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Weitzman revisited: Emission standards vs. taxes with uncertain control costs and market power of polluting firms

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Weitzman revisited: Emission standards vs. taxes with uncertain control costs and market power of polluting firms[*]

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Abstract. It is well known that uncertainty concerning firms' costs as well as market power of the latter have to be taken into account in order to design and choose environmental policy instruments in an optimal way. As a matter of fact, in most actual regulation settings the policy maker has to face both of these complications simultaneously. However, hitherto environmental economic theory has restricted to either of them when submitting conventional policy instruments to a comparative analysis. The article at hand takes a first step in closing this gap. It investigates the welfare effects of emission standards and taxes against the background of uncertain emission control costs and various degrees of the polluting firms' market power.

Keywords: *Cournot oligopoly, external diseconomies of pollution, cost uncertainty, emission standard, emission tax*

JEL Classification: *D62, D89, L13, Q58*

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1. Introduction

The starting point of the present paper is the environmental problem in terms of external diseconomies. More precisely, it considers the standard case of several firms emitting a harmful pollutant in the course of their production and thus causing external damage costs. Trying to internalise the latter, the policy maker – below for simplification referred to as environmental policy agency (short EPA) – will frequently face the following two complications: Firstly, it is not equipped with all the information required to generate the welfare maximising allocation. Secondly, the polluting firms exhibit market power at least to some extent. Environmental economists realised at an early stage that these hitches crucially influence the optimal[1] design and choice of emission control instruments. One stream of literature, initiated by the seminal papers of Weitzman (1974) along with Adar and Griffin (1976), dealt with the question how uncertainty concerning damage and emission control costs affects the relative performance of emission standards, tradable emission licences and emission taxes. They showed that an additive shock to the marginal damage cost function lets the basically given equivalence of these instruments unaffected,[2] while a congruent shock to the marginal control cost function makes their comparative advantage dependant on the relative slopes of the two aforesaid marginal cost functions.[3] Another branch of literature analyses how market power affects internalisation strategies. Buchanan (1969) started the discussion by pointing out that Pigouvian taxation might lead to suboptimal allocations when the polluting firms possess market power, which means an additional distortion to the external diseconomies of pollution. A further milestone was set by Barnett (1980), who derived a rigorous (second best) Pigouvian tax rule tailored to the actuality of a monopolistic polluter, followed by more sophisticated rules for symmetric (Ebert 1992) as well as asymmetric Cournot oligopoly (Simpson 1995). However, there were very few attempts to compare emission control instruments against the background of market power, like e.g. Requate (1993a and b) undertook.

All in all, the review of the respective literature reveals a considerable shortfall: It has very well been detected that both information problems on the part of the EPA and market power of the polluting firms play an essential role for the optimal design and choice of environmental policy instruments (Requate, 2005, pp. 85ff). However, it has been constantly ignored that they emerge in virtually every real problem of environmental regulation simultaneously. The article at hand takes a first step in closing this gap and shows that the interaction between information problems and market power has indeed an impact on optimal environmental policy. It compares two of the most common emission control instruments – standards and taxes[4] – w.r.t. their welfare properties using a static partial framework. Thereby it assumes that the polluting firms

[1] In the remainder, "optimal" is used synonymously to "accomplishing the EPA's goal of welfare maximisation", if applicable subject to market power of the polluting firms and/or incomplete information.

[2] Amongst others, the equivalence between standards, licences and taxes particularly presumes identical cost functions of the regulated firms; see e.g. Tisato (1994).

[3] More precisely, the according policy rule first derived by Weitzman (1974) – in the following called the original Weitzman-rule – tells that the ranking of the mentioned instruments is determined by the relation of the marginal damage and the marginal minimised aggregate control cost function's slope; see section 4.

[4] Naturally it seems obvious to incorporate tradable licences which certainly belong to the most important conventional instruments. Yet a realistic modelling of the former would have to account for strategic effects on the licence market – due to firms' market power – and thus go beyond the scope of the analysis.

have various degrees of market power on the output market and their control costs are uncertain from the EPA's view.
Section 2 sets up the model, whereupon section 3 displays the basic characteristics of the policy intervention game. In Section 4, the comparative analysis of emission standards and taxes starts out for the reference case of perfect competition and generalises the policy rule first derived by Weitzman (1974) by distinguishing two options of emission abatement. Section 5 continues the comparison of instruments for the market structure of symmetric Cournot oligopoly and provides the adequate modification of the original Weitzman-rule, while section 6 focuses on the relation between the degree of market power and the optimal instrument choice. Finally section 7 summarises results and gives a brief outlook on possible further research.
The paper shows, that the EPA might choose the suboptimal instrument when it sticks to the original Weitzman-rule despite the incidence of market power, whereas an increase of the latter leads to an augmentation of this risk. Furthermore, a modified policy rule is provided which guarantees the optimal instrument choice in the absence of polypolistic markets. Withal it is demonstrated, that monopolistic markets can be subsumed as a special case of the symmetric Cournot oligopoly in this regard.

2. The model[5]

Basic framework

Consider $i = 1,\dots,n$ symmetric firms each producing x_i units of a homogenous good at costs amounting to $cp(x_i) = (1/2)x_i^2$, whereas n is exogenously fixed. The price of the good is determined by the linear inverse market demand function $p(X) = a - bX$, given the aggregate output $X = \sum_i x_i$. In the course of production occur emissions of a harmful pollutant proportionally to the output level. Assume that the pollutant only emerges in the industry under consideration.
Each firm can reduce emissions either by decreasing output or by adopting an end-of-pipe technology, i.e. implementing a filter system. Thus the individual emissions actually sent to the environment are $em_i(x_i, v_i^e) = \varepsilon x_i - v_i^e$, with the emission coefficient $\varepsilon > 0$ and the firm specific end-of-pipe abatement effort v_i^e. The latter causes costs on the firm level according to the function $cc^e(v_i^e, u) = (\gamma + u)v_i^e + (1/2)v_i^{e2}$. The monetary value of the damage emanating form the firms' emissions is captured by the damage cost function $DC(EM) = \alpha EM + (1/2)\beta EM^2$, $EM = \sum_i em_i(x_i, v_i^e)$ denoting the aggregate amount of emissions.
After all, let both the inputs for production and end-of-pipe abatement be produced at an exogenously given price on a perfectly competitive market. Thus each firm's costs of production and end of-pipe abatement $cp(x_i)$ and $cc^e(v_i^e)$ coincide with the associated costs incurred by the society.

[5] The basic framework complies with the standard one applied for the comparative analysis of environmental policy instruments; see e.g. Baumol and Oates (1988). The modelling of the uncertainty follows the seminal papers of Weitzman (1974) respectively Adar and Griffin (1976).

Structure of information

All the functions and specifications of the choice variables listed above are common knowledge for the parties involved, with one exception: While the firms are supposed to know their true end-of-pipe control cost function, the EPA is uncertain about the latter in the following sense: It is fully informed regarding the actual value of γ, against what in its eyes u is a random variable.[6] All it knows about u is its probability distribution, which needs not to be specified for the further analysis. Suppose the expectation of u to be $E[u] = 0$ and thus $Var[u] = E[u^2]$. The uncertainty's impact on the end-of-pipe control cost function and the according marginal cost function $mcc^e(v_i^e, u) = \partial cc^e(v_i^e)/\partial v_i^e =$ $(\gamma + u) + v_i^e$ is captured in the subsequent figure:

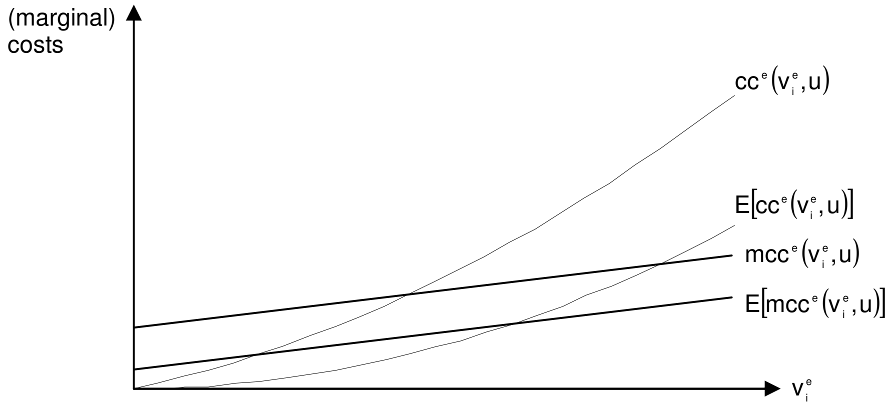

Figure 1: Uncertainty's impact on the (marginal) end-of-pipe control cost function for $u > 0$

As can be seen easily, the random variable enters $mcc^e(v_i^e, u)$ additively. This implies that the uncertainty solely affects its axis intercept, but not its slope. Figure 1 illustrates the progress of $(m)cc^e(v_i^e, u)$ expected by the policy maker on the one hand $(u = 0)$ and the true progress on the other hand, assuming for instance that u actually shows a positive sign.

Final remarks w.r.t. the modelling

The specification of the demand and cost functions along with the modelling of the uncertainty is owed to the endeavour of reproducing the basic characteristics of Weitzman's original setting (see Weitzman 1974), which shall be revisited subject to market power of the polluting firms. Amongst others, the original setting implies a linear marginal damage and aggregate control cost function,[7] at which the latter is exposed to an additive shock. This kind of uncertainty does not only facilitate the exposition, it has beyond a considerable economic content, since factor price variations would cause additive shocks when firms use a Leontief technology (Adar and Griffin, 1976, pp. 183-

[6] Note that not only u itself, but every function entered by u is a random variable. In order to highlight this insight, u will be explicitly listed as an argument of these functions.
[7] For the definition of the marginal aggregate control cost function see sections 4 and 5.

184). Principally, the uncertainty could have also been modelled by assuming that u enters the marginal costs of production in the same way. But it can easily be shown, that this does not translate into an additive shock affecting the aggregate marginal control cost function in case of perfect competition. Except for that, it is not the detailed cause of cost uncertainty that matters, but its corporate impact with market power on the relative performance of emission standards and taxes.

3. Game of policy intervention

Clearly, in the absence of regulation the firms do not have an incentive to render any positive abatement effort. So for perfect competition the standard result applies: From a welfare perspective the firms' output as well as emission level is too high, the abatement effort too low. The situation becomes less clear-cut if the firms exhibit market power, which is an additional distortion to the external diseconomies of pollution. The firms then shorten their output level in order to raise profits, and thus produce ceteris paribus too less in aggregate terms. Depending on which of the two countervailing distortions – external diseconomies vs. output shortage – dominates, the unregulated output and emission level fall short of the first best ones or the other way round. The opposite relation applies for the abatement effort.[8]

Consequently, the EPA, aiming at welfare maximisation, has a reason to intervene in the absence as well as in the presence of market power. An interesting thing to note is that in the latter case it will merely be able to enforce a second best solution via standards or taxes by balancing the two distortions in an optimal way (see Barnett, 1980). Yet, the achievement of the first best allocation requires at least two policy instruments (Baumol and Oates, 1988, p. 81).

The procedure of the policy intervention can be described as a sequential (Bayesian) game whose timing is depicted in figure 2:

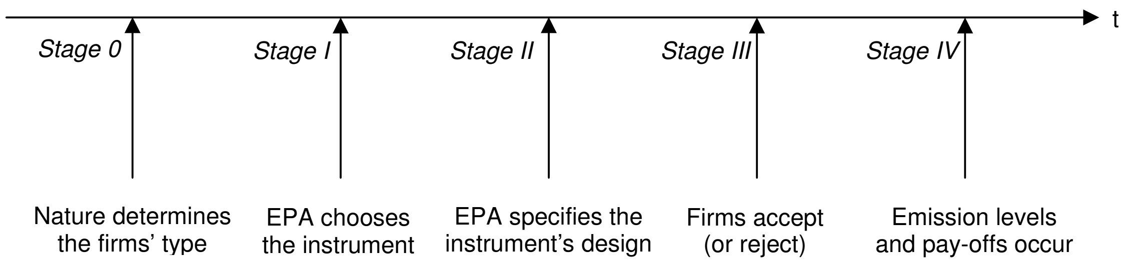

Figure 2: Timing of the policy intervention game

First of all, the nature determines the firms' type, i.e. their cost functions, at which applies the information structure described above. The EPA, since usually endowed with sovereign authority and thus in the position of the Stackelberg-leader, chooses whether to implement emission standards or taxes (stage I). Afterwards it specifies – given risk neutrality, which is presumed throughout the whole analysis – the design of the chosen

[8] By chance it might be that the two distortions just cancel each other out and therefore the unregulated and first best levels coincide. But since this constellation constitutes the great exception it will be neglected throughout the further analysis.

instrument in stage II in order to maximise the expectation of partial welfare. The latter is defined as[9]

[1] $$W(\mathbf{x}, \mathbf{v^e}, u) = U(\mathbf{x}) - \sum_i cp(x_i) - \sum_i cc^e(v_i^e, u) - DC(EM),$$

and hence supposed to be additively separable into the gross utility of consumption $U(\mathbf{x}) = \int p(X)dX$, the aggregate costs of production, end-of-pipe and damage. The counterpart of [1] is constituted by the total costs that come along with a specific amount of emissions

[2] $$C(\mathbf{x}, \mathbf{v^e}, u) = CC(\mathbf{x}, \mathbf{v^e}, u) + DC(EM),$$

whereas

[3] $$CC(\mathbf{x}, \mathbf{v^e}, u) = CC^x(\mathbf{x}) + \sum_i cc^e(v_i^e, u)$$

represents the aggregate control costs and

[4] $$CC^x(\mathbf{x}) = (U(\mathbf{x}^*) - ncp(x^*)) - (U(\mathbf{x}) - \sum_i cp(x_i)), \qquad \mathbf{x} \le \mathbf{x}^*, \exists x_i < x^*$$

the aggregate control costs w.r.t. the output reduction – the loss of the gross utility of consumption excluding the saving of production costs. Remember that owed to the firms' symmetry the individual output in the unregulated equilibrium x^* is identical for all of them. So the EPA's maximisation problem can alternatively be stated as to design the instruments such that the expectation of [2] is minimised, which will be helpful for the further proceeding.

Next, the EPA offers the pursuant occurrence of standards or taxes in terms of a contract to the firms, whose single decision is to comply with the environmental regulation or not – i.e. to accept or reject the contract (stage III). Subsequently, it is taken for granted that the EPA can monitor the firms' emission levels without any costs and enforce compliance by charging a sufficiently high fine in case that the firms reject.[10] So any kind of moral-hazard problem can be ruled out and the firms will always accept the contract, which enables to skip stage III henceforth. Finally (stage IV), the firms choose the output and end-of-pipe abatement level such that their overall compliance costs of regulation are minimised. The latter comprise the combined control costs

[5] $$cc(x_i, v_i^e, u) = cc^x(x_i) + cc^e(v_i^e, u),$$

and if applicable additionally the tax burden. There

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[9] Subsequently, bold print variables denote vectors of firm specific variables.

[10] To prevent rejection, the fine has to meet at least the firms' compliance costs referred to the respective instrument. As the quantification of the adequate fine yields tedious expressions but no further insight it is omitted.

[6] $cc^{x}(x_i) = \pi(x^*, v^{e*}) - \pi(x_i, v^{e*}),\qquad x_i < x^*,\ v^{e*} = 0$

indicates a firm's costs accruing from the emission reduction by decreasing the output level below the one of the unregulated equilibrium, which is nothing but the associated loss of profit π, v^{e*} representing the end-of-pipe abatement effort in the absence of regulation.[11] In opposite to the aggregate end-of-pipe control costs [4] cannot generally be calculated by simply summing up the output reduction costs that the firms are confronted with; see section 5.

Naturally, the game will be solved for the Bayes-Nash equilibrium (short BNE) using backwards induction. The present framework neither allows for problems of asymmetric information because the firms cannot exploit their advance in information, nor for Bayesian updating. The analysis restricts to that BNE which comprises positive output and end-of-pipe abatement levels of all the firms (inner solution), since obviously otherwise the end-of-pipe control cost uncertainty would be irrelevant for the optimal instrument choice. This kind of inner solution has two implications. Firstly, it requires the degree of uncertainty, i.e. the feasible value range of u, to be sufficiently small.[12] Secondly, in the presence of market power the associated output shortage will carry less weight than the distortion of pollution, since both a Bayesian perfect standard and tax inducing a positive end-of-pipe abatement effort necessarily lead to a decrease of the firms' output compared to the unregulated equilibrium as well.

4. Perfect competition

Stage IV

In case of emission standards, which are assumed to be specified in a uniform and absolute manner, the EPA prescribes a certain emission level q to be realised by each firm.[13] So the firms' responses to q concerning the output and end-of-pipe abatement level arise out of the minimisation problem[14]

[7] $$\min_{x_i, v_i^e} \ cc^{PC}(x_i, v_i^e, u) = cc^{xPC}(x_i) + cc^{e}(v_i^e, u) \quad \text{s.t.} \quad em_i(x_i, v_i^e) = q, \text{ where}$$

$$cc^{xPC}(x_i) = \pi^{PC}(x^{*PC}, v^{e*}) - \pi^{PC}(x_i, v^{e*})$$
$$= \left(p(\mathbf{x}^{*\mathbf{PC}})x^{*PC} - cp(x^{*PC})\right) - \left(p(\mathbf{x}^{*\mathbf{PC}})x_i - cp(x_i)\right), \quad x_i < x^{*PC}$$

with the first order condition[15]

[8] $$-\partial cc^{xPC}(x_i)/\partial x_i = \varepsilon\left(\partial cc^{e}(\varepsilon x_i - q, u)/\partial(\varepsilon x_i - q)\right).$$

[11] For the concrete specification which depends on the market structure see sections 4 and 5.

[12] Listing explicitly the parameter restrictions and u's feasible range of values that guarantee the inner solution is very cumbersome but yields no further insights.

[13] The modus of a uniform absolute emission standard is chosen for two reasons: Firstly, it is the standards' prototype which is taken for granted in the respective literature (see Helfand, 1991, p. 622) and thus allows for the comparability of results. Secondly, it keeps the model tractable. Note that the basically given inherent inefficiency of standards does not arise here due to the symmetry of firms.

[14] The superscript "PC" marks occurrences of functions and variables specific to perfect competition.

[15] For the second order condition see appendix A1.

Taking into account the demand side one obtains the individual equilibrium quantities $x^{PC}(q,u)$, $v^{ePC}(q,u)$ and $em^{PC}(q)=q$. In contrast, having to pay a tax rate t per emission unit, each firm faces the problem

$$[9] \qquad \min_{x_i, v_i^e} \quad cc^{PC}(x_i, v_i^e, u) + tem_i(x_i, v_i^e) = cc^{xPC}(x_i) + cc^e(v_i^e, u) + tem_i(x_i, v_i^e)$$

whose solution is defined by[16]

$$[10] \qquad -\partial cc^{xPC}(x_i)/\partial x_i = \varepsilon t; \quad \partial cc^e(v_i^e, u)/\partial v_i^e = t,$$

leading to the equilibrium output, end-of-pipe abatement and emission levels $x^{PC}(t)$, $v^{ePC}(t,u)$ and $em^{PC}(t,u)$. The firms solve their problem both in the standard and tax regime by equating their marginal costs of the two abatement options with regard to further restrictions (standards) or payments (taxes). Facing standards, the firms choose the output and end-of-pipe level simultaneously in a way that their emissions are exactly and with certainty q – consequently $x^{PC}(q,u)$ and $v^{ePC}(q,u)$ encounter uncertainty. Things are slightly different in case of taxation: Here the firms separately adjust their marginal costs of output reduction and end-of-pipe abatement to the tax rate t. Hence $v^{ePC}(t,u)$ and $em^{PC}(t,u)$ are random while $x^{PC}(t)$ is deterministic in the EPA's eyes. This difference will drive the circumstance that standards and taxes are not equal to one another in the presence of uncertain control costs, as will be seen below.

Stage II

Next the EPA can receive the optimally designed standard and tax by minimising the expectation of the total costs over q respectively t subject to the results of stage IV. Thus the optimal standard yields from solving

$$[11] \qquad \min_q \quad E\left[C\left(x^{PC}(q,u), v^{ePC}(q,u), u\right)\right],$$

which implies to equate the expectation of the aggregate marginal control costs and the marginal damage costs related to an infinitesimal decrease in q:[17]

$$[12] \qquad -E\left[\frac{\partial CC\left(x^{PC}(q^{PC},u), v^{ePC}(q^{PC},u), u\right)}{\partial q^{PC}}\right] = \frac{\partial DC(nq^{PC})}{\partial q^{PC}}.$$

Analogously for taxation, the EPA aims at

$$[13] \qquad \min_t \quad E\left[C\left(x^{PC}(t), v^{ePC}(t,u), u\right)\right],$$

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[16] For the second order condition see appendix A2.
[17] For the second order condition and the explicit solution see appendix A3.

by fixing t such that

$$[14] \qquad E\left[\frac{\partial CC\left(x^{PC}\left(t^{PC}\right), v^{ePC}\left(t^{PC},u\right),u\right)}{\partial t^{PC}}\right] = -\frac{\partial DC(\cdot)}{\partial t^{PC}}.$$ [18]

Finally, the EPA makes its instrument choice by comparing the expected total cost levels accompanied with the optimal tax and standard. The respective cost difference amounts to

$$[15] \qquad \Delta^{PC} = E\left[C\left(x^{PC}\left(t^{PC}\right), v^{ePC}\left(t^{PC},u\right),u\right) - \left(C\left(x^{PC}\left(q^{PC},u\right), v^{ePC}\left(q^{PC},u\right),u\right)\right)\right]$$

$$= \phi^2 Var[u]\left(\frac{\beta-\mu}{2\mu^2}\right),$$

$$\text{whereas } \phi = \frac{(1+bn)}{1+bn+\varepsilon^2} \text{ and } \mu = \frac{1+bn}{n+bn^2+n\varepsilon^2}.$$

Clearly, [15] suggests that standards should be preferred to taxes whenever Δ^{PC} shows a positive sign or equivalently $\beta > \mu$, and vice versa (BNE).

Interpretation

In order to comprehend this policy rule it is first of all needed to identify the single components of [15]. For this purpose the two instrument specific first order conditions for the minimisation of the total costs [12] and [14] are made comparable by defining the aggregate control and damage costs induced by standards and taxes as functions of the aggregate abatement effort V, which reads for the case of perfect competition $V^{PC} = EM^{*PC} - EM, \quad EM^{*PC} > EM$. This is accomplished through computing q and t which exactly generate V^{PC}, denoted by $q\left(V^{PC}\right)$ and $t\left(V^{PC},u\right)$.[19] Inserting those into [11] and [13] one obtains

$$[16] \qquad \begin{aligned} DC^q\left(V^{PC}\right) &= DC\left(x^{PC}\left(q\left(V^{PC}\right),u\right), v^{ePC}\left(q\left(V^{PC}\right),u\right)\right) \\ DC^t\left(V^{PC}\right) &= DC\left(x^{PC}\left(t\left(V^{PC},u\right)\right), v^{ePC}\left(t\left(V^{PC},u\right),u\right)\right) \\ CC^q\left(V^{PC},u\right) &= CC\left(x^{PC}\left(q\left(V^{PC}\right),u\right), v^{ePC}\left(q\left(V^{PC}\right),u\right),u\right) \\ CC^t\left(V^{PC},u\right) &= CC\left(x^{PC}\left(t\left(V^{PC},u\right)\right), v^{ePC}\left(t\left(V^{PC},u\right),u\right),u\right). \end{aligned}$$

Palpably, it holds that

$$[17] \qquad DC^q\left(V^{PC}\right) = DC^t\left(V^{PC}\right) = DC\left(V^{PC}\right)$$

just due to definition – a given overall abatement effort generates the same level of damage costs, no matter if induced by standards or taxes. Yet, the finding

[18] For the second order condition and the explicit solution see appendix A4.

[19] This can be simply done by solving $V^{PC}(q) = EM^{*PC} - nq$ for q, respectively $V^{PC}(t) = EM^{*PC} - EM^{PC}(t,u)$ for t.

$CC^q(V^{PC},u) = CC^t(V^{PC},u)$ might appear a little astonishing at first sight. But remembering that all the firms are symmetric and equate their marginal costs of the two abatement options at choice, no matter if confronted with standard or tax policy, it is easy to see that $x^{PC}(q(V^{PC}),u) = x^{PC}(t(V^{PC},u))$ as soon as $v^{ePC}(q(V^{PC}),u) = v^{ePC}(t(V^{PC},u),u)$ and thus the aggregate control costs coincide for the two instruments at hand.[20]

As a second important insight, it can be shown that taxes and standards do not only lead to identical aggregate control costs, but both also ensure that V^{PC} is accomplished efficiently from an aggregate point of view:

[18] $CC^q(V^{PC},u) = CC^t(V^{PC},u) = CC^{min}(V^{PC},u)$.

Thereby $CC^{min}(V^{PC},u)$ constitutes the minimised aggregate control cost function, which results from solving

[19] $\min_{\mathbf{x},\mathbf{v^e}} \quad CC(\mathbf{x},\mathbf{v^e},u) \quad \text{s.t.} \quad V^{PC} = EM^{*PC} - EM$

and inserting the results into [3]. Minimising the aggregate control costs is tied to the following two premises: Firstly, each firm has to render its abatement effort in a socially efficient way (intra-firm efficiency). Looking at the two abatement options, it can easily be seen that each firm's marginal costs of a specific abatement effort reflect precisely the respective costs accruing on the aggregate level: Under the assumption of a perfectly competitive market for the end-of-pipe inputs, the according price and thus the (marginal) end-of-pipe control costs exactly report the society's opportunity costs for producing the "end-of-pipe good". Basically the same applies for the output option: Reducing the output level for one marginal unit leads to costs on the firm level to the amount of $-\partial cc^{xPC}(x_i)/\partial x_i = p^{*PC} - \partial cp(x_i)/\partial x_i$, the equilibrium price reflecting the consumers' marginal willingness to pay less the associated saving of production costs, which corresponds to the costs of that measure incurred by society – the loss of consumers' and producers' surplus. Note that the costs of output reduction only exhibit this form when the firms are price takers. Since each firm equates its marginal costs of both abatement options due to its own ambition of cost minimisation, it automatically minimises the according costs on the social level: $-\partial CC^{xPC}(\cdot)/\partial \varepsilon x_i = \partial cc^{xPC}(\cdot)/\partial \varepsilon x_i = \partial cc^e(\cdot)/\partial v_i^e$ for $x_i = x^{PC}(q,u)$ and $v_i^e = v^{ePC}(q,u)$ as well as for $x_i = x^{PC}(t)$ and $v_i^e = v^{ePC}(t,u)$.

Secondly, socially efficient abatement requires that the total emission reduction V^{PC} is distributed in a cost minimising way over the firms, i.e. the aggregate marginal control costs associated with the individual abatement efforts of all the firms have to coincide (inter-firm efficiency). As shown above, this condition is clearly fulfilled since every firm realises the same output and end-of-pipe abatement level for both policy regimes and

[20] Of course, this result depends crucially on the symmetry assumption: Asymmetric firms adopting their marginal control costs to the uniform tax rate will inevitably realise different output and end-of-pipe abatement levels compared to the case of a uniform standard.

furthermore employs the identical technology: $-\partial CC^{xPC}(\cdot)/\partial \varepsilon x_1 = -\partial CC^{xPC}(\cdot)/\partial \varepsilon x_2 = \ldots = -\partial CC^{xPC}(\cdot)/\partial \varepsilon x_n$ and moreover $\partial cc^{e}(\cdot)/\partial v_1^{e} = \partial cc^{e}(\cdot)/\partial v_2^{e} = \ldots = \partial cc^{e}(\cdot)/\partial v_n^{e}$, again given the quantities occurring in the standard and tax regulated equilibrium.
Summarising, it can be stated that due to [17] and [18] the problem of determining the optimal standard and tax can be alternatively to [11] and [13] posed as

$$[20] \qquad \min_{V^{PC}} \quad E\left[CC^{min}\left(V^{PC},u\right)\right] + DC\left(V^{PC}\right),$$

implying to adjust the expectation of the minimised aggregate marginal control costs[21]

$$[21] \qquad MCC^{min}\left(V^{PC},u\right) = \frac{\partial CC^{min}\left(V^{PC},u\right)}{\partial V^{PC}} = \phi(u+\gamma) + \frac{ab\varepsilon}{(1+b+bn)\left(1+bn+\varepsilon^2\right)} + \mu V^{PC}$$

and the marginal damage costs

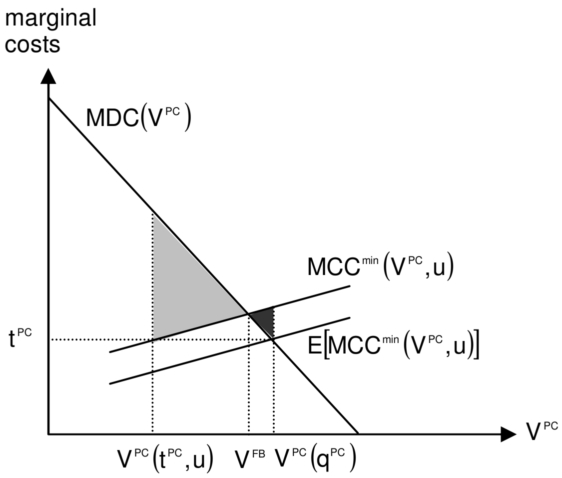
$$[22] \qquad MDC\left(V^{PC}\right) = -\frac{\partial DC\left(V^{PC}\right)}{\partial V^{PC}} = \alpha + \beta\left(EM^{*PC} - V^{PC}\right).$$

In the end, q^{PC} and t^{PC} result from plugging the optimal V^{PC} into $q\left(V^{PC}\right)$ along with $t\left(V^{PC},u\right)$ and if appropriate building expectations.
So obviously the optimal choice of instruments solely depends on the relation between the slopes of $MDC\left(V^{PC}\right)$ and $MCC^{min}\left(V^{PC},u\right)$: Standards shall be preferred to taxes when the marginal damage costs run steeper than the minimised aggregate marginal control costs, i.e. $\beta > \mu$, and vice versa. The level of the latter (ϕ) as well as the variance of u indeed determines the magnitude of the difference in total expected costs but they play absolutely no role for its sign. As these findings exactly coincide with the policy rule first derived by Weitzman (1974) it hereby has been proved that the latter holds for the more general case of two abatement options. Hence state

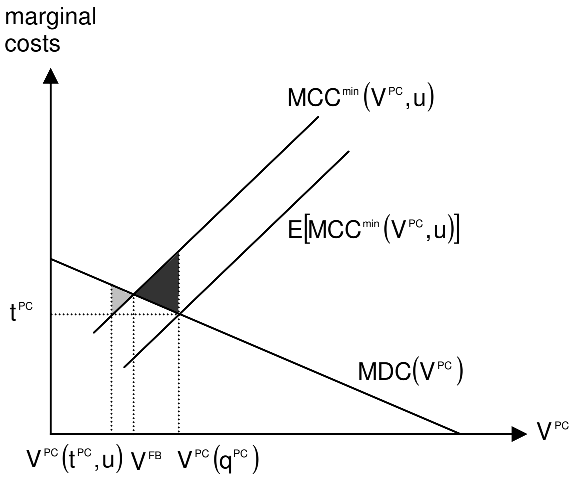
Proposition 1: *The original Weitzman-rule can be generalised for the case of two abatement options.*

Thus in the following [15] will be referred to as the generalised original Weitzman-rule. The critical question to answer is evidently how this policy rule comes to existence:

[21] u produces an additive shock w.r.t. the minimised aggregate control cost function which corresponds to the original Weitzman-setting.



a) $\beta > \mu$



b) $\beta < \mu$

Figure 3: Generalised original Weitzman-rule for $u > 0$

Figure 3 depicts the first order condition for the optimal standard (q^{PC}) and tax (t^{PC}) contingent on V^{PC}. Both yield from the intersection of $MDC(V^{PC})$ and $E[MCC^{min}(V^{PC},u)]$. For instance, it is presumed that u is actually positive, i.e. $MCC^{min}(V^{PC},u)$ runs above $E[MCC^{min}(V^{PC},u)]$ throughout the relevant value range of V^{PC}. q^{PC} accurately enforces the aggregate abatement effort being optimal in terms of expectation $V^{PC}(q^{PC})$. Due to the EPA's erroneous belief $V^{PC}(q^{PC})$ deviates from the first best aggregate abatement effort V^{FB} which equates $MCC^{min}(V^{PC},u)$ with $MDC(V^{PC})$. The resulting welfare loss or overall cost saving potential shows as

$$[23] \qquad dwl(q^{PC},u) = \int_{V^{FB}}^{V^{PC}(q^{PC})} \left(MCC^{min}(V^{PC},u) - MDC(V^{PC})\right) dV^{PC},$$

corresponding to the dark shaded area. By contrast, the firms' response to the optimal tax $V^{PC}(t^{PC},u)$ differs from the response expected by the EPA, $V^{PC}(q^{PC})$, since the firms align their true marginal control costs with t^{PC}. Again, the total costs are not minimised, since $MDC(V^{PC})$ and $MCC^{min}(V^{PC},u)$ fall apart. This time the respective welfare loss reads

$$[24] \qquad dwl(t^{PC},u) = \int_{V^{PC}(t^{PC},u)}^{V^{FB}} \left(MDC(V^{PC}) - MCC^{min}(V^{PC},u)\right) dV^{PC},$$

which is congruent to the light shaded area. Apparently, the policy recommendation of the generalised original Weitzman-rule is approved by the graphical analysis: Provided that the marginal damage costs run steeper than the aggregate marginal control costs

$(\beta > \mu)$ like depicted in figure 3a, it holds that $dwl(q^{PC},u) < dwl(t^{PC},u)$ and thus standards should be preferred to taxes: In case of μ being relatively small, already an insignificant error of the EPA – the true u only slightly deviates from zero – leads to a rather large difference between V^{FB} and $V^{PC}(t^{PC},u)$. Since moreover the damage costs react sensitively to variations of the aggregate abatement effort owed to a relatively large occurrence of β, V^{PC} should be controlled in a preferably accurate way, which can solely be accomplished through standard policy.

The economic intuition for the superiority of taxes, $dwl(q^{PC},u) > dwl(t^{PC},u)$, when $\beta < \mu$ – see figure 3b – becomes clearest by conceiving the extreme case of a horizontal marginal damage cost function $(\beta = 0)$. Here the EPA can enforce the first best aggregate abatement effort despite its lack of information by simply adjusting the tax rate to the axis intercept of the marginal damage costs α. The cost minimising firms will then for sure generate V^{FB}, against what the optimal standard still fails at full internalisation. This advantage of the tax policy persists as long as $\beta < \mu$. Note that the sign of the instrument specific welfare losses' difference applies for any allowed occurrence of u and consequently as well for the expected difference as a whole.

5. Symmetric Cournot oligopoly

Stage IV

Facing standard policy, each oligopolist solves[22]

$$[25] \quad \min_{x_i, v_i^e} \; cc^C(x_i, v_i^e, u) = cc^{xC}(x_i) + cc^e(v_i^e, u) \quad \text{s.t.} \quad em_i(x_i, v_i^e) = q \text{, where}$$

$$cc^{xC}(x_i) = \pi^C(x^{*C}, v^{e*}) - \pi^C(x_i, v^{e*})$$
$$= \left(p(\mathbf{x}^{*C})x^{*C} - cp(x^{*C})\right) - \left(p((n-1)x^{*C} + x_i)x_i - cp(x_i)\right), \quad x_i < x^{*C}$$

by setting the output and end-of-pipe abatement level such that

$$[26] \quad -\partial cc^{xC}(x_i)/\partial x_i = \varepsilon\left(\partial cc^e(\varepsilon x_i - q, u)/\partial(\varepsilon x_i - q)\right)$$

with identical meaning as [8]. Taking further into account that by reason of symmetry the equilibrium quantities will be the same for all the firms and employing the Cournot conjecture, one obtains the output, end-of-pipe abatement and emission level of the standard regulated Cournot-Nash-Equilibrium (short CNE) $x^C(q,u)$, $v^{eC}(q,u)$ and $em^C(q) = q$.[23]

Under the tax regime, the firms' minimisation problem turns out to be

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[22] The superscript "C" marks occurrences of functions and variables specific to symmetric Cournot oligopoly.

[23] For the second order condition, the existence and uniqueness of the standard regulated CNE see appendix A5.

[27] $$\min_{x_i, v_i^e} \quad cc^C(x_i, v_i^e, u) + tem_i(x_i, v_i^e) = cc^{xC}(x_i) + cc^e(v_i^e, u) + tem_i(x_i, v_i^e),$$

with the familiar first order condition

[28] $$-\partial cc^{xC}(x_i)/\partial x_i = \varepsilon t; \quad \partial cc^e(v_i^e, u)/\partial v_i^e = t.$$

The computation of the CNE under taxation produces $x^C(t)$, $v^{eC}(t,u)$ and $em^C(t,u)$.[24] Again, the minimisation of the firms' costs implies in both regimes to combine the two abatement options in a way that balances the respective marginal costs. The firms hereby explicitly take into account their influence on the equilibrium price. Like under perfect competition, they choose the output and end-of-pipe abatement level in two separate steps when facing taxation. This implies the output level to be the sole channel of strategic interaction and to be deterministic in equilibrium, against what the equilibrium end-of-pipe abatement and emission level are random from the EPA's perspective. Contrary, in the standard regulated CNE the amount of emissions is certain, while the output as well as the end-of-pipe abatement level is a function of u and beyond subject to strategic interaction, as the firms here fix x_i and v_i^e simultaneously.

Stage II

Minimising the expectation of the instrument specific total costs and anticipating the firms' equilibrium responses of stage IV results in the optimal instruments' designs. Thus, when implementing standards the EPA aspires to

[29] $$\min_{q} \quad E\left[C\left(x^C(q,u), v^{eC}(q,u), u\right)\right].$$

The optimal standard satisfies[25]

[30] $$-E\left[\frac{\partial CC\left(x^C(q^C,u), v^{eC}(q^C,u), u\right)}{\partial q^C}\right] = \frac{\partial DC(nq^C)}{\partial q^C}.$$

In case of taxation, the EPA's programme and the associated first order condition read[26]

[31] $$\min_{t} \quad E\left[C\left(x^C(t), v^{eC}(t,u), u\right)\right] \text{ and}$$

[32] $$E\left[\frac{\partial CC\left(x^C(t^C), v^{eC}(t^C,u), u\right)}{\partial t^C}\right] = -\frac{\partial DC(\cdot)}{\partial t^C}.$$

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[24] For the second order condition, the existence and uniqueness of the tax regulated CNE see appendix A6.
[25] For the second order condition and the explicit solution see appendix A7.
[26] For the second order condition and the explicit solution see appendix A8. Furthermore it can be shown that the optimal tax is below the Pigou-level, which is owed to the additional distortion of market power and corresponds to the standard result of Barnett (1980).

Stage I

Given the market structure of symmetric Cournot oligopoly, the difference in the optimally designed instruments' expected total cost levels turns out to be

$$[33] \qquad \Delta^C = E\left[C\left(x^C\left(t^C\right), v^{eC}\left(t^C,u\right), u\right) - C\left(x^C\left(q^C,u\right), v^{eC}\left(q^C,u\right), u\right)\right]$$

$$= \phi^{C^2} Var[u]\left(\frac{\beta - \mu^C}{2\mu^{C^2}}\right),$$

$$\text{at which } \phi^C = \frac{(1+b+bn)^2 + (1+bn)\varepsilon^2}{\left(1+b+bn+\varepsilon^2\right)^2} > \phi \text{ and}$$

$$\mu^C = \frac{(1+b+bn)^2 + (1+bn)\varepsilon^2}{n\left(1+b+bn+\varepsilon^2\right)^2} > \mu .$$[27]

Palpably, Δ^C exhibits the same structure as Δ^{PC}. However ϕ^C and μ^C, whose meaning will be revealed below, replace ϕ and μ. Thus, standards are superior to taxes for $\Delta^C > 0$ or equivalently $\beta > \mu^C$ and vice versa (BNE).

Interpretation

The reason for the discrepancy between Δ^C and Δ^{PC} as well as the accompanied modification of the policy rule becomes clear in turn by scrutinising the first order conditions for q^C and t^C: Just like in the case of perfect competition, the solution of [29] and [31] prescribes to choose q and t such that the marginal damage costs and the expected aggregate marginal control costs coming along with each instrument are balanced. Once more the instruments' first order conditions can be made comparable by restating the associated damage and aggregate control costs in dependence of $V^C = EM^{*C} - EM$, $EM^{*C} > EM$ – the overall abatement effort relating to the Cournot oligopoly. Therefore plug $q\left(V^C\right)$ and $t\left(V^C,u\right)$[28] into [29] and [31], which produces

$$[34] \qquad \begin{aligned} DC^q\left(V^C\right) &= DC\left(x^C\left(q\left(V^C\right),u\right), v^{eC}\left(q\left(V^C\right),u\right)\right) \\ DC^t\left(V^C\right) &= DC\left(x^C\left(t\left(V^C,u\right)\right), v^{eC}\left(t\left(V^C,u\right),u\right)\right) \\ CC^q\left(V^C,u\right) &= CC\left(x^C\left(q\left(V^C\right),u\right), v^{eC}\left(q\left(V^C\right),u\right),u\right) \\ CC^t\left(V^C,u\right) &= CC\left(x^C\left(t\left(V^C,u\right)\right), v^{eC}\left(t\left(V^C,u\right),u\right),u\right). \end{aligned}$$

Due to the firms' symmetry it holds that $DC^q\left(V^C\right) = DC^t\left(V^C\right) = DC\left(V^C\right)$ and $CC^q\left(V^C,u\right) = CC^t\left(V^C,u\right)$. The reasoning for these equivalences is exactly the same as in section 4. However, there is one crucial difference relative to perfect competition which drives the modification of the generalised original Weitzman-rule. Looking at the

[27] For the proof of these relations see appendix A9.

[28] These result from solving $V^c(q) = EM^{*c} - nq$ for q respectively $V^c(t) = EM^{*c} - EM^c(t,u)$ for t. $t\left(V^c,u\right)$ simply complies with the horizontal aggregation of the firms' marginal control costs because of [28].

oligopolists' marginal control costs of output reduction, it can be seen easily that these only capture a part of the corresponding costs occurring on the social level: The former – which are merely the loss of profit resulting from an infinitesimal decrease of the output level – amount to (w.r.t. the Cournot conjecture):

[35] $$-\frac{\partial cc^{xC}(x_i)}{\partial x_i}=\frac{\partial \pi^C(x_i, v^{e*})}{\partial x_i}=MR_i(x_i)-\frac{\partial cp(x_i)}{\partial x_i}$$

$$\text{whereas } MR_i(x_i)=\frac{\partial\left(p\left((n-1)x^{*C}+x_i\right)x_i\right)}{\partial x_i}$$

depicts the (residual) marginal revenue of firm i, given the equilibrium quantities of all the other firms. Now consider the respective aggregate costs of a firm's marginal output decrease, which are relevant for the EPA when calculating the instruments' optimal design:

[36] $$-\frac{\partial CC^{xC}\left((n-1)x^{*C}+x_i\right)}{\partial x_i}=\frac{\partial\left(U\left((n-1)x^{*C}+x_i\right)-\sum_{i=1}^{n} cp(x_i)\right)}{\partial x_i}=$$
$$=p\left((n-1)x^{*C}+x_i\right)-\frac{\partial cp(x_i)}{\partial x_i}.$$

[36] reflects the impact of a marginal output reduction on the partial welfare, namely the resultant loss of the consumers' and producers' surplus, which complies with the difference of the marginal willingness to pay (respectively the residual demand for firm i) and the marginal saving of production costs. The relation between the marginal costs of output reduction emerging on the firm and aggregate level is illustrated in figure 4:

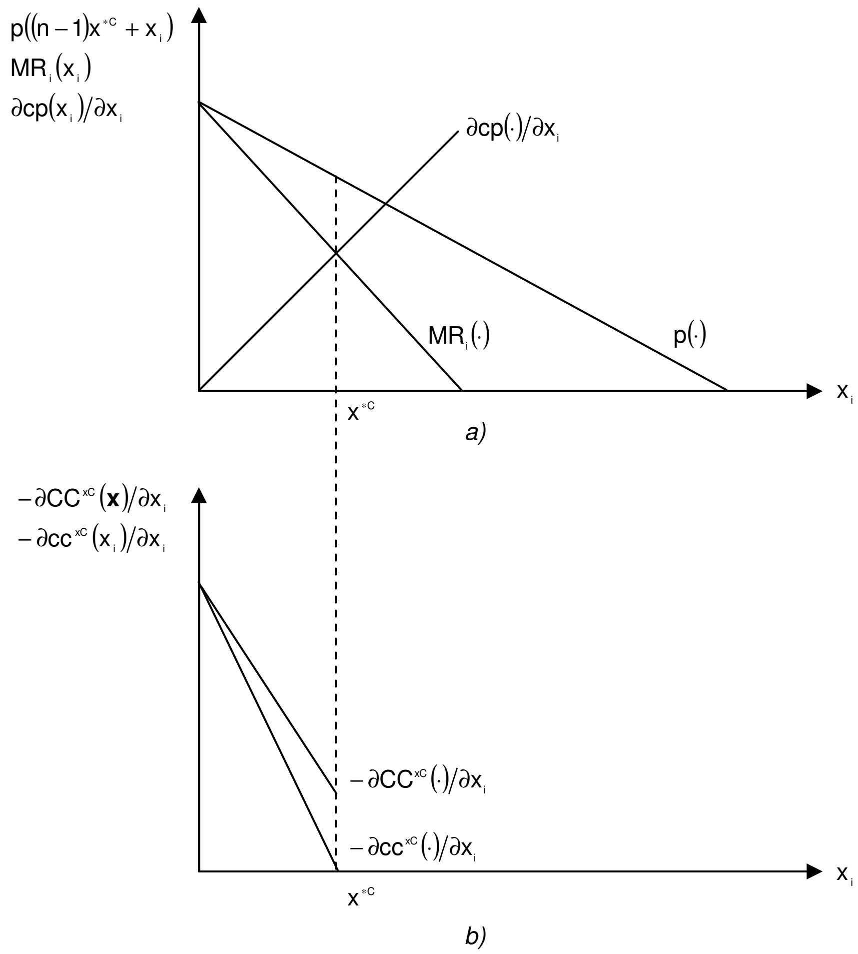

Figure 4: Marginal costs of output reduction on the firm and aggregate level

Naturally, for a linear demand function, the (residual) marginal revenue runs below the (residual) marginal willingness to pay, as shown in figure 4a. So it becomes evident that a firm's marginal output decrease causes lower costs on the firm than on the aggregate level by opposing [35] to [36].[29] This is visualised in figure 4b, where the firm's and the aggregate marginal costs are derived out of the difference between the marginal revenue respectively the marginal willingness to pay and the marginal costs of production.[30] When faced with standard or tax policy, each firm equals its marginal costs of the two abatement options and thus hinders the aggregate control costs from being minimised, i.e. the intra-firm efficiency is hurt: $-\partial CC^{xC}(\cdot)/\partial \varepsilon x_i > \partial cc^{xC}(\cdot)/\partial \varepsilon x_i = \partial cc^{e}(\cdot)/\partial v_i^e$ for $x_i = x^C(q,u)$ and $v_i^e = v^{eC}(q,u)$ as well as for $x_i = x^C(t)$ and $v_i^e = v^{eC}(t,u)$.[31] Consequently

Proposition 2: *Both the optimal standard q^C and the optimal tax t^C fail to enforce the first best allocation in terms of expectation.*

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[29] For the proof see appendix A10.

[30] However, the end-of-pipe abatement option leads ceteris paribus still to the same marginal costs from the firms' and from the aggregate point of view.

[31] Though, the inter-firm efficiency condition is still fulfilled with the reasoning familiar from the case of perfect competition.

Due to the relation between the firms' and the aggregate marginal costs of output reduction revealed above, the firms abate too much via the output option and too less via end-of-pipe: They abuse their market power to shift a part of the control costs upon the consumers. Therefore the aggregate control costs realisable in case of standard or tax policy are higher than the minimised aggregate control costs: $CC^q(V^C,u) = CC^t(V^C,u) > CC^{min}(V^C,u)$ within V^C's feasible range of values for the inner solution.[32] As a matter of course, it is the realisable aggregate marginal control cost function[33]

$$\begin{aligned} MCC^C(V^C,u) &:= \frac{\partial CC^q(V^C,u)}{\partial V^C} = \frac{\partial CC^t(V^C,u)}{\partial V^C} = \\ &= \phi^C(u+\gamma) + \frac{ab\varepsilon}{(1+b+bn)(1+b+bn+\varepsilon^2)} + \mu^C V^C \end{aligned} \quad [37]$$

whose expectation has to be equated with the marginal damage costs for the optimal instruments' design. So necessarily the former's slope μ^C and level parameter ϕ^C enter the modified Weitzman-rule. Opposing [37] to [21] reveals that realisable aggregate marginal control cost function runs on a higher level but exhibits a smaller slope compared to the minimised one.[34] To recapitulate set up

Proposition 3: *Against the background of uncertain control costs and a polluting symmetric Cournot oligopoly standards are superior to taxes when the marginal damage costs run steeper than realisable aggregate marginal control costs and vice versa.*

After all, the modified Weitzman-rule can in turn be visualized graphically:

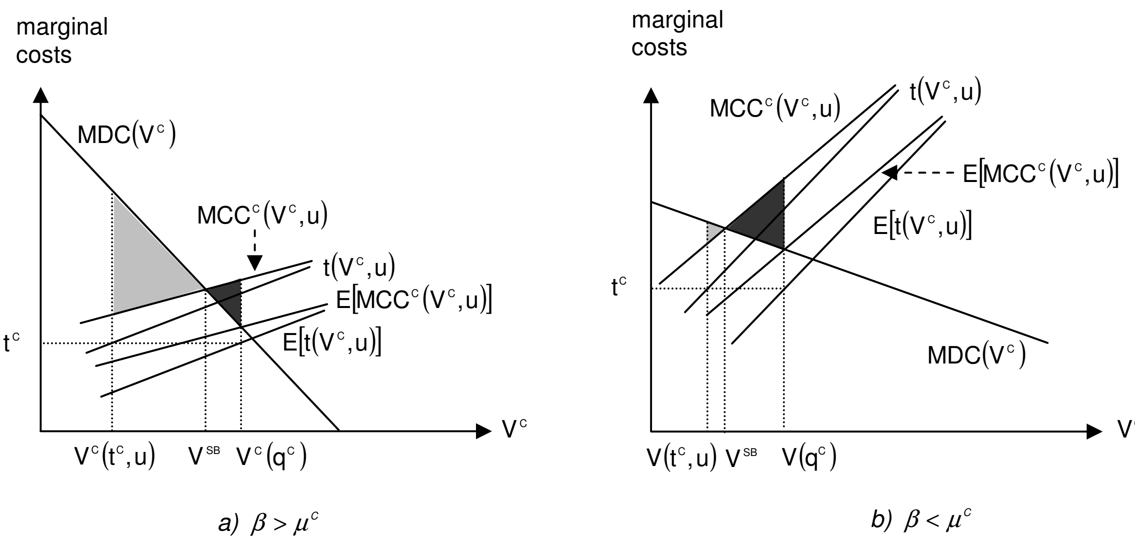


Figure 5: Modified Weitzman-rule for u > 0

[32] As the handling of the parameter restrictions which guarantee the inner solution is very cumbersome but yields no further insights, the proof is neglected.
[33] Note that u produces an additive shock to $MCC^c(V^c,u)$ as well.
[34] The causes for this relation are rather technical and thus not exposed in detail at this point. For this purpose see appendix A11 which also contains the proof.

Figure 5 illustrates the welfare implications of the optimal standard and tax for the exemplary case of u being actually larger than zero. As demonstrated above, q^C and t^C balance the marginal damage and the expected aggregate marginal control costs realisable for the EPA. Seeing that the aggregate abatement effort can be accurately controlled by standards, $V^C(q^C)$ is determined out of the intersection between $E[MCC^C(V^C,u)]$ and $MDC(V^C)$. Clearly due to the EPA's erroneous belief, $V^C(q^C)$ deviates from the second best aggregate abatement level V^{SB}, which equates the true realisable aggregate marginal control costs and the marginal damage costs. Remember that owed to the additional distortion of market power, neither standards nor taxes succeed in generating the first best allocation for which reason V^{SB} has to serve as reference point for the comparative analysis of instruments. So the welfare loss induced by the optimal standard is congruent to the dark shaded area in figure 5 and can be computed as follows:

$$[38] \qquad dwl(q^C,u) = \int_{V^{SB}}^{V^C(q^C)} \left(MCC^C(V^C,u) - MDC(V^C)\right) dV^C.$$

As the firms' and the aggregate marginal control costs diverge, of course t^C does not correspond to the level of $E[MCC^C(V^C,u)]$ and $MDC(V^C)$ in their intersection. It is in fact obtained by inserting $V^C(q^C)$, the aggregate abatement effort which is expected to be optimal, into the expectation of $t(V^C,u)$, the horizontal aggregation of the firms' marginal control costs.[35] Of course, given that the firms' true costs do not coincide with the EPA's expectation, the emerging abatement effort is $V^C(t^C,u)$, which deviates from the second best level as well. This time the arising welfare loss is

$$[39] \qquad dwl(t^C,u) = \int_{V^C(t^C,u)}^{V^{SB}} \left(MDC(V^C) - MCC^C(V^C,u)\right) dV^C,$$

corresponding to the light shaded area in figure 5. When the marginal damage costs run steeper than realisable overall marginal control costs, i.e. $\beta > \mu^C$, it holds that $dwl(q^C,u) < dwl(t^C,u)$ as illustrated in figure 5a.[36] As this is the case for every possible value of u unequal to zero, the expected welfare loss of standards is smaller than the one induced by taxation as well and thus standards are the optimal choice. For $\beta < \mu^C$ results the opposite policy recommendation, as can be seen from figure 5b. The economic intuition behind the modified Weitzman-rule exactly corresponds to the one behind the original rule.

[35] Since as proved in appendix A10 the firms' marginal costs of output reduction run steeper than the associated aggregate marginal costs but exhibit a lower level, the same relation necessarily applies for $t(V^c,u)$ and $MCC^c(V^c,u)$.

[36] Note that the slopes of $MCC^c(V^c,u)$ and $t(V^c,u)$ are positively correlated because they are determined by the same parameters entering in the identical direction; see appendix A12 for the proof.

6. Degree of market power and optimal instrument choice

Conceive the EPA would base its decision upon the generalised original Weitzman-rule despite the polluting firms constitute a symmetric Cournot oligopoly, and thus implement standard instead of tax policy whenever $\beta > \mu$ and vice versa. However as shown above, standards are only superior to taxes if $\beta > \mu^C$. Since $\mu^C > \mu$, the EPA chooses standards by mistake, i.e. although taxes would generate the higher expected welfare level, whenever $\mu^C > \beta > \mu$. Yet, it is straightforward to realise that because of $\mu^C > \mu$ an aberrant implementation of taxes instead of standards is never possible. Summarise this finding as

Proposition 4: *Applying the generalised original Weitzman-rule despite market power of the polluting firms comprises the risk of a suboptimal instrument choice, which solely contains a falsely implementation of standards.*

Obviously, this risk grows with increasing size of the interval $[\mu;\mu^C]$, which is $\mu^C - \mu$. Taking into account that both μ and μ^C are functions of the firms' number n it can easily be shown that[37]

[40] $$\frac{\partial\left(\mu^C(n) - \mu(n)\right)}{\partial n} < 0.$$

Consequently applies

Proposition 5: *The risk of the suboptimal instrument choice described in proposition 4 grows with decreasing number of the firms and thus increasing degree of market power.*

Finally bear in mind

Proposition 6: *The modified Weitzman-rule for a symmetric Cournot oligopoly can be adapted to the case of a monopolistic polluter.*

For this purpose simply set $n = 1$ within [33]:

[41] $$\Delta^M = \Delta^C(n = 1).$$ [38]

7. Conclusion

In almost every actual emission control setting the environmental policy agency (EPA) is confronted with two kinds of complications appearing simultaneously: On the one

[37] The causes for this finding are rather technical and thus not exposed in detail at this point. For this purpose see appendix A13 which also contains the proof.
[38] The superscript "M" marks variables and functions specific to a monopolistic market structure.

hand, the polluting firms nearly always exhibit at least some market power, on the other hand, the EPA is indeed never equipped with all the information it needs for reaching the full resolution of distortions with environmental policy instruments. Thereby information problems focus particularly on firms' cost functions. Environmental economic theory so far has admittedly detected that both complications influence the optimal design and choice of conventional instruments, however to date it failed to analyse their mutual impact.

The present paper takes a first step in overcoming this default. It analyses the welfare properties of emission standards and taxes within a static partial framework against the background of uncertain emission control costs from the EPA's perspective and assumes concurrently that the polluting firms constitute a symmetric Cournot oligopoly.

The main insight is that these two complications in fact interact. Hence the existent policy rule, originally derived by Weitzman (1974) under the premise of perfect competition, which tells whether to choose standards or taxes when control costs are uncertain, might give wrong advice when firms possess market power. Beyond generalising the original Weitzman-rule for two abatement options, the paper provides a modified rule which is based on a different concept of aggregate control costs and guarantees the optimal choice of instruments in the case of a symmetric Cournot oligopoly. Furthermore it is shown, that the EPA's risk of choosing the wrong instrument when sticking to the generalised original Weitzman-rule in the Cournot setting grows with increasing degree of market power. At last, the modified policy rule contains the adequate policy recommendations for the special case of a monopolistic polluter.

As a matter of course, the specificity of the model demands caution in adopting these findings to any actual regulation scenario. Yet, Weitzman (1974) weakened this caveat by arguing that the presumed linearity of the aggregate marginal control cost and damage cost function allows for interpreting the results as an approximation for more general functions – provided that the feasible value range of the random variable is sufficiently small. For a critical discussion of that point see Malcomson (1978) and Weitzman (1978).

Clearly, there are much more combinations of information problems and market forms left which could serve as basis for the comparative analysis of conventional environmental policy instruments. Though, future research should especially focus on those combinations which promise essentially new interdependencies between the complications under regard. For instance, removing the assumption of symmetric firms would introduce the allocative inefficiency of production which probably affects the optimal environmental policy vitally. The same applies for markets featuring price competition, which is well known to exhibit a completely different dimension of strategic interaction.

Appendices

Some of the results listed below presume the parameter restrictions guaranteeing the inner solution. However, as the handling of the latter is very cumbersome but yields no further insights the respective proofs will be neglected.

Appendix A1: Firms' second order condition in case of standards (perfect competition)

As the Hessian of the Lagrangian associated with [7]

$$H^{qPC} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

is strictly positive definite, [8] defines a global minimum.

Appendix A2: Firms' second order condition in case of taxes (perfect competition)

As the Hessian of the firms' overall compliance costs under taxation

$$H^{tPC} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

is strictly positive definite, [10] defines a global minimum.

Appendix A3: Optimal standard – second order condition and explicit solution (perfect competition)

Since the expectation of the total costs is strictly convex in q, i.e.

$$\frac{\partial^2 E[C(\cdot)]}{\partial q^2} = \frac{n\left((1+bn)(1+n\beta)+n\beta\varepsilon^2\right)}{1+bn+\varepsilon^2} > 0,$$

the optimal standard

$$q^{PC} = \frac{(1+bn)(\gamma-\alpha)+a\varepsilon-\alpha\varepsilon^2}{(1+bn)(1+n\beta)+n\beta\varepsilon^2} \in \left\langle 0; em^{*PC} \right\rangle \text{ for the inner solution}$$

yields a global minimum of the former.

Appendix A4: Optimal tax – second order condition and explicit solution (perfect competition)

Since the expectation of the total costs is strictly convex in t, i.e.

$$\frac{\partial^2 E[C(\cdot)]}{\partial t^2} = \frac{n(1+bn+\varepsilon^2)((1+bn)(1+n\beta)+n\beta\varepsilon^2)}{(1+bn)^2} > 0\,,$$

the optimal tax

$$t^{PC} = \frac{(1+bn)(n\beta\gamma+\alpha)+an\beta\varepsilon}{(1+bn)(1+n\beta)+n\beta\varepsilon^2}$$

yields a global minimum of the former.

Appendix A5: Properties of the standard regulated CNE

The second order condition of [25] is fulfilled because the Hessian of the associated Lagrangian

$$H^{qC} = \begin{pmatrix} 1+2b & 0 \\ 0 & 1 \end{pmatrix}$$

is strictly positive definite. Beyond, the existence and uniqueness of the standard regulated CNE apply since the firms' response functions concerning output and end-of-pipe abatement are linear and decreasing in the rivals' output:

$$rx_i(X_{-i},q,u) = \frac{a-\varepsilon(u+\gamma-q)}{1+b+\varepsilon^2} - \frac{b}{1+b+\varepsilon^2}X_{-i}$$

$$rv_i^e(X_{-i},q,u) = \frac{\varepsilon(a-\varepsilon(u+\gamma))-(1+b)q}{1+b+\varepsilon^2} - \frac{b\varepsilon}{1+b+\varepsilon^2}X_{-i}$$

Appendix A6: Properties of the tax regulated CNE

Considering the Hessian of the firms' compliance costs under taxation

$$H^{tC} = \begin{pmatrix} 1+2b & 0 \\ 0 & 1 \end{pmatrix}$$

and the response functions of the firms

$$rx_i(X_{-i},t)=\frac{a-\varepsilon t}{1+b}-\frac{b}{1+b}X_{-i}$$

$$rv_i^e(t,u)=\frac{t-u-\gamma}{\delta}$$

yields the same results as A5.

Appendix A7: Optimal standard – second order condition and explicit solution (Cournot oligopoly)

Due to

$$\frac{\partial^2 E[C(\cdot)]}{\partial q^2}=n\beta^2+\frac{bn+b^2n+(bn)^2}{(1+b+bn+\varepsilon^2)}+\frac{n+bn^2}{1+b+bn+\varepsilon^2}>0$$

the expectation of the total costs is strictly convex in q which is why the optimal standard

$$q^C=\frac{a\varepsilon(1+b(2+n)+\varepsilon^2)+\gamma((1+b+bn)^2+(1-bn)\varepsilon^2)-\alpha(1+b+bn+\varepsilon^2)^2}{(1+b+bn)^2(1+n\beta)+\varepsilon^2(2n(1+b+bn)\beta+1+bn)+n\beta\varepsilon^4}$$

$\in \langle 0;em^{*C}\rangle$ for the inner solution

yields a global minimum of the former.

Appendix A8: Optimal tax – second order condition and explicit solution (Cournot oligopoly)

Due to

$$\frac{\partial^2 E[C(\cdot)]}{\partial t^2}=n(1+n\beta)+\frac{n\varepsilon^2(2n\beta+2bn\beta+2bn^2\beta+1+bn)}{(1+b+bn)^2}+\frac{n^2\beta\varepsilon^4}{(1+b+bn)^2}>0$$

the expectation of the total costs is strictly convex in t which is why the optimal tax

$$t^C=\frac{(1+b+bn)^2(n\beta\gamma+\alpha)+a\varepsilon(n\beta(1+b+bn)-b)}{(1+b+bn)^2(1+n\beta)+\varepsilon^2(2n(1+b+bn)\beta+1+bn)+n\beta\varepsilon^4}$$
$$+\frac{\varepsilon^2(1+b+bn)(n\beta\gamma+\alpha)+an\beta\varepsilon^2}{(1+b+bn)^2(1+n\beta)+\varepsilon^2(2n(1+b+bn)\beta+1+bn)+n\beta\varepsilon^4}$$

>0 for the inner solution

yields a global minimum of the former.

Appendix A9: ϕ^C vs. ϕ and μ^C vs. μ

$$\phi^C - \phi = \frac{(b\varepsilon)^2}{(1+bn+\varepsilon^2)(1+b+bn+\varepsilon^2)^2} > 0$$

$$\mu^C - \mu = \frac{(b\varepsilon)^2}{n(1+bn+\varepsilon^2)(1+b+bn+\varepsilon^2)^2} > 0$$

Appendix A10: Firms' vs. aggregate marginal costs of output reduction

The difference between the marginal costs of output reduction occurring on the aggregate and the firm level is strictly positive within the relevant range of values concerning the output quantity:

$$\left(-\frac{\partial CC^{xC}\left((n-1)x^{*C}+x_i\right)}{\partial x_i}\right)-\left(-\frac{\partial cc^{xC}(x_i)}{\partial x_i}\right)=$$
$$=\frac{a(n-1)(1+b(2+n))}{1+b+bn}+\left(1-\left(n+b\left(n^2-2\right)\right)\right)x_i>0,\quad \text{for } x_i\in\left\langle 0;x^{*C}\right\rangle,\ n\geq 2.$$

Appendix A11: Minimised vs. realisable aggregate marginal control costs

Comparing $MCC^{min}(V^C,u)$ and $MCC^C(V^C,u)$ yields

w.r.t. the level

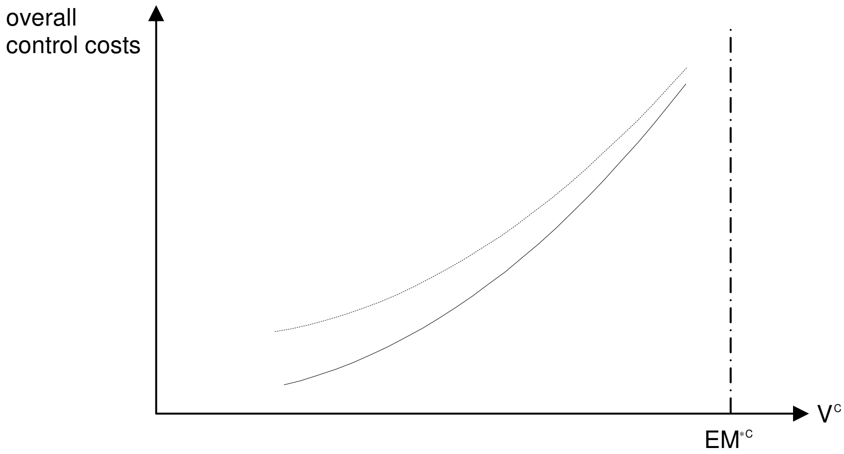
$$\left(MCC^{min}(V^C,u)-MCC^C(V^C,u)\right)\Big|_{V^C=0}=$$
$$=\frac{ab^2\varepsilon}{(1+b+bn)(1+bn+\varepsilon^2)(1+b+bn+\varepsilon^2)}-(\gamma+u)(\phi-\phi^{min})$$

>0 for the inner solution;

w.r.t. the slope

$\mu-\mu^C<0$, see A9.

So $MCC^{min}(V^C,u)$ runs on a higher level opposite to $MCC^C(V^C,u)$ but exhibits a smaller slope. The causes for this relation become clear through contemplating the progression of the associated overall control cost functions within V^C's feasible value range for the inner solution:



- - - - - - - - - aggregate control costs induced by standards and taxes
———— minimised aggregate control costs

Figure 6: Minimised vs. instruments' aggregate control costs

At first recall that both standards and taxes hurt the intra-firm efficiency condition and thus the aggregate control costs induced by standards and taxes run above the minimised ones.

The crux for $MCC^{C}(V^{C},u)$ to grow faster than $MCC^{min}(V^{C},u)$, i.e. $\mu^{C} > \mu$, is the following: As demonstrated in figure 4, the gap between the aggregate marginal control costs w.r.t. output shortage and the firms' costs shrinks with increasing abatement effort. Thus, the higher V^{C}, the less impact has the abatement inefficiency coming along with standards and taxes. Consequently, the instruments' and the minimised aggregate control costs converge as V^{C} tends to EM^{*C}, the maximal overall abatement effort. This in turn has two kinds of implications: Firstly, the minimised cost function runs steeper than the instruments' cost function and thus necessarily $MCC^{min}(V^{C},u)$ possesses a higher level than $MCC^{C}(V^{C},u)$. Secondly, the convergence of the cost functions requires that their slopes assimilate as well for growing V^{C} and so $\mu^{C} > \mu$.

Appendix A12: Relation between the slopes of $MCC^{C}(V^{C},u)$ and $t(V^{C},u)$

$$\frac{\partial^2 MCC^{C}(V^{C},u)}{\partial V^{C}\partial b} = \frac{\varepsilon^2\left(n + b(1+n)(2+n) + n\varepsilon^2\right)}{n\left(1 + b + bn + \varepsilon^2\right)^3} > 0$$

$$\frac{\partial^2 t(V^{C},u)}{\partial V^{C}\partial b} = \frac{(1+n)\varepsilon^2}{n\left(1 + b + bn + \varepsilon^2\right)^2} > 0$$

$$\frac{\partial^2 MCC^C(V^C,u)}{\partial V^C \partial n} = \frac{-(1+b+bn)^3 - \left(2+b\left(3+b+3n+bn^2\right)\right)\varepsilon^2 - \varepsilon^4}{n^2\left(1+b+bn+\varepsilon^2\right)^3} < 0$$

$$\frac{\partial^2 t(V^C,u)}{\partial V^C \partial n} = \frac{-(1+b+bn)^2 - (1+b)\varepsilon^2}{n^2\left(1+b+bn+\varepsilon^2\right)^2} < 0$$

$$\frac{\partial^2 MCC^C(V^C,u)}{\partial V^C \partial \varepsilon} = -\frac{2\varepsilon\left(1+\varepsilon^2+b\left(3+b(1+n)(2+n)+n\left(2+\varepsilon^2\right)\right)\right)}{n\left(1+b+bn+\varepsilon^2\right)^3} < 0$$

$$\frac{\partial^2 t(V^C,u)}{\partial V^C \partial \varepsilon} = -\frac{2(1+b+bn)\varepsilon}{n\left(1+b+bn+\varepsilon^2\right)^2} < 0$$

Appendix A13: Number of firms and the deviation between μ^C and μ

Consider the impact of the firms' number n on the intra-firm efficiency of abatement

$$\left.\frac{\partial\left(-\partial CC^{xC}(\cdot)/\partial \varepsilon x - \partial cc^e(\cdot)/\partial v_i^e\right)}{\partial n}\right|_{x_i = x^C\left(q\left(V^C\right),u\right) = x^C\left(t\left(V^C,u\right)\right),\, v_i^e = v^{eC}\left(q\left(V^C\right),u\right) = v^{eC}\left(t\left(V^C,u\right),u\right)} =$$

$$= -\frac{ab^2}{\varepsilon(1+b+bn)^2} - \frac{(1+b)\left(bn^2(u+\gamma) + b(1+2n)V + \left(1+\varepsilon^2\right)V\right)}{n^2\left(1+b+bn+\varepsilon^2\right)^2} < 0$$

Clearly, as n decreases each firm gains more market power and thus passes a greater share of the control costs on to consumers by abating relatively more through output shortage and relatively less through end-of-pipe. Therefore, the intra-firm inefficiency, i.e. the gap between the aggregate marginal costs of each firm's output reduction and end-of-pipe abatement effort grows. This in turn entails an augmentation of the difference between the aggregate control costs induced by standards and taxes and the minimised ones within V^C's feasible range of values w.r.t. the inner solution (see figure 6, A11).

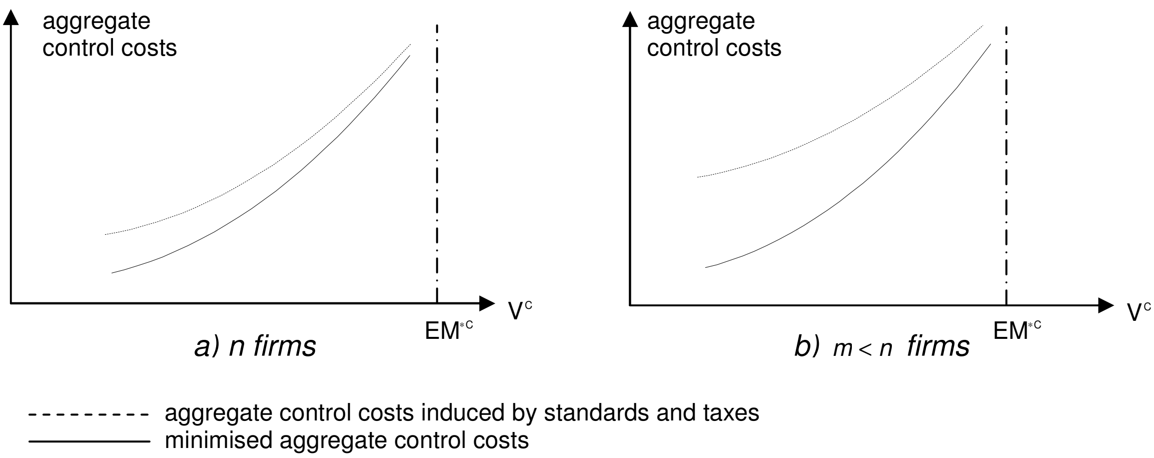


Figure 7: Minimised vs. instruments' aggregate control costs with varying number of firms

These two cost functions converge as V^C tends to EM^{*CN} (which is positively correlated with n) as well in case of a smaller number of firms $m < n$, for the same causes exposed in A11, leading immediately to the following two corollaries: Firstly, for given V^C the relative slope of the minimised aggregate control cost function and the instruments' cost function raises, i.e. the difference in the levels of the associated marginal cost functions goes up, with decreasing n:

$$\left.\frac{\partial\left(MCC^{min}\left(V^C,u\right)-MCC^C\left(V^C,u\right)\right)}{\partial n}\right|_{V^C=0} < 0 \text{ for the inner solution.}$$

Secondly, as the convergence of the cost functions implies that their slopes assimilate, a larger difference in the levels of the marginal cost functions requires that the relative slope of the marginal overall cost function induced by standards and taxes and the minimised one μ^C/μ accretes when n falls:

$$\frac{\partial\left(\mu^C(n)-\mu(n)\right)}{\partial n} = -\frac{(b\varepsilon)^2\left(2b^2n(1+2n)+b(1+5n)\left(1+\varepsilon^2\right)+\left(1+\varepsilon^2\right)^2\right)}{n^2\left(1+bn+\varepsilon^2\right)^2\left(1+b+bn+\varepsilon^2\right)^3} < 0\,.$$

References

Adar, Z. and Griffin, J. M. (1976): “Uncertainty and the choice of pollution control instruments,” *Journal of Environmental Economics and Management* 3, 178-188.

Barnett, A. H. (1980): “The Pigouvian tax rule under monopoly,” *American Economic Review* 70, 1037-1041.

Baumol, W. J. and Oates, W. E. (1988): *The theory of environmental policy*, Cambridge, MA: Cambridge University Press.

Buchanan, J. M. (1969): “External diseconomies, corrective taxes and market structure,” *American Economic Review* 59, 174-177.

Ebert, U. (1992): “Pigouvian tax and market structure: The case of oligopoly and different abatement technologies,” *Finanzarchiv* 49, 154-166.

Helfand, G. E. (1991): “Standards versus standards: The effects of different pollution restrictions,” *American Economic Review* 81, 622-634.

Malcomson, J. M. (1978): “Prices vs. quantities: A critical note on the use of approximations,” *Review of Economic Studies* 45, 203-207.

Requate, T. (1993a): “Pollution control in a Cournot Duopoly via taxes or permits,” *Journal of Economics* 58, 255-291.

Requate, T. (1993b): “Pollution control under imperfect competition: Asymmetric Bertrand duopoly with linear technologies,” *Journal of Institutional and Theoretical Economics* 149, 415-442.

Requate, T. (2005): “Environmental policy under imperfect competition – a survey,” Christian-Albrechts-Universität Kiel, Department of Economics: *Economics Working Paper*, No. 2005-12.

Simpson (1995): “Optimal pollution taxation in a Cournot duopoly,” *Environmental and Resource Economics* 6, 359-369.

Tisato, P. (1994): “Pollution standards vs. charges under uncertainty,” *Environmental and Resource Economics* 4, 295-304.

Weitzman, M. L. (1974): “Prices vs. quantities”. *Review of Economic Studies* 41, 477-491.

Weitzman, M. L. (1978): “Reply to “Prices vs. quantities: A critical note on the use of approximations” by James M. Malcomson,” *Review of Economic Studies* 45, 209-210.