Inducing Technical Change by Standard Oriented Environmental Policy: The Role of Information[*]

by

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Abstract

In their seminal 1971-paper, W. J. Baumol and W. E. Oates analyzed effluent charges and "command and control" regarding their ability to attain a given standard of environmental quality at minimum cost. In the subsequent literature transferable discharge permits (TDPs) have been added to the portfolio of standard oriented environmental policy instruments.
We put these instruments in a dynamic context. There, cost minimization is defined in an intertemporal setting allowing for induced technical change. It turns out that the relative performance of alternative policy instruments regarding their "dynamic cost-effectiveness" crucially depends upon the information available to the involved agents. Under adverse informational conditions only a TDP-system with future markets is dynamically cost-effective.

Key Words: "pricing and standards" approach, environmental policy, induced technical change, incomplete information

JEL-classification: Q58, Q55

I. Introduction

Traditionally, the economic theory of environmental policy has followed the *Leitbild* of internalizing externalities: External effects destroy the social optimality property of a competitive market system. Applying strategies of internalization (e.g. Pigouvian taxes) the policy maker may restore the social optimality of private equilibria.

In their seminal 1971-contribution W.J. Baumol and W.E. Oates propose a somewhat more modest approach: Due to the obvious difficulties to assess marginal damage full internalization may be impossible. Instead of aiming to achieve the socially optimal allocation the policy maker may have to be content to achieve "somewhat arbitrary standards for an acceptable environment" (Baumol and Oates, 1971, p. 44) which are not pareto-optimal, in general.

Environmental policy instruments which are used within this framework are called "standard oriented environmental policy instruments" (as opposed to internalization strategies) in this paper. Obvious candidates are effluent charges, transferable discharge permits and individual emission standards ("command and control"[1]).

Consider the literature in the two strands of environmental economics, the internalization approach and the standard oriented approach. Both original approaches are static and so is the most part of the subsequent discussion. The static approaches have dealt with the question: How do alternative policy instruments perform regarding their ability to make polluters apply a given control technology to the "right" extent? However, over the past decade, the incentives of environmental policy instruments to introduce progress in abatement technology have grown to become a major topic in environmental economics. The more recent dynamic approaches supplement the original static analysis by asking the question: How do alternative policy instruments perform regarding their ability to make polluters develop the "right" abatement technologies? Of course, a comprehensive treatment has to answer both questions simultaneously.

1 There is a possible source of confusion in how the term „standard" has been used in the literature. On the one hand, "standard" is meant to be an aggregate level of emissions. The goal of environmental policy is to make sure that equilibrium aggregate emissions do not exceed this target. It is in this sense of the term that we use the expression "standard oriented environmental policy" in this paper. (This is also the sense in which the term is used in the quotation from Baumol and Oates (1971), above.) On the other hand, the term "standard" has been used in the literature to denote an *instrument* of environmental policy. Here, the standard is an upper emission limit addressed to the individual polluter. The standard in this sense is one of many instruments with which the standard in the former sense (the policy *goal*) may be achieved. To avoid confusion we use the terms "command and control" or "quota" when referring to the individual emission standard in the instrumental sense.

A review of these dynamic approaches allowing for induced technical change shows that most contributions follow the internalization approach.[2] In this context, the "right" technology is defined by the socially optimal allocation. Only a minority of contributions analyzes induced technical progress in a standard oriented framework defining "the right" technology by the cost-effective allocation.[3]

There is a fundamental divergency between the dynamic internalization approaches and the dynamic standard oriented approaches in the literature. With the exception of some older papers, in the internalization literature a clear cut intertemporal norm of social optimality is defined against which the intertemporal equilibria of alternative internalizations strategies are measured. Socially optimal activity levels are compared to instrument specific equilibrium activity levels, regarding emission abatement quantities in different periods and regarding investments into technical progress.[4]

Surprisingly, a convincing analogous measuring rod serving to evaluate alternative policy instruments within the standard oriented framework has not yet been presented in the literature. A concept of achieving pre-determined environmental standards which are defined over time at minimum *cost* to society needs still to be developed in a setting allowing for induced technical progress. In the static model the relevant concept of cost is pollution abatement cost. In the dynamic model this understanding of "cost" has to be adjusted in two respects: First, pollution abatement cost has to be observed in different periods of time. Second, the cost of investing into better future abatement technology has to be acknowledged as an element of the cost to society.

Instead of creating this kind of a normative concept, most of the literature on standard oriented environmental policy and induced technical change has ranked the alternative instruments according to how strong an incentive they provide to polluters to invest into better abatement technology.[5] However, this criterion is not necessarily in accordance to the

[2] Surveys can be found in, e.g., Jaffe et al. (2002), Requate (2005a).

[3] Requate (2005), Tables 1 and 2, compares 28 papers on induced environmental technical progress according to a variety of criteria. 23 of those use a damage function, which is a prerequisite for internalization. Only 5 do without, as is warranted within the standard oriented approach.

[4] See, e.g., Fischer et al. (2003), Hoel and Karp (2002), Parry (1995), (1998), Requate and Unold (2001), (2003).

[5] See e.g., Jung et al. (1996), Milliman and Prince (1989), Montero (2002). This criterion is also part of the folklore in environmental economics textbooks, see, e.g. Hanley et al. (2001), p. 258, Perman et al. (2003), Table 7.1, p. 203 and pp. 236/7, and Russell (2001), pp. 202/3. The latter author observes "that the relevant published research avoids the efficiency question and explores instead the simpler question of which instrument provides the *largest* incentive for seeking and adopting technical change …" (p. 202).

requirements of standard oriented environmental policy striving to achieve a pre-determined environmental goal at minimum cost.[6]

Another criterion used in the literature on the dynamics of standard oriented environmental policy is that the regulator's aim is "simply to implement a target, $\hat{E}$, irrespective of damage or abatement cost" (Requate and Unold (2001), p. 543). Obviously, this is also at odds with the idea of cost-effective standard oriented environmental policy.[7]

The *first motivation* of the paper at hand is to develop the missing measuring rod for the evaluation of standard oriented environmental policy instruments in a dynamic framework allowing for induced technical change. Having established this norm it is used to analyze conditions under which effluent charges, transferable discharge permits and command and control are cost-effective means to achieve the intertemporal policy goal. It turns out that the results crucially depend upon the quality of information the economic agents (the regulator and the polluters) have. The *second motivation* of this paper is to design alternative information scenarios and to show how the relative performances of the alternative standard oriented policy instruments change with changing information scenarios.[8]

Emphasis on information is in line with a fundamental result of the earlier (i.e., static) discussion of standard oriented environmental policy. In their 1971-paper Baumol and Oates already pointed to the following fact: the task of the policy maker, to achieve the specified reduction in aggregate pollution (the "standard") at minimum cost to the society can, in principle, be achieved using command and control just as it can be achieved using effluent charges. The fundamental difference between the two policy instruments is that the

[6] Ranking policy instruments according to their incentives to innovate makes sense within the specific set of assumptions in Jung et al. (1996). Particularly, these authors assume that technical progress is costless. (See their footnote 5, p. 97: "We … do not consider … R & D expenditures.") In a world where technical progress only provides benefits and no cost, maximum technical progress and optimal technical progress are identical. Of course, this assumption reduces the analysis to a special case which should not carry much weight in the discussion. Consequently, in the concluding section of their paper the authors acknowledge that "a larger welfare analysis would have to consider other policy goals than technology promotion" (p.109).

[7] Most of the aforementioned paper is on induced technical progress within the internalization framework. The above citation is taken from the brief paragraph on "The Ranking of Incentives to Adopt New Technologies for an Aggregate Emission Standard". The authors imply that a normative concept to evaluate alternative policy instruments cannot be developed within this standard oriented approach. They conclude their section on standard oriented instruments with the remark: "Hence we will assume in the following that a social damage function is known. This allows us to determine the *optimal* number of firms that should adopt the new technology, …" Then, the framework of the paper is changed from one of standard orientation to one of internalization.

[8] In this respect our paper is also related to the literature focussing on the timing and commitment of environmental policies in the presence of induced technical change, cf. e.g., Denicolo (1999), Kennedy and Laplante (1999), and Laffont and Tirole (1996a), (1996b), Requate (2005b). Our paper differs from these works in that we study the outcome of the standard oriented approach and assume ex-ante regulation.

information requirements to fulfil the task are much higher when command and control is used instead of charges. Indeed, “how the least-cost set of relative quotas could be arrived at in practice by the regulator is not clear, since this obviously would require …extensive information on each polluter’s marginal cost function” (Baumol and Oates, 1971, p. 46).
Of course informational aspects of policy making are even more complicated in the dynamic setting with induced technical change than in the initial static model. In the former, knowledge about the productivity of investments into better abatement technology is an issue which is absent in the static analysis by definition.

The paper is organized as follows: In the next section we introduce the model and derive the conditions for cost-effective levels of abatement and investment in technical progress. In section III we examine the standard oriented policy instruments, i.e., command and control, pollution taxes, as well as tradable permit regimes with and without future market, under different information scenarios. Section IV summarizes the results and points to policy conclusions as well as questions for future research.

II. Social cost minimization

We consider an industry with *n* firms, $i \in N = \{1,...,n\}$, which emit a global pollutant, E, in a two period setting. Without regulation the equilibrium emission level of each firm is assumed to be $\frac{1}{n}E^{max}$ in each period.
Aggregate emissions of period *t*, $t \in \{0,1\}$, shall be reduced to the exogenously given policy target level $\overline{E}_t$ with $\overline{E}_1 \leq \overline{E}_0 < E^{max}$. Thus, the corresponding emission abatement targets are $\overline{X}_t = E^{max} - \overline{E}_t$ with $\overline{X}_1 \geq \overline{X}_0 > 0$.
Emission abatement causes firm specific costs:[9]

(1) $$C_0^{(i)}(X_0^{(i)}) + I_0^{(i)} + C_1^{(i)}(X_1^{(i)}, I_0^{(i)}),$$

where $C_0^{(i)}$ and $C_1^{(i)}$ are twice continuously differentiable with $\partial C_t^{(i)} / \partial X_t^{(i)} > 0$, $\partial^2 C_t^{(i)} / \partial(X_t^{(i)})^2 > 0$, $C_1^{(i)}(X_1^{(i)}, 0) = C_0^{(i)}(X_1^{(i)})$, $\partial C_1^{(i)} / \partial I_0^{(i)} < 0$, $\partial^2 C_1^{(i)} / \partial(I_0^{(i)})^2 > 0$ and $\partial^2 C_1^{(i)} / \partial X_1^{(i)} \partial I_0^{(i)} < 0$.

[9] Opposed to that, the analysis of standard oriented environmental policy in Montero (2002) is limited to the case of symmetric firms.

Abatement costs of period 1 may be reduced by investments into improvements of abatement technology, I_0, in period 0. Note that abatement cost functions may (and in general do) differ between the firms. In particular for period 1 this may be due to unequal productivity of investments.

The aggregated abatement levels are given by $X_t = \sum_i X_t^{(i)}$ with $t \in \{0,1\}$.

We assume that there are neither discounting nor technology spillovers.[10]

Following the idea of standard oriented environmental policy the social planner strives to attain the prespecified level of pollution control at minimum cost to society.

Technically speaking the optimization task is to minimize the social abatement cost function:

(2) $$\min \ TC = \sum_i (C_0^{(i)}(X_0^{(i)}) + I_0^{(i)} + C_1^{(i)}(X_1^{(i)}, I_0^{(i)}))$$

under the two constraints

(2.a) $$\sum_i X_t^{(i)} = \bar{X}_t \,,\ t \in \{0,1\}.$$

From the Lagrange Function:

(3) $$L = \sum_i \left(C_0^{(i)}(X_0^{(i)}) + I_0^{(i)} + C_1^{(i)}(X_1^{(i)}, I_0^{(i)}) \right) - \lambda_0 \left((\sum_i X_0^{(i)}) - \bar{X}_0 \right) - \lambda_1 \left((\sum_i X_1^{(i)}) - \bar{X}_1 \right)$$

we get the following first order conditions (additional to (2.a)):[11]

(3.a) $$\partial L / \partial X_0^{(i)} = \partial C_0^{(i)} / \partial X_0^{(i)} - \lambda_0 = 0 \ \forall i \in I \quad \Rightarrow \partial C_0^{(i)} / \partial X_0^{(i)} = \partial C_0^{(j)} / \partial X_0^{(j)} \ \forall i, j \in N \,,$$

(3.b) $$\partial L / \partial X_1^{(i)} = \partial C_1^{(i)} / \partial X_1^{(i)} - \lambda_1 = 0 \ \forall i \in I \quad \Rightarrow \partial C_1^{(i)} / \partial X_1^{(i)} = \partial C_1^{(j)} / \partial X_1^{(j)} \ \forall i, j \in N \,,$$

(3.c) $$\partial L / \partial I_0^{(i)} = 1 + \partial C_1^{(i)} / \partial I_0^{(i)} = 0 \ \forall i \in I \qquad \Rightarrow \partial C_1^{(i)} / \partial I_0^{(i)} = -1 \ \forall i \in N \,.$$

Solving this system of equations leads to the cost-effective abatement and investment levels $X_0^{(i)**}, X_1^{(i)**}, I_0^{(i)**} \ (i = 1,...,n)$.

The interpretation of the first order conditions is straight forward. Equations (3.a) and (3.b) state that the environmental protection goal $\bar{E}_t$ is achieved cost-effectively in each period when marginal abatement cost of firms are equalized. These conditions are the dynamic

[10] Fischer et al. (2003) and Jaffe et al. (2005) consider spillovers. However, they do not focus on standard oriented policy.

[11] Here and in the following we assume interior solutions.

equivalent of the well-known least cost condition of static standard oriented environmental policy analysis. Equation (3.c) states that in the cost minimum firms invest in technical progress up to the level where their future marginal abatement cost savings equal marginal R&D cost (which are normalized to 1 in the model).

III. Positive analysis

We analyze the standard oriented instruments command-and-control regulation, effluent charges, and transferable discharge permits in three different information scenarios.

- In the first scenario it is assumed that all relevant functions are common knowledge.
- In the second scenario we assume that aggregate abatement cost functions of period 0 and 1 are common knowledge whereas individual abatement cost functions are private knowledge to the firms. This scenario reflects the traditional assumptions of the literature on standard oriented environmental policy.[12]
- In the last scenario the assumptions about available information are further weakened. As in the previous scenario it is assumed that present aggregate abatement cost is common knowledge. However, neither the social planner nor the firms know the aggregate abatement cost function of period 1, which depends on (aggregate) firm specific R&D productivities. As in the second scenario, present and future individual abatement costs are private information of the firms.

Formatiert: Nummerierung und Aufzählungszeichen

III.1 The full information scenario:

Individual and aggregate abatement cost functions are common knowledge

It is assumed that the involved parties have all relevant information, i.e., aggregate marginal abatement costs (equations (4) and (5)) as well as private marginal abatement costs (equations (6) and (7)) for both periods. These marginal abatement cost functions are given by:

[12] In the static models on standard oriented environmental policy the conditions used to define our second information scenario generate the textbook case of effluent charges being superior to command and control. To quote one for the many: "… the emission tax, …, attains the target at least cost, and so is cost efficient. This result is rather powerful …EPA … does not need to know the abatement cost function of each firm. Knowledge of aggregate abatement function alone is sufficient … Compare this result with the case of command and control instruments; there, knowledge of every firm's marginal abatement cost function is required – a much more demanding information requirement." (Perman et al., 2003, p. 219.) Note that in the European literature the term "cost efficiency" is often used instead of "cost-effectiveness".

(4) $$MC_0^{\Sigma}(X_0) = \frac{dC_0^{\Sigma}}{dX_0}$$

with (4.a) $C_0^{\Sigma}(X_0) = \min_{X_0^{(i)}} \sum_i C_0^{(i)}(X_0^{(i)})$ w.r.t. $\sum_{i \in I} X_0^{(i)} = X_0$,

(5) $$MC_1^{\Sigma}(X_1) = \frac{dC_1^{\Sigma}}{dX_1}$$

with (5.a) $C_1^{\Sigma}(X_1) = \min_{X_1^{(i)}, I_0^{(i)}} \sum_i \left(C_1^{(i)}(X_1^{(i)}, I_0^{(i)}) + I_0^{(i)} \right)$ w.r.t. $\sum_{i \in I} X_1^{(i)} = X_1$,[13, 14]

(6) $$MC_0^{(i)}(X_0^{(i)}) = \frac{\partial C_0^{(i)}}{\partial X_0^{(i)}},$$

(7) $$MC_1^{(i)}(X_1^{(i)}) = \frac{dC_1^{(i)}}{dX_1^{(i)}}$$

with (7.a) $C_1^{(i)}(X_1^{(i)}) = \min_{I_0^{(i)}} C_1^{(i)}(X_1^{(i)}, I_0^{(i)}) + I_0^{(i)}$.

a) Command and control

Since the regulator knows marginal individual abatement costs (6) and (7) he chooses abatement quotas $\overline{X}_t^{(i)}$, $\overline{X}_t^{(j)}$ such that $MC_0^{(i)}(\overline{X}_0^{(i)}) = MC_0^{(j)}(\overline{X}_0^{(j)}) \; \forall i, j \in N$.

The corresponding abatement and investment levels coincide with the social least cost solution, i.e., $X_0^{(i),Q} = X_0^{(i)**}$, $X_1^{(i),Q} = X_1^{(i)**}$, $I_0^{(i),Q} = I_0^{(i)**}$ $(i = 1,...,n)$.

b) Tax

Using the aggregate marginal abatement cost functions (4) and (5) the regulator determines for each period the tax rate $T_t = MC_t^{\Sigma}(\overline{X}_t)$. It is assumed that the regulator announces both tax levels at the beginning of period 0.

Hence firm *i* minimizes the cost function:

(8) $$C_T^{(i)}(X_0^{(i)}, X_1^{(i)}, I_0^{(i)}) = C_0^{(i)}(X_0^{(i)}) + T_0(\frac{1}{n}E^{max} - X_0^{(i)}) + I_0^{(i)} + C_1^{(i)}(X_1^{(i)}, I_0^{(i)}) + T_1(\frac{1}{n}E^{max} - X_1^{(i)}) .$$

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[13] Note that (5.a) could also be written as $C_1^{\Sigma}(X_1) = \min_{X_1^{(i)}} \sum_i \left(\tilde{C}_1^{(i)}(X_1^{(i)}) \right)$ w.r.t. $\sum_{i \in I} X_1^{(i)} = X_1$ and with $I_0^{(i)}(X_1^{(i)}) = \text{argmin} \left(I_0^{(i)} + C_1^{(i)}(X_1^{(i)}, I_0^{(i)}) \right)$, $\tilde{C}_1^{(i)}(X_1^{(i)}) = I_0^{(i)}(X_1^{(i)}) + C_1^{(i)}(X_1^{(i)}, I_0^{(i)}(X_1^{(i)}))$. I.e., to each $X_1^{(i)}$ corresponds a cost-effective investment level $I_0^{(i)}(X_1^{(i)})$. Equation (5) implies that this investment level (which is determined by (3.c)) is chosen. This corresponds with the equilibrium behaviour of the firms which know their private marginal abatement costs in each information scenario.

[14] Note that from (4.a) and (5.a) again we get the first order conditions (3.a)-(3.c).

The first order conditions are:

(8.a) $\partial C_T^{(i)} / \partial X_0^{(i)} = \partial C_0^{(i)} / \partial X_0^{(i)} - T_0 = 0 \;\Rightarrow \partial C_0^{(i)} / \partial X_0^{(i)} = \partial C_0^{(j)} / \partial X_0^{(j)} = T_0 \;\forall i,j \in N$,

(8.b) $\partial C_T^{(i)} / \partial X_1^{(i)} = \partial C_1^{(i)} / \partial X_1^{(i)} - T_1 = 0 \;\Rightarrow \partial C_1^{(i)} / \partial X_1^{(i)} = \partial C_1^{(j)} / \partial X_1^{(j)} = T_1 \;\forall i,j \in N$,

(8.c) $\partial C_T^{(i)} / \partial I_0^{(i)} = 1 + \partial C_1^{(i)} / \partial I_0^{(i)} = 0 \quad \Rightarrow \partial C_1^{(i)} / \partial I_0^{(i)} = -1 \;\forall i \in N$.

Hence the first order conditions imply (3.a)-(3.c) and the emission reduction is cost-effective. Thus for the corresponding aggregated abatement levels $X_t^{\Sigma,T} = \sum X_t^{(i),T}$ it follows from (4) and (5) that $X_t^{\Sigma,T} = \bar{X}_t$ holds for $T_t = MC_t^{\Sigma}(\bar{X}_t)$. Thus the tax levels T_t induce the intended abatement level via cost-effective emission reductions and investments,
i.e., $X_0^{(i),T} = X_0^{(i)**}, X_1^{(i),T} = X_1^{(i)**}, I_0^{(i),T} = I_0^{(i)**} \;(i = 1,...,n)$.

c) Permits

In the permit scenarios we assume a closed trade between *n* price-taking firms. Thus strategic behaviour is ruled out.[15] We further assume that permits are grandfathered to the firms. Each firm receives the amount $\frac{1}{n}\bar{E}_t$ in period *t*.[16] In analogy to what has been said with respect to the tax rate above, we assume that the amount of permits to be given away in the two periods, is announced at the beginning of period 0.

Since the aggregated marginal abatement cost functions (4) and (5) are common knowledge the firms may solve the game by backward induction, forecast the equilibrium permit price of period 1 $P_1 = MC_1^{\Sigma}(E^{max} - \bar{E}_1)$ and choose their optimal investment level in period 0.

Thus firm *i* minimizes the cost function:

(9) $$C_P^{(i)}(X_0^{(i)}, X_1^{(i)}, I_0^{(i)})$$
$$= C_0^{(i)}(X_0^{(i)}) + P_0(\frac{1}{n}(E^{max} - \bar{E}_0) - X_0^{(i)}) + I_0^{(i)} + C_1^{(i)}(X_1^{(i)}, I_0^{(i)}) + P_1(\frac{1}{n}(E^{max} - \bar{E}_1) - X_1^{(i)}) .$$

The first order conditions are:

(9.a) $\partial C_P^{(i)} / \partial X_0^{(i)} = \partial C_0^{(i)} / \partial X_0^{(i)} - P_0 = 0 \;\Rightarrow \partial C_0^{(i)} / \partial X_0^{(i)} = \partial C_0^{(j)} / \partial X_0^{(j)} = P_0 \;\forall i,j \in N$,

(9.b) $\partial C_P^{(i)} / \partial X_1^{(i)} = \partial C_1^{(i)} / \partial X_1^{(i)} - P_1 = 0 \;\Rightarrow \partial C_1^{(i)} / \partial X_1^{(i)} = \partial C_1^{(j)} / \partial X_1^{(j)} = P_1 \;\forall i,j \in N$,

(9.c) $\partial C_P^{(i)} / \partial I_0^{(i)} = 1 + \partial C_1^{(i)} / \partial I_0^{(i)} = 0 \quad \Rightarrow \partial C_1^{(i)} / \partial I_0^{(i)} = -1 \;\forall i \in N$.

[15] For an analysis of imperfect permit markets see, e.g., Montero, 2002. This paper is confined to the case of firms having complete information on present and future prices (Montero, 2002, p. 26).
[16] However the allocation rule is not crucial for our subsequents results.

Thus the first order conditions imply (3.a)-(3.c) and the emission reduction is cost-effective. Further in equilibrium we have $P_t = MC_t^{\Sigma}(\overline{X}_t)$ because higher prices would lead to an excess supply and lower prices to an excess demand. The corresponding equilibrium abatement and investment levels coincide with the social least cost solution, i.e.,

$X_0^{(i),P} = X_0^{(i)**}, X_1^{(i),P} = X_1^{(i)**}, I_0^{(i),P} = I_0^{(i)**} \ (i = 1,...,n)$.

d) Comparison

In the full information scenario all standard oriented instruments lead to the cost minimizing abatement and investment levels.

III.2 The "textbook information scenario":

Aggregate abatement cost functions are common knowledge

In this scenario equations (4) and (5), i.e., aggregate marginal abatement cost of both periods, are common knowledge.[17] Equations (6) and (7), i.e., individual marginal abatement cost of both periods, are private knowledge of the firms.

a) Command and control

In III.1 we have seen that the regulator needs the knowledge about private marginal abatement costs to determine cost-effective abatement norms. Thus, when we weaken our assumptions on available information going from the first scenario to the second, the regulator loses the very information that is needed to design cost-effective command and control policy. The information about aggregate marginal abatement costs remaining in scenario 2, is useless to the regulator.

Thus he might choose any partition of abatement levels which satisfies $\overline{X}_t^{(i)} = \delta_t^{(i)}\overline{X}_t$ with $\sum_i \delta_t^{(i)} = 1, \delta_t^{(i)} \geq 0$. Hence firm *i* minimizes the cost function:

(10) $C_Q^{(i)}(I_0^{(i)}) = C_0^{(i)}(\delta_0^{(i)}\overline{X}_0) + I_0^{(i)} + C_1^{(i)}(\delta_1^{(i)}\overline{X}_1, I_0^{(i)})$.

[17] If effluent charges are applied it is the regulator using common knowledge about aggregate abatement cost functions determining the tax rates. If transferable discharge permits are applied, instead, the firms are the actors using common knowledge on aggregate abatement cost functions to determine their expectations about permit prices.

Of course the chosen partition of the regulator will deviate from the cost-effective solution in general. Since without regulation the equilibrium emission level of each firm equals $\frac{1}{n}E^{max}$ it is plausible to assume that the regulator chooses the uniform abatement quota $\overline{X}_t^{(i)} = \frac{1}{n}\overline{X}_t$, which leads to the cost-effective solution in case of symmetric firms.

If firms are asymmetric with respect to their marginal abatement cost a uniform abatement quota implies that firms with marginal abatement costs below (above) average abate too little (too much) compared to the cost-effective solution. Since $dI_0^{(i)} / dX_1^{(i)} = -\frac{\partial^2 C_1^{(i)} / \partial X_1^{(i)} \partial I_0^{(i)}}{\partial^2 C_1^{(i)} / \partial I_0^{(i)2}} > 0$ (which follows from (3.c)) the same holds for the individual investment levels.

It is important to note that the corresponding aggregate investment levels may exceed or fall below the cost-effective aggregate investment level if abatement norms are set on non cost minimizing levels.

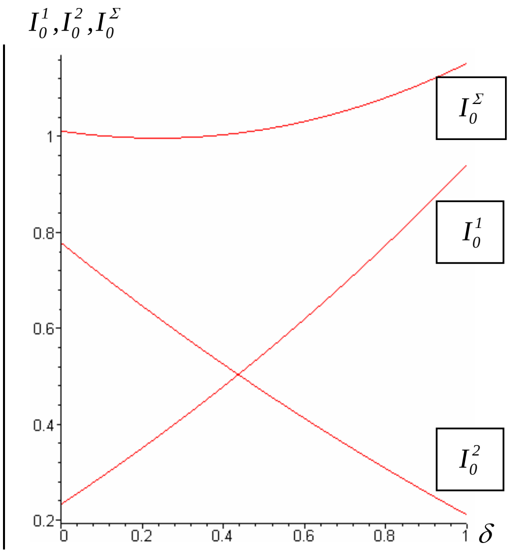
To illustrate this result we use the following example:

Example 1:

Consider two firms with abatement cost functions $C_1^{(1)}(X_1^{(1)}, I_0^{(1)}) = \frac{e^{\alpha X_1^{(1)}}}{(I_0^{(1)}+1)^{\beta}}$ and $C_1^{(2)}(X_1^{(2)}, I_0^{(2)}) = \frac{e^{a X_1^{(2)}}}{(I_0^{(2)}+1)^{b}}$ and assume that the regulator chooses abatement norms $\overline{X}_1^{(1)} = \delta \overline{X}_1$ and $\overline{X}_1^{(2)} = (1-\delta)\overline{X}_1$ with $0 < \delta < 1$.

In Figure 1, $I_0^{(1)}(\delta), I_0^{(2)}(\delta)$ and $I_0^{\Sigma}(\delta)$ are shown for $\overline{X}_1 = 5, \alpha = a = 1, \beta = 10$ and $b = 12$. For these parameter values the optimal division is $\delta^{**} = 0.219$ with corresponding investment levels $I_0^{(1)}(\delta^{**}) = 0.362, I_0^{(2)}(\delta^{**}) = 0.635$ and $I_0^{\Sigma}(\delta^{**}) = 0.9967$.

Aggregate investments are minimized at $\delta_{I_{min}} = 0.238$ with $I_0^{\Sigma}(\delta_{I_{min}}) = 0.9966$ and are larger than $I_0^{\Sigma}(\delta^{**})$ for $\delta < \delta^{**} = 0.219$ or $\delta > 0.256$. For the uniform abatement quota, $\delta = 1/2$, we get $I_0^{\Sigma}(½) = 1.015$. These results are illustrated in figures 1 and 2.



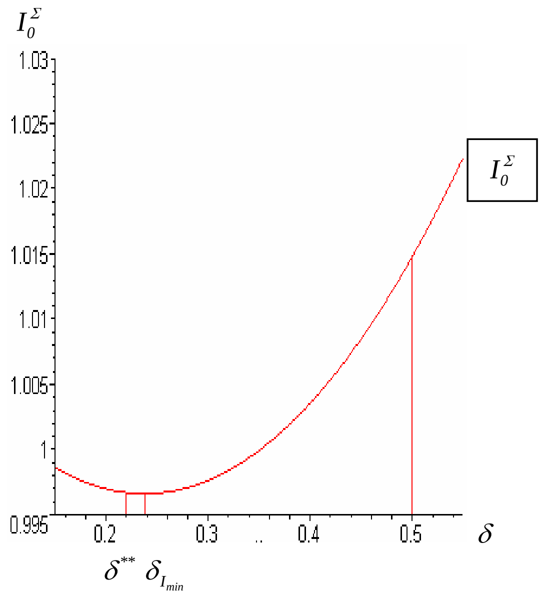


Figure 1: Individual and aggregate investment levels

Figure 2: Aggregate investment levels (section drawn to a larger scale)

b) Tax

Since the regulator only needs equations (4) and (5) to set the cost-effective tax rate, (see III.1.b.) the weakening of information assumptions from scenario 1 to scenario 2 does not influence equilibrium and abatement levels in the tax regime.

Thus, the fundamental result of the cost-effectiveness of the standards and charges approach carries over from the traditional static model to the dynamic case of information scenario 2.

c) Permits

As in the tax regime equilibrium abatement levels are the same as in the full information scenario. The reason is that the firms only need information about aggregate marginal abatement costs to be able to calculate the future permit price and thus to make the individual cost minimizing investment decisions in period 0.

Thus, permits are dynamically superior to command and control within the framework of information scenario 2, just as they are in the static models traditionally analysed in the literature.

d) Comparison

The worsening of information conditions from our first to our second scenario turned out to be fatal in case of command-and-control regulation. Opposed to that it has no consequences for effluent charges or transferable discharge permits. Using these kinds of policies, no common knowledge about individual cost functions is necessary to generate cost-effective equilibria. In fact for each of these policies, information requirements for the cost-effective solution are even lower than their "common knowledge"-specification in scenario 2. Under the tax regime only the regulator but not the firms need information about aggregate marginal abatement costs. Under the permit regime it is just the other way around.

III.3 The weak information scenario:

The present aggregate abatement cost function is common knowledge

In this scenario equation (4), i.e., the current aggregate marginal abatement cost function, is common knowledge. Equations (6) and (7), the individual marginal abatement cost functions are private knowledge to the firms. These assumptions are the same as in the previous scenario. The difference between the second and the third scenario relates to information available about future aggregate marginal abatement cost. To calculate these, the involved parties must be informed about each firm's individual R&D-productivity. In the weak information scenario we assume that none of the involved agents has this information. Therefore, the future aggregate marginal abatement cost function (5) is unknown.

a) Command and control

As explained above, the regulator applying command and control loses all the information needed to design this kind of a policy cost-effectively, when information conditions deteriorate going from the first to the second scenario. Thus, the further withdrawal of information from the second to the third scenario is of no concern to the regulator assigning individual reduction quotas within the command and control approach.

b) Tax

If the regulator has no information about the productivity of innovation (and thereby no information on future aggregate marginal abatement cost) the question arises of how the tax rate in the future period is to be calculated. An obvious possibility is that the rate is based on aggregate marginal abatement cost of period 0, i.e., $T_1^0 = MC_0^{\Sigma}(\bar{X}_1)$.[18] Hence from $MC_1^{\Sigma}(\bar{X}_1) < MC_0^{\Sigma}(\bar{X}_1) = T_1^0 = MC_1^{\Sigma}(\sum_i X_1^{(i)}(T_1^0))$ it follows that aggregate (and individual) abatement in period 1 exceeds the abatement target (as is well-known to the literature). Additionally from $dX_1^{(i)} / dI_0^{(i)} > 0$ (see section III.2.a) it follows that the individual and aggregate innovation levels exceed the cost minimizing ones.

c) Permits

If firms have no information about future aggregate marginal abatement cost the permit market equilibrium in period 1 depends on firms' expectations about the future permit price. In the following we consider two kinds of price expectations.

In a *first case* we assume that firms form their expectations concerning the permit price in period 1 based on the aggregate marginal abatement cost function of period 0, i.e.,

(11) $P_1^0 = MC_0^{\Sigma}(E^{max} - \bar{E}_1) = MC_0^{\Sigma}(\bar{X}_1)$.[19]

We analyse this case because it provides a frame under which the conditions of the transferable discharge permit system are most similar (and thereby: most comparable) to the situation under the effluent charge policy as described above. In the transferable permit case the firms' expectations that aggregate marginal abatement cost (and thereby thepermit price) will not change from period 1 to period 2 are analogous to the assumption used above for the effluent charge policy: the regulator assumes that aggregate marginal abatement cost do not change over time and fixes the tax rates accordingly. Therefore, the expected permit price P_1^0 in this price expectations case is identical to the tax rate T_1^0 explained above.

Thus, investment levels in period 0 are the same as under the tax regime. However abatement levels in period 1 are lower than under the tax regime since under the tax regime abatement exceeds the target $\bar{X}_1$ which is not possible under the permit regime by definition.

Thus under the permit regime the overestimation of the future permit price leads to too high investment levels in period 0 given the exogenous aggregate abatement target of period 1.

[18] This is an assumption widely used in the literature. (See, e.g., Milliman and Prince, 1989, Jung et al., 1996, Montero, 2002, as well as Fischer et al., 2003, who assume that policies remain fixed at their pre-innovation levels for the most part of their analysis (p.525).)

[19] It should be noted that this assumption is consistent with the assumption that firms are price takers in the permit market (implying that a single firm cannot affect the aggregate marginal abatement cost function of period 1 by investment in R&D).

In the case briefly examined above, each firm decides to invest (and thereby changes its individual marginal abatement cost function) but expects aggregate marginal abatement cost to be unchanged over time. However, this setting is not very plausible. It requires the firms to be “presumptuous” in that each firm believes it is the only one to understand the dynamic incentives of the TDP-policy and thereby being the only one deciding to invest.

For higher plausibility, we investigate a *second case* regarding price expectations. Here, we assume that firms anticipate that aggregate investment in R&D decreases abatement cost in period 1 and hence lowers the future permit price.

More specifically we assume that firm *i* forms its price expectations according to the following mechanism:

- First, we consider the optimal abatement level of firm *i* in period 1. Since firm *i* does not know future aggregate marginal abatement cost it is not possible to determine the optimal abatement level from

(12) $$MC_1^{(i)}(\bar{X}_1^{(i)}) = MC_1^{\Sigma}(\bar{X}_1).$$

Thus firm *i* must form an expectation concerning its optimal abatement level in period 1. It assumes that firms are symmetric in R&D-productivity insofar that the cost-effective division of a given abatement level, and in particular of the abatement level $\bar{X}_1$, remains unchanged from period 0 to period 1. I.e., firm *i* assumes that the solution $\bar{X}_1^{(i)}$ from (12) equals the solution $\bar{X}_1^{(i),0}$ from (13):

(13) $$MC_0^{(i)}(\bar{X}_1^{(i),0}) = MC_0^{\Sigma}(\bar{X}_1).$$

Thus firm *i* plans to abate $\bar{X}_1^{(i),0}$ in period 1.

- Second, the firms act on the assumption that the relation of their individual marginal abatement cost (with/without optimal investments in technical progress) equals the relation of aggregate marginal abatement cost. Thus expected aggregate marginal abatement costs are determined by

(14) $$\frac{E^{(i)}\left[MC_1^{\Sigma}(\bar{X}_1)\right]}{MC_0^{\Sigma}(\bar{X}_1)} = \frac{MC_1^{(i)}(\bar{X}_1^{(i),0})}{MC_0^{(i)}(\bar{X}_1^{(i),0})}$$

and the expected price is given as

$$E^{(i)}\left[P\right]=E^{(i)}\left[MC_1^{\Sigma}(\bar{X}_1)\right]=\frac{MC_0^{\Sigma}(\bar{X}_1)}{MC_0^{(i)}(\bar{X}_1^{(i),0})}MC_1^{(i)}(\bar{X}_1^{(i),0})=MC_1^{(i)}(\bar{X}_1^{(i),0}).\tag{15}$$ [20]

If firms are homogenous the price expectations of the firms coincide and prove to be true in the future. Thus the firms choose the optimal investment levels in period 0 and the market equilibrium is cost-effective.

The cost-effective solution may also result if firms are heterogeneous. This is so in the special case of $MC_1^{(i)}(\bar{X}_1^{(i),0})=MC_1^{(j)}(\bar{X}_1^{(j),0})\ \forall i\neq j$.

However, in most cases of heterogenous firms the market equilibrium is not cost-effective and aggregate investment may deviate from the cost-effective outcome in both directions.

d) Permit trading in a future market

Now we assume that permits for period 1 may already be traded at the beginning of period 0.[21] As in the previous scenarios permits are grandfathered to the firms and each firm receives $\frac{1}{n}\bar{E}_t$. This situation is equivalent to the permit market in the full information scenario 1.

Again firm *i* minimizes cost function (9) which results in the cost-effective solution with equilibrium permit prices $P_t=MC_t^{\Sigma}(\bar{X}_t)$.

Thus, the result of static policy analysis, maintaining that permits are cost-effective (even in the case of heterogeneous firms) carries over to the dynamic setting of the weak information scenario if (and only if) the permit regime includes future markets.

e) Comparison

In the following we want to compare the social cost[22] under the different permit regimes (including the two alternative assumptions regarding price expectations), the tax regime and command-and-control in the weak information scenario.

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[20] Note that the price expectation of firm *i* only depends of $\bar{X}_1^{(i)}$ and its own marginal abatement cost although also in this specification of the permit market firm *i* is assumed to be a price taker. Further note that the ex ante expected abatement level $\bar{X}_1^{(i),0}$ in fact are chosen in period 1 if (and only if) the price expectations of the firm turn out to be correct ex post.

[21] Note that as in the previous scenario permits are valid either in period 0 or in period 1.

[22] In the terminological tradition of the literature, "social cost" is often used to signify the sum of private cost and external cost. It should be clear from the context of this paper that the term is used in a different meaning above: External cost is not acknowledged in a standard oriented setting by definition. Here, social cost comprises aggregate abatement cost in the two periods plus aggregate investment cost.

It turned out that only the permit market with future trading leads to cost-effective results independent of symmetry or asymmetry between firms. Without future trading the permit market with anticipation of technical progress induced price declines at least turned out to be cost-effective in case of symmetric firms. Opposed to that the permit market without this anticipation does not achieve cost-effective results in any case due to the overinvestment in technical progress. Of course the superiority of the permit market with price decline anticipation over the permit market without price decline anticipation can be extended from the case of identical firms to cases in which the asymmetry between the firms is moderate.[23]

Comparing the permit regime without price decline anticipation with the tax regime it turns out that social cost are lower under the permit regime than under the tax regime. The reason is that individual (and aggregate) investments in technological progress coincide under the two instruments whereas abatement costs are higher under the tax regime because of too high abatement levels.[24] This result is independent from whether firms are symmetric.

The comparison between the quota regime ("command and control") and the other instruments is ambiguous.

In case of symmetric firms the uniform abatement quota leads to cost-effective results, just as permits with future markets as well as permits with price decline anticipation do. Opposed to that, taxes and permits without price decline anticipation are not cost-effective. Under the tax regime cost-ineffectiveness results from an overfulfillment of the abatement target and under the permit regime without price decline anticipation lacking cost-effectiveness results from an overinvestment due to too high price expectations.[25]

If we introduce asymmetries between firms, non-transferable quotas and transferable discharge permits with price decline expectations lose the cost-effectiveness property they possess for the case of identical firms. Of course, taxes and permits without price decline expectations are not cost-effective for heterogeneous firms as they have been shown to be for identical firms.

[23] A general proof of this superiority however is not possible. The reason is that in the case of asymmetric firms some of them overestimate the price decline and thus make too low investments in R&D. It cannot be ruled out that this negative overestimation effect may be stronger than the positive price decline anticipation effect.

[24] An overfulfillment of the abatement target might be desirable from the social point of view if the abatement target is set too low according to a welfare function which comprises environmental damages. However, the positive effects on environmental damages is not appreciated in a standard oriented approach by definition.

[25] Here and in the following we refer to the case where firms price expectations depend on aggregate marginal abatement cost in period 0.

So we have three standard oriented environmental policy instruments which are not cost-effective in the case of heterogeneous firms, i.e. command and control, taxes and permits without future markets. The latter instrument has been analyzed in this paper in two forms, one with price decline expectations of the participating firms and one without.
It would be interesting to rank these instruments according to their degree of cost-ineffectiveness. However, this turns out to be impossible in general terms. Relative failure of the aforementioned instruments crucially depends upon the degree of firm heterogeneity:
If differences in marginal abatement costs are large enough, the failure of uniform abatement quotas under command-and-control regulation overcompensates the failure from overabatement resp. overinvestment under the tax resp. permit regime.
The case where overcompensation occurs is illustrated in the following example.

Example 2:[26, 27]
Consider Example 1 with $\bar{X}_0 = \bar{X}_1 = 5, \alpha = 2, a = 1, \beta = 0{,}1$ and $b = 0{,}2$.

The cost-effective abatement levels in period 0, which do not change under the different policy regimes, are $X_0^{(1)**} = 1.44, X_0^{(2)**} = 3.56$.

The cost minimizing levels of abatement in period 1 and investment are given by $X_1^{(1)**} = 1.33, X_1^{(2)**} = 3.67, I_0^{(1)**} = 0.39, I_0^{(2)**} = 4.56$. The corresponding social cost are given by $SC^{**} = 99.61$.

Under uniform command-and-control regulation in period 1 $\bar{X}_1^{(1)} = \bar{X}_1^{(2)} = \bar{X}_1 / 2 = 2.5$ the firms choose investment levels $I_0^{(1),Q} = 10.61$ and $I_0^{(2),Q} = 1.10$. The social cost are $SC^Q = 191.33$.

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[26] Note that the restriction on two firms, which is a bit inconsistent with the assumption of price takers in the permit market, is not crucial for the subsequent results. It only eases their presentation.
[27] In the example and in Table 1, below, we use the following superscripts: cost-effective solution (**), non transferable abatement quotas (Q), emission taxes (T), transferable discharge permits (P), permits without future market and expected *constant* permit price (PC), permits without future market but with price *decline* anticipation due to investments in technical progress (PD), and permits with *future market* (PFM).

From $T_1^0 = \alpha e^{\alpha X^{(1)}} = ae^{\alpha X^{(2)}}$ and $X_1^{(1)} + X_1^{(2)} = \bar{X}_1$ it follows that the tax rate is to be set at $T_1^0 = 35.32$. Minimization of firm 1's cost function $I_0^{(1)} - T_1^0 X_1^{(1)} + \frac{e^{\alpha X_1^{(1)}}}{(I_0^{(1)}+1)^\beta}$ gives $X_1^{(1),T} = 1.46, I_0^{(1),T} = 0.77$. Firm 2 chooses $X_1^{(2),T} = 3.96, I_0^{(2),T} = 6.06$. The social cost are given by $SC^T = 112.78$.

Under the permit regime with *expected constant permit price* firms choose $I_0^{(1),PC} = 0.77$ and $I_0^{(2),PC} = 6.06$. Since firms are price taker in period 1 firm 1 minimizes $I_0^{(1)} + \frac{e^{\alpha X_1^{(1)}}}{(I_0^{(1),PC}+1)^\beta} - P_1 X_1^{(1)}$ from which follows $X_1^{(1)}(P_1)$. The equilibrium price $P_1 = 26.70$ is determined by $X_1^{(1)}(P_1) + X_1^{(2)}(P_1) = \bar{X}_1$. Corresponding abatement levels are $X_1^{(1),PC} = 1.32, X_1^{(2),PC} = 3.68$. Social cost are given by $SC^{PC} = 99.86$.

Under the permit regime with *expected lower permit price* in period 1 firm 1 expects the permit price $E^{(1)}(P) = 33.54$ and chooses $I_0^{(1),PD} = 0.68$. Firm 2 expects a permit price $E^{(2)}(P) = 25.50$ and chooses $I_0^{(2),PD} = 4.10$. The equilibrium price is $P_1 = 27.94$ and the corresponding abatement levels are $X_1^{(1),PD} = 1.34, X_1^{(2),PD} = 3.66$. Social cost are given by $SC^{PD} = 99.66$.

Summarizing the results of our example, we have: $SC^{**} < SC^{PD} < SC^{PC} < SC^T < SC^Q$.

However, using different functional forms and/or parameter values, a different welfare ordering of the instruments might result.

IV. Summary and conclusions

In this paper we evaluated the standard-oriented environmental policy instruments, command and control (i.e. non transferable quotas), emission tax, and transferable discharge permits in a dynamic framework allowing for induced technical change in abatement technology. We did so using three alternative information scenarios. The results are summarized in Table 1.

	full information scenario	traditional information scenario	weak information scenario
symmetric firms	$SC^{**} = SC^{Q} = SC^{T} = SC^{P}$	$SC^{**} = SC^{Q} = SC^{T} = SC^{P}$	$SC^{**} = SC^{PFM} = SC^{PD} = SC^{Q}$ $SC^{**} < SC^{PC} < SC^{T}$
asymmetric firms	$SC^{**} = SC^{Q} = SC^{T} = SC^{P}$	$SC^{**} = SC^{T} = SC^{P} < SC^{Q}$	$SC^{**} = SC^{PFM} < SC^{Q}$, $SC^{**} \leq SC^{PD}$ $SC^{**} < SC^{PC} < SC^{T}$

Table 1: Social cost relations in the alternative information scenarios

In the *full information scenario* all policy instruments achieve the cost-effective abatement and the corresponding investment target independently of whether firms are symmetric or asymmetric.

In the *traditional information scenario*, where the involved parties know only aggregate marginal abatement cost, the environmental goal is always achieved cost-effectively under taxes and permits. Opposed to that, a uniform abatement standard leads to cost-ineffectiveness in case of asymmetric firms. The design of a cost-effectively differentiated command and control policy is not feasible due to the particular incompleteness of information by which this scenario is defined.

This result is the intertemporal analogon to classical (static) analysis of standard oriented environmental policy originating with the seminal 1971-article by Baumol and Oates. There, the "market based instruments" are superior to command and control in terms of cost-effectiveness.

Things change in the *weak information scenario*, where the involved parties have no information about R&D productivity and, hence, future abatement cost of the industry. In this case only a permit regime with a future market ensures cost-effectiveness when firms are heterogeneous.[28]

Obviously, the pessimistic assumptions about the availability of information on future abatement technology applied in this scenario are suggestive for many real world

[28] Beyond this clear cut result table 1 shows some ambiguity in the ranking of alternative policy instruments for the weak information scenario with asymmetric firms. This is due to the quite general form of the relevant functions that have been used in the main part of this paper. It is worth noting that the use of specific (but still conventional) functions leads to a clear cut policy ranking, as given at the end of paragraph III, above.

applications. Therefore, even within the limits of the highly stylized model presented above the findings under the weak information scenario have some policy implications. These relate to the choice of environmental policy instruments in general, and to the design of transferable discharge permit systems in particular. E.g., consider the carbon emission trading system, as recently introduced by the European Union. The purpose of this policy has been to enable the member states to carry the emission reduction loads they accepted within the EU-burden sharing agreement under the Kyoto Protocol "in a cost-effective and economically efficient manner".[29] The system is doomed to miss this goal since there is no provision for trading in future markets. To the contrary, it is not even clear how many permits will be allocated in future periods. Moreover, firms must make investment decisions with long time horizons (particularly in the energy sector) in a situation where it is unclear whether the system will be extended beyond the year 2012, and if so what the future design of the system will be. Under these circumstances there is no reason to assume that firms will be able to anticipate future permit prices and thereby make intertemporally cost-effective decisions on abatement and investment.[30] The results presented above produce *prima facie* evidence that cost-effectiveness of the system can be improved by establishing markets in which permits for future periods may be traded.

It is an obvious task for future research to investigate whether the results presented in this paper carry over to a framework which is more general than the one used above. E.g., the analysis might be extended allowing for non-competitive firms, imperfect research and/or permit markets, uncertainty with respect to the success of research, and knowledge spillovers between firms. In addition, technical progress might be modelled as a process of learning by doing, which could affect the results of our comparative analysis of environmental policy instruments.

The model given in this paper may serve as a starting point for these and other extensions.

[29] EU-Directive 2003/87/EC, Article 1.

[30] There are some (rather restrictively designed) possibilities for banking and borrowing of permits. However, these provisions are not allocatively equivalent to future markets for permits. An economic assessment of EU-emissions trading is given in Endres and Ohl (2005).

References

Baumol, W.J. and W.E. Oates (1971), The Use of Standards and Prices for Protection of the Environment, Swedish Journal of Economics 73, 42-54.

Denicolo, V. (1999), Pollution-Reducing Innovations under Taxes or Permits, Oxford Economic Papers 51, 184-199.

Endres, A. and C. Ohl (2005), Kyoto Europe? – An Economic Evaluation of the European Emission Trading Directive, European Journal of Law and Economics 19, 17-39.

Fischer, C, I.W.H. Parry, and W.A. Pizer (2003), Instrument Choice for Environmental Protection When Technological Innovation is Endogenous, Journal of Environmental Economics and Management 45, 523–545.

Hanley, N., J.F. Shogren and B. White (2001), Introduction to Environmental Economics, Oxford.

Hoel, M. and L. Karp (2002), Taxes versus Quotas for a Stock Pollutant, Resource and Energy Economics 24, 367-384.

Jaffe, A.B., R.G. Newell, and R.N. Stavins (2002), Environmental Policy and Technological Change, Environmental and Resource Economics 22, 41-69.

Jaffe, A.B., R.G. Newell, and R.N. Stavins (2005), A Tale of Two Market Failures: Technology and Environmental Policy, Ecological Economics 54, 164-174.

Kennedy, P.W. and B. Laplante (1999), Environmental Policy and Time Consistency: Emission Taxes and Emissions Trading, in E. Petrakis et al. (ed.), Environmental Regulation and Market Power, Cheltenham.

Laffont, J.-J. and J. Tirole (1996a), Pollution Permits and Compliance Strategies, Journal of Public Economics 62, 85-125.

Laffont, J.-J. and J. Tirole (1996b), Pollution Permits and Environmental Innovation, Journal of Public Economics 62, 127-140.

Milliman, S.R. and R. Prince (1989), Firm incentives to promote technological change in pollution control, Journal of Environmental Economics and Management 17, 247-65.

Montero, J-P. (2002), Permits, Standards, and Technology Innovation, Journal of Environmental Economics and Management 44, 23-44.

Perman, R., Y. Ma, J. McGilvray and M. Common (2003), Natural Resource and Environmental Economics, 3rd edition, Harlow et al.

Parry, I.W.H. (1995), Optimal Pollution Taxes and Endogenous Technological Progress, Resource and Energy Economics 17, 69-85.

Parry, I.W.H. (1998), Pollution regulation and the efficiency gains from technological innovation, Journal of Regulatory Economics 14, 229-54.

Requate, T. (2005a), Dynamic Incentives by Environmental Policy Instruments – a Survey, Ecological Economics 54, 175-195.

Requate, T. (2005b), Commitment and Timing of Environmental Policy, Adoption of New Technology, and Repercussions on A&D, Environmental and Resource Economics 31, 175-199.

Requate, T. and W. Unold (2001), On the Incentives of Environmental Policy Instruments to Adopt Advanced Abatement Technology if Firms are Asymmetric, Journal of Institutional and Theoretical Economics 157, 536-554.

Requate, T. and W. Unold (2003), Environmental Policy Incentives to Adopt Advanced Abatement Technology: Will the True Ranking Please Stand up?, European Economic Review 47, 125-146.

Russell, C.S. (2001), Applying Economics to the Environment, New York, Oxford.