention is paid to the output market. We summarize the different contributions in the next sections. Table 2 gives an overview over the different features of the models.

4.1. Innovation incentives and welfare gains under perfect competition on the final market

Biglaiser and Horowitz (1995) and Parry (1995, 1998) were the first to rigorously combine the issues of innovation and adoption. Biglaiser and Horowitz (1995) consider a competitive polluting industry with

Table 2
Models of innovation and diffusion

Authors	Policy instruments	Timing of game/behavior of regulator	R&D stochastic	Marginal damage	Special attention to output market	Policy ranking
Biglaiser and Horowitz (1995)	Emission taxes plus technological standard	Interim, ex ante	Yes	Constant	No	–
Denicolo (1999)	Emission taxes, auctioned/free permits	Ex post, ex ante	No	Increasing	Yes	For damage not too high: 1. Taxes 2. Permits For high damage: 1. Permits 2. Taxes
Fisher et al. (2003)	Emission taxes, auctioned permits, free permits	Myopic, ex post	No	Increasing	No	Ambiguous
Katsoulacos and Xepapadeas (1996)	Emission taxes cum R&D subsidies	Ex ante	No	Increasing	Yes	–
Innes and Bial (2002)	Emission taxes and emission standards	Ex ante	Yes	Increasing	Yes	1. Taxes cum standards 2. Taxes
Laffont and Tirole (1996b)	Permits, advanced allowances (future market for permits), options, incentive contract, permits and securities and licensing tax	Interim, ex ante	Yes	Increasing	No	1. Options 2. Advanced allowances 3. Spot market permits
Montero (2002b)	Emission taxes, emission standard, auctioned permits, free permits	Exogenous emission target	No	–	Yes	Ambiguous
Parry (1995)	Emission taxes	Ex ante	Yes	Constant, increasing	No	–
Parry (1998)	Emission taxes, free permits, performance standards and output quota	Myopic, interim	Yes	Constant	Yes	Ambiguous
Parry et al. (2003)	Not specified	Ex post	No	Constant, increasing	No	–
Requate (in press)	Uniform emission taxes, menu of taxes auctioned permits	Ex ante, interim, ex post	Yes	Increasing	No	1. Menu of tax rates 2. Uniform taxes 3. Permits

an exogenously given number of ex ante symmetric firms each of which can engage in R&D. The new technology is randomly drawn from a cumulative distribution which is identical for all firms. Thus, innovation size and R&D success are stochastic. A patent is granted to a successful firm, and other firms can use this technology when paying a license fee and installation costs. Since adoption costs are independent of which particular technology is adopted, the regulator always wants an adopting firm to adopt the best available technology. If the regulator makes an interim commitment (i.e. after R&D but before adoption) to both an emission tax equal to marginal damage and to a technological standard which either specifies the firms which have to adopt the best available technology or which specifies the firms which have to adopt the "lowest acceptable" technology, then the efficient levels of pollution, production, and adoption will be induced. The level of R&D effort, however, is too low compared to the socially optimal level.

Parry (1995) sharply separates the polluting from the R&D sector. In contrast to most of the other contributions there is free entry on both markets. Each upstream firm conducts one R&D project to develop a new abatement technology for the polluting downstream sector but does not need it for its own production. Both the probability of R&D success and the industry's R&D cost rise with the number of R&D firms. If a firm is successful, it is granted a patent and becomes a monopolist. The ex ante symmetric downstream firms can adopt the new technology by paying a license fee. Parry shows that a rising tax rate leads to a smaller number of polluting firms in the downstream market. Since those with the highest willingness to pay for the new technology stay in the market, a higher tax also induces a higher license fee. Parry studies only the tax instrument with ex ante commitment to the tax rate before the upstream firms engage in R&D, and he derives the second best optimal tax rate for the cases of linear and convex damage and with and without the possibility of costless imitation. If imitation is not possible, the second best optimal tax rate turns out to be smaller than marginal damage. This is a typical finding for second best optimal taxation under imperfect competition. If imitation is possible, however, the second best optimal tax rate may be smaller or greater than marginal damage. This ambiguity may be caused by the assumption of free entry which induces a further market imperfection. Requate (1997) also found in a model of emission taxes in a Cournot model with pollution and free entry, and even without R&D, that the second best tax rate may exceed or fall short of marginal damage.

In a variant of this model Parry (1998) allows for incomplete diffusion, and besides taxes, he also studies tradable permits and an instrument mix consisting of a performance standard and a production quota. For permits and performance standards he distinguishes the cases of ex ante and interim commitment. Employing numerical simulations he finds that emission taxes yield higher welfare than permits, with the difference depending crucially on the potential size of innovation. The same holds for performance standards under ex ante commitment. For interim commitment, however, the difference in efficiency almost vanishes. For the case of emission taxes he shows that imitation does not necessarily imply large inefficiency in the R&D market. Therefore, imitation does not call for "research subsidies or tightening environmental regulation beyond the Pigouvian level" (p. 252).

In contrast to the previous authors, Fisher et al. (2003) abstract from patent races and consider a model with a large number of competitive polluting firms, one of which, called the innovator, is able to engage in R&D in order to improve its own abatement technology in the first place. The other symmetric polluting firms can either pay a license fee to adopt the new technology, or they can freely use an imperfect imitation. Despite this possibility complete diffusion is socially optimal. Considering emission taxes, auctioned and free permits as policy instruments the regulator is assumed to be myopic by ex ante committing to the Pigouvian levels with respect to the conventional technology. For the case of constant marginal damage the authors find that if no imitation is possible, emission taxes induce the first-best outcome. If imitation is possible, taxes dominate free permits with respect to welfare. Depending on how imperfectly the innovative technology can be imitated, welfare under taxes might exceed or fall short of welfare under auctioned permits. Emission taxes are superior if imitation is easy. For the case of increasing marginal damage the authors find that the steeper the marginal damage curve the more do permits dominate the tax regime. It is worth to note that in equilibrium imitation never occurs. It only serves as an outside option for the polluting firms and thus drives down the license fee. Furthermore, in contrast to Requate and Unold (2001, 2003), Fisher et al. (2003) find that free and auctioned permits do not perform equivalently in this model since the innovator is able to exercise market power, and his price strategy depends on his own initial endowment of permits. This endowment effect is similar to the one pointed out in Hahn's (1984) model who considers permit markets with one firm exercising market power. The endowment effect found by Fisher et al. is likely to be small, however, if the share of permits owned by the R&D firm is small.

Laffont and Tirole (1996b) study the innovation incentives of permits in a regime where, just as in their companion paper (Laffont and Tirole, 1996a), the regulator takes into account the shadow cost of public funds and thus is interested in reducing the burden on tax payers by taking advantage of the permit revenues. A single upstream firm engages in R&D and might invent a pollution-free technology. The authors show that if the regulator commits ex interim (i.e. after R&D but before the innovator's pricing decision) to a permit price, the innovator does not engage in R&D because he will make no profit. Since permits and innovation are perfect substitutes, the innovator will always undercut the permit price which drives down the price to zero. Laffont and Tirole further find that if the regulator prior to R&D sells a certain amount of permits and commits himself not to issue additional permits on the spot market after R&D success, then the innovation incentive is always smaller than optimal, and the induced level of adoption may be sub-optimal as well. Moreover, emissions are too high. However, the regulator can restore the first best outcome by offering an optimal ex ante incentive contract to the innovator, committing to purchase the invention at a certain price and to sell the licenses at the optimal Ramsey price.

4.2. Timing and commitment

As has become clear from the above summaries, most authors either assume that the regulator moves first and is able to ex ante commit to both the type and the level of his policy instrument, or that the regulator moves after observing R&D success and/or the degree of adoption, a setting we referred to as ex post regulation. It has been shown by Requate and Unold (2001, 2003) that under pure adoption and competitive conditions ex ante and ex post regulation are (almost) equivalent. If, by contrast, there is only one firm to be regulated, this equivalence breaks down, as Amacher and Malik (2002) have shown. If we study innovation, there are typically few firms which engage in R&D and even fewer that will be successful. Hence we would expect the timing to be crucial for the incentives to innovate. This is the focus of the papers by Denicolo (1999) and Requate (in press) who compare the different timings and commitment strategies with respect to welfare. Following Parry (1995), Denicolo (1999) and Requate (in press) sharply distinguish between a sector that develops and a sector that uses the new technology. This separation is well supported by empirical evidence. Lanjouw and Mody (1996) found that 81% of all innovations in air emissions clean up was developed by machinery industry but only 5% have been used by the same sector. For water cleaning technology we obtain 83% and 2%, respectively, and for energy production from renewable resources the numbers are 85% and 8%, respectively.

Denicolo (1999) was the first to explicitly compare ex ante and ex post regulation for both emission taxes and tradable permits in a model with an upstream monopolistic R&D firm and many polluting downstream firms. The perfectly competitive firms produce an output with constant returns to scale. Emissions are proportional to output. The new technology has a lower emissions-per-output ratio than the conventional one, and the degree of reduction depends on R&D investment. Denicolò finds that taxes and permits are equivalent for ex post regulation. For ex ante commitment, by contrast, the instruments are not equivalent and both always lead to underinvestment in R&D. If the regulator commits to the second-best optimal level of the instruments, it depends on the social cost of pollution whether taxes perform better or worse than permits.

Requate (in press), similar to Parry (1995), studies the relationship between adoption of new technology and R&D incentives. For this purpose he studies a monopolistic upstream innovator which invests R&D

effort in order to find a new, exogenously given abatement technology. The R&D effort determines the probability of success. If research was successful, the innovator produces the new technology at constant marginal cost. Then a large number of asymmetric polluting downstream firms decide whether or not to adopt the new technology. The incentive for both, to adopt new technology and to engage in R&D, is analyzed for emission taxes and auctioned permits.

The industry process can be divided into four stages: (i) R&D activity, (ii) pricing of new technology, (iii) adoption of new technology, and (iv) decision of downstream firms on short term abatement (see Fig. 5). This structure gives rise to four different timings of environmental policy: (A) ex ante commitment before R&D, using a uniform tax (or permit) policy; (B) ex ante commitment before R&D, using a menu of different tax rates (or permit policies, respectively) contingent on R&D success; (C) interim commitment after observing R&D but before adoption of new technology, and finally (D) ex post regulation after observing both R&D and the rate of adoption. In all cases Requate discusses both regulation by prices (taxation) and regulation by quantities (issuing tradable permits). It is easy to see that the two policies must be equivalent in scenario (D). This is so because when the regulator is the last to move, he knows both the marginal damage and the aggregate marginal abatement costs. Hence he is able to implement each aggregate emission target by either charging a tax or by issuing the corresponding number of permits.

The main result of that analysis is that commitment to a menu of tax rates (timing B) dominates all other policy regimes. Moreover, the tax regime outperforms the permit regime for both interim regulation (timing C) and commitment to a menu of policy levels contingent on R&D success (timing B). The reason is that under a tax regime and commitment before the innovator engages in pricing of his new technology, the innovator is not able to influence the tax rate whereas he can influence the permit price by pricing higher or lower, or equivalently, by holding down or raising output. To be more precise, by pricing higher, other things equal, demand for the technology falls. But at the same time demand for permits by those firms which still hold the old technology rises. Higher demand for permits leads to higher permits prices and thus raises the willingness to pay for the advanced abatement technology. The bottom line is that the innovators' effective inverse demand function for the new technology is more elastic under permits than under taxes, and thus the distortion through monopoly power on the market for new technology is more severe under the permit regime compared to the tax regime.

Moreover, Requate (in press) finds that under interim commitment the second best tax rate exceeds marginal damage under some mild assumptions on the

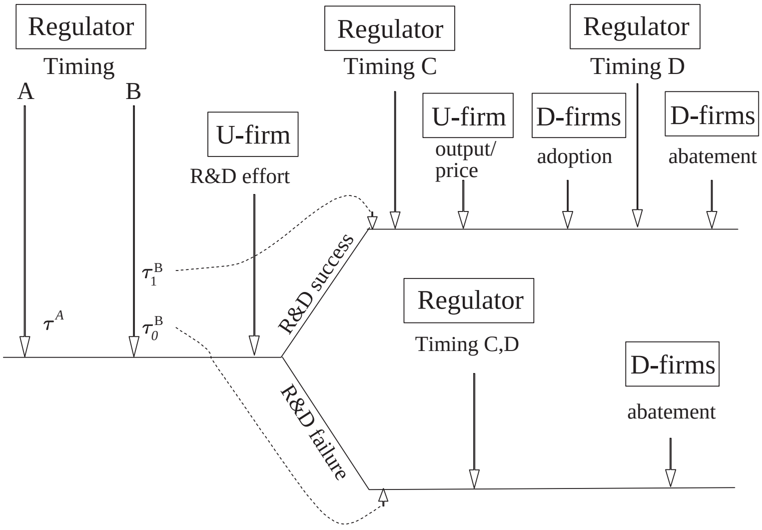

Fig. 5. The structure of the different regulation games.

demand for new technology. The intuition here is that the innovator produces less units of the new technology than socially optimal. Hence the regulator can enhance the demand for new technology by raising the tax rate. Under timing A and B, by contrast, the tax rate may exceed or fall short of marginal damage. Here the reason is that under these timings the regulator tries also to influence the R&D effort. Note that timing A is similar to Parry's set-up, who obtains a tax rate lower than marginal damage, but incurs a further market imperfection through sub-optimal market entry.

Requate further argues that a first best allocation can be restored if the regulator has control over three policy instruments: an emission tax in order to reduce pollution, an output subsidy in order to give incentives to the monopolist to increase output, and finally a profit tax or subsidy, in order to equalize the monopolist's private value of innovation to the social value of innovation. Nevertheless, even with three instruments, the timing of the regulator does matter: Since under commitment to a tax policy the demand function for new technology faced by the innovator is less elastic, the output subsidy required to obtain the first best allocation will be smaller compared to a permit policy. Thus, if the regulator faces social costs to raise public funds, he will prefer a timing which is less costly in terms of total subsidies to be paid to industry in order to obtain a first best, or at least less distorted allocation.

4.3. Imperfect competition on the final goods market

Whereas the contributions studied so far have abstracted from the output market, some authors investigate incentives to innovate with the special focus on imperfect competition on the output market. Katsoulacos and Xepapadeas (1996) assume Cournot competition whereas Innes and Bial (2002) assume Bertrand competition with homogenous goods. Montero (2002b) considers both the case of price competition with differentiated commodities and Cournot competition.

Katsoulacos and Xepapadeas (1996) study a Cournot (i.e. quantity setting) duopoly with emissions proportional to output. Both firms are able to reduce their emissions-per-output ratio by investing in R&D and enjoy spillovers through the other firm's R&D effort. The regulator ex ante commits to both an emission tax and an R&D subsidy (which can also take negative values). The authors find that the optimal tax rate falls short of marginal damage while the optimal subsidy is positive if the spillover effects are sufficiently high, and negative otherwise. The intuition for this result is as follows: on the one hand, firms tend to underinvest in R&D because the private return from R&D is smaller than the social return and because firms do not account for consumers' surplus. On the other hand, firms strategically tend to overinvest in R&D in order to increase market shares.

With a similar set-up Petrakis and Xepapadeas (2003) study a model of innovation with market power on the output market. Surprisingly they find that cases exist where time consistent policies lead to higher welfare than commitment strategies.

Innes and Bial (2002), by contrast, study innovation incentives for a Bertrand (i.e. price setting) duopoly with homogenous products. By investing in R&D the firms can find a certain incremental innovation that would lower both their marginal cost of production and their marginal abatement cost. Since R&D success is stochastic, no, one or both firm(s) may be successful. If firms are ex post symmetric, the regulator is able to implement efficient pricing and efficient levels of both production and abatement by levying the corresponding Pigouvian tax. If, however, firms are ex post asymmetric, the regulator is not able to implement the first best allocation by levying a tax only. The emission tax that is optimal with respect to the new technology would enable the winner of the R&D race to serve the entire market and to produce less than efficient. The regulator can solve this problem by combining an emission tax lower than marginal damage with a non-uniform relative standard which requires the winner to comply with the first-best standard and the loser with a laxer standard. The authors further look at a setting where the regulator is not able to observe R&D outcomes without any cost. Surprisingly however, the regulator can nevertheless induce the firms to report their technologies truthfully and thus can implement the first-best allocation by ex ante committing to a similar policy, i.e. by committing to levy an emission tax, to set a non-uniform relative standard contingent on the firms' technology reports and to monitor the firms with a certain probability.

Building on his companion paper (Montero, 2002a), Montero (2002b) allows for R&D spillovers and assumes imperfect competition on both the output and the permit market throughout his analysis. He studies Cournot as well as price competition with differentiated products. Besides emission standards and permits he also analyses emission taxes. Montero finds that if the marginal cost of both firms is constant, there is no strategic effect when levying an emission tax. Taxes may provide more, less, or the same incentive to invest in innovation than emission standards and auctioned permits whereas free permits offer less incentive than taxes. With price competition on the output market, by contrast, taxes provide a higher incentive than an emission standard which in turn provides a higher incentive than free permits. Auctioned permits again can offer more, less or the same incentive than taxes. Montero concludes, that in the Cournot case, either emission standards, taxes, or auctioned permits can provide the highest incentive, whereas in the case of price competition this holds either for taxes or for auctioned permits.

I would like to close this section by emphasizing a recent contribution by Parry et al. (2003) who open up a somewhat anti-innovative perspective by showing that within a dynamic framework including the aspect of time explicitly, in many cases the net present value of innovation is small. They argue that environmental improvements by even optimally employing new technologies may be small compared to optimally exploiting existing abatement opportunities. After all they conclude, that "these findings appear to contradict earlier assertions by some economists that technological advance might be more important than achieving optimal pollution control in the design of environmental policies" (p. 252).

5. Concluding remarks

In this paper I surveyed recent developments on the incentives provided by environmental policy instruments to adopt advanced abatement technology and to engage into R&D to develop such new technology. I started with some critical remarks on the ranking of environmental policy instruments in the traditional literature, a ranking derived by comparing aggregate cost savings rather than by investigating the firms' incentives to invest in equilibrium. I have argued that the comparison of environmental policy instruments leads to quite different results if the number of firms which adopt new technology is determined endogenously through equilibrium considerations.

With all the special results it seems to be difficult to draw clear conclusions on which policy instruments dominate other policy instruments. I think, however, one can draw the main conclusion that instruments which provide incentives through the price mechanism, by and large, perform better than command and control policies. Even though, it is important that the regulator either anticipates the new technologies to a certain extent or that he reacts in an optimal way on invention and adoption of new technology. Under competitive conditions and perfect foresight, different authors established the result that ex ante commitment and ex post optimal policies generate equivalent or at least similar allocations. Under imperfect market conditions, the policy conclusions are less clear cut.

Under myopic environmental policies or long term commitment to the levels of policy instruments, by contrast, emission taxes tend to provide a stronger incentive to invest in both R&D and adoption of new technology as compared to emission allowances. The reason is that the permit price falls if new technology diffuses, providing a lower incentive for firms with old technology to invest in pollution reducing technology.

One shortcoming of the research is that one of the most commonly used instruments, namely the relative (or generation performance) standard is usually not studied. One reason is that many researchers look at the polluting sector only and do not pay attention to the output market. To model the relative standard, it is necessary to also take into account the firms' decisions on output. According to my knowledge, Montero (2002a) was the only one who studied this kind of standard. He finds, however, that this policy instrument does not perform very well compared to market based instruments such as tradable permits.

Note that most of the contributions on adoption and R&D incentives follow the tradition of the industrial organization literature since they are concerned with dynamic games of a finite number of stages. In reality, however, we observe a permanent process of research firms engaging in R&D and polluting firms adopting new technology. Furthermore, a regulator will not be able to commit to the level of his policy instruments for once and for all. Hence an important path for further research is to account for such processes in a more complex dynamic framework in order to improve dynamic environmental policy design. As mentioned above, the approach by van Soest and Bulte (2001) who employ the option value approach, developed by Dixit and Pindyck (1994), is one of the most promising steps into that direction.

At the beginning of this survey we quoted Kneese and Schulze who emphasized that the long term incentives provided by environmental policy instruments to spur the development of new technology are possibly more important than the criteria of static efficiency. Contrasting from this view, Parry et al. (2003) stress that the welfare gain from innovation is sometimes not much greater than the welfare gain of efficiently abating pollutants by means of conventional technologies. I think this is an important point. Resources to engage in R&D are scarce. Hence environmental technological progress may crowd out other strands of welfare enhancing technological progress. It is often the same people (and political parties) who urge for the adoption of particular technologies such as wind and solar power, and at the same time vote for rather inefficient instruments of regulation. Incentives for the right rate and the right direction of technological progress are important. But, the potential of traditional technology should also be efficiently exploited. Hence both the long and the short term incentives of environmental policy instruments must be considered.

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