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

CLEMENS HEUSON
University of Augsburg[Ψ] *and Bavarian Graduate Program in Economics*

Abstract. Studies dealing with the optimal choice of pollution control instruments under uncertainty have invariably taken it for granted that regulated firms face perfectly competitive markets. By introducing the product market into the stochastic framework of Weitzman (1974), this paper shows for the case of a polluting symmetric Cournot oligopoly that Weitzman's policy rule for choosing emission standards vs. taxes with uncertain abatement costs is biased in the presence of market power. Since the oligopolists take into account their influence on the market price, their total abatement effort, including the restriction of output, is less vulnerable to miscalculations of the tax rate compared to price-taking firms. Consequently, the comparative advantage of instruments is shifted in favour of taxes. In a further step, the provided policy recommendations are generalised by abolishing the assumption that firms are symmetric.

Keywords: *external diseconomies of pollution, Cournot oligopoly, cost uncertainty*
JEL Classification: *D89, L13, Q58*

[Ψ] Department of Economics, Universitätsstraße 16, D-86159 Augsburg, Germany
Email: clemens.heuson@wiwi.uni-augsburg.de; Tel.: +49 (0) 821 598-4062; Fax: +49 (0) 821 598-4217

1. Introduction

There are two fundamental ways of coping with industrial pollution: either by imposing a direct constraint on emission levels, that is, implementing emission standards or tradable emission permits, or by artificially establishing the non-existent price for pollution, that is, implementing emission taxes. Economists realised at an early stage that the optimal[1] choice of these modes of regulation might be crucially influenced by the regulator's uncertainty concerning damage and abatement costs, given de facto in any real world regulation setting. Initially, Weitzman (1974), Fishelson (1976) and Adar and Griffin (1976) showed that an additive shock (representing the regulator's uncertainty) to the marginal damage cost function leaves the basically given equivalence of standards, permits and taxes unaffected,[2] while a congruent shock to the marginal abatement cost function makes their comparative advantage solely dependent on the relative slopes of the two aforementioned marginal cost functions. However, this result holds only when the two shocks are uncorrelated, as was later highlighted by Stavins (1996).

Each of these studies takes for granted that a specific abatement effort causes the same costs both at the social level as well as to regulated firms, and thus implicitly presumes that the latter act in perfectly competitive markets. Clearly, this assumption does not apply to many serious pollution problems. For example, the production of toxic substances within the EU chemical industry, which is well known to feature oligopolistic or even monopolistic market structures, has grown at almost the same rate as the EU GDP between 1995 and 2005 (European Environment Agency, 2007). Another famous example is given by the carbon dioxide emissions arising from the energy sector, where firms compete, at least locally, à la Cournot (Requate, 2005).

It is therefore vitally important for policy makers to comprehend the market power's impact on the optimal choice of prices vs. quantities under uncertainty. To address this need, the present paper establishes the missing link between the abovementioned uncertainty literature and the field of environmental policy under imperfect competition,[3] beginning with the seminal work of Buchanan (1969). Buchanan points out that Pigouvian taxation usually leads to suboptimal allocations when the polluting firms possess market power as it exacerbates the associated output shortage, whereas the latter constitutes an additional distortion besides the external diseconomies of pollution. Clearly, both distortions could be completely resolved by combining any traditional pollution control instrument with an output subsidy (Baumol and Oates, 1988). However, the latter is generally not implementable for political reasons; thus the regulator must opt for the second-best solution. A further milestone was made by Barnett (1980), who derives a rigorous second-best tax rule tailored to the actuality of a monopolistic polluter, followed by more sophisticated rules for symmetric Cournot oligopoly (Ebert, 1992) as well as asymmetric Cournot oligopoly (Simpson, 1995). In addition, several studies deal with the optimal instrument choice in the presence of market power, most

[1] Hereafter, 'optimal' is used synonymously with 'accomplishing the regulator's goal of welfare maximisation' (if applicable subject to market power of the polluting firms and/or uncertainty).

[2] Amongst others, this equivalence – which is a common insight in environmental economics; see for example Baumol and Oates (1988) – particularly presumes identical cost functions of the regulated firms or the possibility to set firm specific standards, respectively (Tisato, 1994). Only under these assumptions standards provide an efficient allocation of the overall abatement effort among firms, like taxes and permits do in any case.

[3] Requate (2005) provides a comprehensive survey of this vast field, which is necessarily only covered in part by the following treatises.

notably Requate (1993a and b), who compares tradable permits and taxes for regulating a polluting Cournot and Bertrand duopoly.

Building upon the two strands of literature initiated by Weitzman (1974) and Buchanan (1969), the present paper investigates the combined impact of cost uncertainty on the part of the regulator and market power of polluting firms on the optimal choice between price- and quantity-based pollution control instruments. For simplification, Weitzman's assumption of uncorrelated control and damage cost uncertainties is adopted. This makes it possible to neglect damage cost uncertainty, as it does not affect the firms' behaviour and is consequently irrelevant for the instruments' ranking, regardless of whether competition is perfect or not.[4] Besides, the comparison of regulation modes solely comprises standards and taxes although it would seem natural to incorporate tradable permits. Given the firms' market power, a realistic modelling of the permit trade would have to account for strategic effects and thus goes beyond the scope of the analysis; see Requate (2005). The model employed extends Weitzman's (1974) framework – the standard approach for investigating uncertainty in environmental economics – by explicitly incorporating the product market. This introduces the option of reducing emissions not only by adopting an abatement technology but also via output shortage.

The paper shows that the inclusion of the product market does not change the results obtained by Weitzman (1974) – provided there is perfect competition, which implies per definition that the costs associated with the two abatement options are the same from social and firm perspective and thus fulfils the crucial premise of Weitzman's policy rule. However, his rule is biased in favour of standards when the polluting firms exhibit market power, which is proven for the case of a symmetric Cournot oligopoly. To grasp the intuition behind that result, first recall Weitzman's policy rule, which states that quantity rather than price controls should be implemented if and only if marginal damage costs run steeper than marginal abatement costs, and vice versa. The underlying mechanism is that when abatement costs are uncertain, standards provide a deterministic emission but a stochastic marginal abatement cost level, whereas the exact opposite applies for taxes. Clearly, the standards' characteristics turn out to be more valuable when the marginal damage costs' slope is relatively high, which reflects that a small increase of emissions can have severe impacts on the environment. Analogously, the opposite constellation requires putting a cap on abatement costs via taxes, because choosing an erroneously low standard might result in excessively high abatement costs.

Now consider the introduction of market power. Contrary to a polypolistic firm, a Cournot oligopolist takes into account the influence of her output decision on the equilibrium price, which triggers two kinds of effects. First, the oligopolists' marginal output shortage costs only cover a part of the according cost incurred by a price-taking firm, which are in turn perfectly congruent to the costs at the social level. Hence, the oligopolists

[4] As is well known, quantity-based modes of regulation control the firms' behaviour in a direct manner whereas price-based modes operate indirectly, through the firms' profit maximisation efforts. Hence, the regulator's uncertainty concerning abatement costs necessarily leads to differing performance between prices and quantities. On the other hand, damage cost uncertainty does indeed affect the optimal emission target level's identification, but it does not hinder the regulator from similarly enforcing the target through prices or quantities (Weitzman, 1974; Adar and Griffin, 1976; Fishelson, 1976). This well established result holds for any type of market structure since the pivotal independence of the firms' profit from damage costs is clearly not tied to the question of whether or not firms possess market power.

render – from the social perspective – a 'too high' share of their abatement burden through output reduction and a 'too low' share through the abatement technology. That is, they use their market power to pass a part of the abatement costs on to consumers via the output channel. However, the associated inefficiency affects standards and taxes equally and is consequently irrelevant to the optimal instrument choice. It simply reflects the well known fact that one instrument is not enough to completely resolve both distortions.

Second, the marginal output shortage costs respond more sensitively to changes in the production level and thus run steeper than if the market were perfectly competitive. This implies an increased slope for the aggregate marginal abatement cost function as well. On the one hand, this indicates that miscalculations of the tax rate due to the regulator's information problem have a weaker impact on the firms' overall abatement effort. On the other hand, the increase of abatement costs associated with a suboptimally strict standard policy is more severe in the presence of the oligopolistic output shortage; because of this, the taxes' benefits with respect to the cap on abatement costs gain importance. This shift in the instruments' comparative advantage in favour of taxes is proven to be positively correlated with the degree of market power.

Abolishing the premise of symmetric firms and assuming, contrary to Weitzman (1974), the more realistic case of uniform standards rather than firm-specific standards, provides further insights. First, the standards' well-known drawback with respect to abatement efficiency comes to rise and shifts the comparative advantage of instruments in favour of taxes. Second, contrary to the recommendations in the extant literature, the extent of uncertainty has to be taken into account for the optimal instrument choice. Adequate modifications of Weitzman's policy rule are derived for perfect competition and Cournot oligopoly for both symmetric and asymmetric firms in each case.

The next section introduces the model setup and presents the basic problem. Section 3 provides the comparative analysis of instruments under perfect competition. Section 4 considers the case of a Cournot oligopoly. The consequences of abolishing the assumption of symmetric firms are revealed in Section 5. Finally, Section 6 offers conclusions and some scope for future research.

2. The model

The modelling framework for the comparative analysis of environmental policy instruments with abatement cost uncertainty and market power of polluting firms aims to guarantee the comparability of results with Weitzman (1974). Specifically, this requires a presumption of (approximately) linear marginal costs and benefits as well as an additive shock to the marginal abatement cost function. These demands are accomplished in the following way.

Consider $i = 1,...,n$ symmetric firms each producing x_i units of a homogenous good at costs amounting to $c_p(x_i) = Cx_i + (c/2)x_i^2$, where n is exogenously fixed. Total output is given by $X = \sum_i x_i$. Producing one unit of output causes ε emission units of a harmful pollutant. Assume that the latter only emerges in the industry under consideration. Each firm can reduce emissions either by decreasing the output level or by adopting an end-of-pipe abatement technology. The latter allows for an arbitrary shortage of total emissions without having to alter the production volume. Thus, the individual amount of emissions actually discharged into the environment is $em_i(x_i, a_{ei}) = \varepsilon x_i - a_{ei}$, where a_{ei} denotes the end-of-pipe abatement effort. Suppose that the end-of-pipe technology can be described by the cost function $c_e(a_{ei}, \theta) = (Z + \theta)a_{ei} + (z/2)a_{ei}^{\;2}$.

Due to the need for linear marginal costs mentioned earlier, the firms' cost function must be modelled as being additively separable into production and abatement components, which allows for zero emissions without ceasing production.[5] The inputs for both production and end-of-pipe abatement are produced at an exogenously given price in a perfectly competitive market. Thus, $c_p(x_i)$ and $c_e(a_{ei}, \theta)$ not only represent the associated costs at the firm level, but also those incurred by society.

Consumers' preferences can be mapped into the quasi-linear utility function $U(X,Y) = BX - (b/2)X^2 + Y$, where Y represents the aggregate amount of a Numéraire, which is produced in an exogenous market and thus can be neglected throughout the further analysis. Consequently, the linear inverse demand is $p(X) = B - bX$.

Finally, the monetary value of the environmental damage caused by the firms' emissions is captured by the damage cost function $C_D(EM) = DEM + (d/2)EM^2$, $EM = \sum_i em_i(x_i, a_{ei})$ marking the aggregate amount of emissions. For the sake of simplification, assume that neither the producers nor the consumers of the considered good are affected by the environmental damage.

Apart from removing damage cost uncertainty, the structure of information is modelled along the lines of Weitzman (1974). End-of-pipe abatement costs are perfectly known by the firms, but include, for the regulator, a stochastic element θ with familiar density $dF(\theta)$.[6] According to Weitzman, θ does not arise from genuine randomness within the firms' abatement process. Rather, it reflects the regulator's information gap; that is, the latter perceives $c_e(a_{ei}, \theta)$ as an estimate or approximation.[7] The present paper adheres to this interpretation, so in the remainder, θ and the related risk always refers to the regulator's perception.

Without loss of generality, θ is standardised so that its expectation is zero, that is, $E[\theta] = 0$ and thus $Var[\theta] = E[\theta^2]$. Obviously, θ generates an additive shock to the marginal end-of-pipe abatement costs. As there is only one end-of-pipe technology available, the cost shocks are perfectly correlated among the firms. The present paper focuses on that special case in order to present the central point of the combined impact of uncertainty and market power on the optimal instrument choice as simply as

[5] This approach is rather rare in the respective literature; see for example Ebert (1992). Most models are based on a non-separable cost function $c(x_i, em_i)$ or $c(x_i, a_{ei})$ respectively, which accounts for the fact that total abatement given a positive output level usually involves prohibitively high costs; see for example Requate (2005). However, this way of modelling is necessarily associated with non-linear marginal costs and is thus incompatible with the framework given in Weitzman (1974).

[6] Note that not only θ itself, but every function entered by θ is a random variable. In order to highlight this insight, θ will be explicitly listed as an argument of these functions.

[7] In consideration of this structure of information, the mechanism design literature provides approaches to elicit the private information of firms. However, these usually induce administrative costs that are much higher than those of the conventional instruments; see for example Glachant (1998). Thus, the implementation of mechanisms instead of emission standards or taxes cannot be recommended without carefully taking into account the respective administrative costs, which again goes beyond the scope of this paper.

possible. Other than the regulator's end-of-pipe abatement cost uncertainty, there is no information problem for any agent.

Environmental regulation can be described as a Stackelberg game. Since the regulator usually possesses sovereign authority, she occupies the position of the Stackelberg leader. In stage one, given the common assumption of risk-neutral preferences, the regulator chooses to implement one of the instruments – uniform absolute emission standards or uniform emission taxes – to maximise expected welfare. In stage two, the firms decide upon output and end-of-pipe abatement effort. Throughout the paper it is assumed that the emissions generated by each firm can be perfectly monitored by the regulator without any costs. Moreover, the regulator can induce the firms to meet the instrument-specific demands by credibly threatening an adequate fine for the case of disobeying. Thus, any room for moral hazard is ruled out.[8]

Similar to Weitzman (1974) and the associated literature, the analysis restricts itself to the interior solution, that is, to that subgame perfect equilibrium that comprises positive output and end-of-pipe abatement levels of all the firms; end-of-pipe cost uncertainty would otherwise be obsolete in considering the optimal instrument choice.

3. Perfect competition

This section shows that introducing a perfectly competitive product market in the framework established by Weitzman (1974) does not change his policy rule. Section 3.1 derives the coefficient of the instruments' comparative advantage, which is investigated in Section 3.2.

3.1 Optimal instrument choice

Backwards induction begins at the second stage. Facing uniform absolute emission standards, the firms choose output and end-of-pipe abatement levels to maximise profits, regarding the constraint that their emissions must not exceed the level s.[9]

$$\max_{\{x_i, a_{ei}\}} \quad \pi_i^{PC}(x_i, a_{ei}, \theta) = R^{PC}(x_i) - c_p(x_i) - c_e(a_{ei}, \theta) \quad s.t. \quad em_i(x_i, a_{ei}) \le s \qquad (1)$$

$R^{PC}(x_i) = px_i$ represents the individual revenue. Seeing that profit maximisation requires that the constraint is binding, the first order condition can be stated as

$$(1/\varepsilon)\left(\partial\left(R^{PC}(x_i) - c_p(x_i)\right)/\partial x_i\right) = \partial c_e(a_{ei}, \theta)/\partial a_{ei}\Big|_{a_{ei} = \varepsilon x_i - s} \qquad (2)$$

As the firms have two abatement options available, namely output shortage and end-of-pipe abatement, which are, due to the cost structure, independent from each other,

[8] Montero (2002) reconsiders Weitzman (1974) for the case of incomplete enforcement.
[9] The modus of uniform absolute emission standards is chosen for two reasons. First, it is the standards' prototype taken for granted in the respective literature and thus allows for the comparability of results; see Helfand (1991). Second, it keeps the model tractable while enabling the capture of the standards' inherent inefficiency, which emerges when polluters are heterogeneous (see Section 5). The constraint within (1) reflects the common way of modelling uniform absolute emission standards; see for example Helfand (1991).

(2) requires bringing the associated marginal costs in line. The marginal costs of output shortage are simply given by the loss of producing one less unit, that is, the marginal loss of revenue less the marginal saving of production costs (left hand side of (2)). The marginal costs of the end-of-pipe option on the right hand side of (2) are self-explanatory. Taking the demand side into account as well gives the equilibrium quantities of output, end-of-pipe abatement and emissions depending on *s*:[10]

$$x^{PC}(s,\theta)=\frac{B-C-\varepsilon(Z+\theta-zs)}{bn+z\varepsilon^{2}+c},\ a_e^{PC}(s,\theta)=\varepsilon x^{PC}(s,\theta)-s,\ em^{PC}(s)=s \qquad (3)$$

Standards force the firms to coordinate their output and end-of-pipe decision in order to comply with the binding emission constraint in (1). Hence, firms fix x_i and a_{ei} simultaneously, which entails two implications. On the one hand, the regulator can enforce the designated emission level despite her lack of information. However, she is uncertain about the way in which firms split their total abatement burden between the two options of reducing emissions; from her point of view, both equilibrium output and end-of-pipe abatement effort are random. On the other hand, all the equilibrium quantities depicted in (3) depend on *s*. The relations $\partial x^{PC}(s,\theta)/\partial s>0$, $\partial a_e^{PC}(s,\theta)/\partial s<0$ and $\partial em^{PC}(s)/\partial s>0$ require no explanation.

In the tax regime, firms have to pay a rate of *t* per emission unit discharged into the environment. So their problem reads

$$\max_{\{x_i,a_{ei}\}}\quad \pi_i^{PC}(x_i,a_{ei},\theta)=R^{PC}(x_i)-c_p(x_i)-c_e(a_{ei},\theta)-t\,em_i(x_i,a_{ei}) \qquad (4)$$

The profit maximising strategy brings the marginal costs of each abatement option in line with the tax rate as follows:

$$(1/\varepsilon)\left(\partial\left(R^{PC}(x_i)-c_p(x_i)\right)/\partial x_i\right)=t=\partial c_e(a_{ei},\theta)/\partial a_{ei} \qquad (5)$$

Contrary to standards, firms set x_i and a_{ei} independently from each other according to (5), which is why the tax regulated equilibrium comprises random emission and end-of-pipe abatement but deterministic output quantities from the regulator's perspective. For the same reason, all the equilibrium quantities are functions of *t*:

$$x^{PC}(t)=\frac{B-C-\varepsilon t}{bn+c},\ a_e^{PC}(t,\theta)=\frac{t-Z-\theta}{z},\ em^{PC}(t,\theta)=\varepsilon x^{PC}(t)-a_e^{PC}(t,\theta) \qquad (6)$$

Not surprisingly, the following relations hold: $\partial x^{PC}(t)/\partial t<0$, $\partial a_e^{PC}(t,\theta)/\partial t>0$ and $\partial em^{PC}(t,\theta)/\partial t<0$. The fact that standards produce a random output but a deterministic emission level and the exact opposite applies for taxes drives the difference in the instrument-specific expected welfare levels (see Section 3.2 for further explanation).

[10] Since the equilibrium quantities are identical for all the firms, the subscript '*i*' can be omitted. The equilibrium output given in (3) similarly defines the equilibrium abatement effort in terms of output shortage compared to the unregulated equilibrium.

Next, social welfare is defined as the sum of consumers' surplus and firms' total revenue net of the aggregate costs of production, end-of-pipe abatement and environmental damage:[11]

$$W(\boldsymbol{x},\boldsymbol{a_e},\theta)=\int p(X)dX-\sum_i c_p(x_i)-\sum_i c_e(a_{ei},\theta)-C_D(EM) \tag{7}$$

The regulator's problem in stage one is to set *s* or *t* respectively, so that the *expectation* of (7) is maximised given the firms' responses in the second stage, (3) and (6). This problem can be equivalently restated along the lines of Weitzman (1974), by minimising the *expectation* of

$$\left(\int_0^{X^{PC}} p(X)dX-nc_p\left(x^{PC}\right)\right)-\left(\int_0^{X} p(X)dX-\sum_i c_p(x_i)\right)+\sum_i c_e(a_{ei},\theta)+C_D(EM), \tag{8}$$

the sum of the aggregate abatement and damage costs. While damage costs are obviously represented by $C_D(EM)$ within the present setting, the aggregate abatement costs need to be specified more precisely, as Weitzman (1974) only considers one abatement option. From the social perspective, emission reduction via output shortage causes opportunity costs or abatement costs respectively according to the related loss of consumers' and producers' surplus as compared to the unregulated aggregate equilibrium output $X^{PC}=n(B-C)/(bn+c)$. Additionally, aggregate abatement costs comprise the sum of the firms' end-of-pipe costs.[12] The equivalence between (7) and (8) turns out to play an essential role for checking whether Weitzman's rule holds within the present framework.

Hence, the optimal standard s^{*PC} fulfils the familiar first order condition of balancing the expected marginal saving of aggregate abatement costs and marginal damage costs:

$$E\left[\begin{array}{l} p\left(X^{PC}(s,\theta)\right)\dfrac{\partial X^{PC}(s,\theta)}{\partial s}-n\dfrac{\partial c_p\left(x^{PC}(s,\theta)\right)}{\partial x^{PC}(s,\theta)}\dfrac{\partial x^{PC}(s,\theta)}{\partial s}- \\ -n\dfrac{\partial c_e\left(a_e^{PC}(s,\theta),\theta\right)}{\partial a_e^{PC}(s,\theta)}\dfrac{\partial a_e^{PC}(s,\theta)}{\partial s} \end{array}\right]=\frac{\partial C_D(ns)}{\partial s} \tag{9}$$

Assuming that the tax revenue will be burned out such that it causes no distortions within the market in question, the optimal tax rate t^{*PC} satisfies

$$\begin{array}{l} p\left(X^{PC}(t)\right)\dfrac{\partial X^{PC}(t)}{\partial t}-n\dfrac{\partial c_p\left(x^{PC}(t)\right)}{\partial x^{PC}(t)}\dfrac{\partial x^{PC}(t)}{\partial t}- \\ -nE\left[\dfrac{\partial c_e\left(a_e^{PC}(t,\theta),\theta\right)}{\partial a_e^{PC}(t,\theta)}\dfrac{\partial a_e^{PC}(t,\theta)}{\partial t}\right]=\dfrac{\partial C_D\left(E\left[EM^{PC}(t,\theta)\right]\right)}{\partial E\left[EM^{PC}(t,\theta)\right]}\dfrac{\partial E\left[EM^{PC}(t,\theta)\right]}{\partial t} \end{array} \tag{10}$$

---

[11] In what follows, bold print variables represent vectors $\in \Re^n$, which comprise all of the firms' implementations of a specific control variable.

[12] Keep in mind the assumption that the market for end-of-pipe inputs is perfectly competitive and thus a given end-of-pipe effort causes the same costs at the firm and social levels (see Section 2).

which can be interpreted analogously to (9). Solving for s^{*PC} and t^{*PC} explicitly is straightforward. However, it yields tedious expressions but no further insights and is thus omitted.

It is natural to define the comparative advantage of standards over taxes under perfect competition as the ex ante expected difference in social welfare generated by s^{*PC} and t^{*PC}:

$$\begin{aligned} \Delta^{PC} &= E\left[W\left(\boldsymbol{x}^{\boldsymbol{PC}}\left(s^{*PC},\theta\right),\boldsymbol{a}_{\boldsymbol{e}}^{\boldsymbol{PC}}\left(s^{*PC},\theta\right),\theta\right)-W\left(\boldsymbol{x}^{\boldsymbol{PC}}\left(t^{*PC}\right),\boldsymbol{a}_{\boldsymbol{e}}^{\boldsymbol{PC}}\left(t^{*PC},\theta\right),\theta\right)\right]= \\ &= n^2 Var[\theta]\left(\frac{d-\alpha^{PC}}{2z^2}\right) \qquad \text{where} \quad \alpha^{PC}=\frac{z(bn+c)}{n\left(bn+z\varepsilon^2+c\right)} \end{aligned} \tag{11}$$

From this follows:

Proposition 1. *Within the model framework depicted in Section 2, the optimal choice between emission standards and taxes for regulating perfectly competitive polluters with uncertain abatement costs obeys the following policy rule: Standards should be preferred to taxes if and only if* $\Delta^{PC} > 0 \quad \Leftrightarrow \quad d > \alpha^{PC}$*, and vice versa, provided that both the optimal standard* s^{*PC} *and tax* t^{*PC} *meet the demands of the interior solution; that is, induce each firm to implement a positive equilibrium output and end-of-pipe abatement level.*

3.2 Examining the coefficient of comparative advantage

Naturally, the key question is whether the result depicted in proposition 1 conforms to the renowned policy rule established in Weitzman (1974). The latter suggests that standards should be preferred to taxes if and only if marginal damage costs run steeper than marginal abatement costs, and vice versa. What does Weitzman's rule look like when translated into the present framework? To answer this question, it is necessary to identify the essential components of this rule – the marginal damage and abatement cost function's slope. It is clear that the former corresponds to *d*. However, figuring out the counterpart of Weitzman's abatement cost concept is somewhat more demanding. His analysis considers only one possibility of reducing emissions and assumes that the firms' abatement costs perfectly represent the corresponding costs that occur at the social level. As Weitzman additionally allows for individually set standards in the case of asymmetric polluters, the overall abatement effort is always rendered efficiently in his setting, regardless of whether it is enforced through standards or taxes. Consequently, deriving the equivalent to Weitzman's abatement cost concept, the minimised aggregate abatement cost function $C_A^{min\,PC}(A,\theta)$, can be accomplished by solving the following problem:

$$\begin{aligned} &\min_{\{\boldsymbol{x},\boldsymbol{a_e}\}} \left(\int_0^{X^{PC}} p(X)dX - nc_p\left(x^{PC}\right)\right)-\left(\int_0^{X} p(X)dX-\sum_i c_p(x_i)\right)+\sum_i c_e(a_{ei},\theta) \\ &\quad s.t. \quad EM^{PC}-EM=A \end{aligned} \tag{12}$$

(12) requires minimising the aggregate abatement costs subject to a given overall abatement effort *A*, i.e. the emission reduction compared to the unregulated aggregate

level $EM^{PC} = \varepsilon X^{PC}$.[13] Keep in mind that the aforementioned costs comprise the loss of consumers' and producers' surplus, relative to the unregulated aggregate equilibrium output X^{PC}, as well as total end-of-pipe abatement costs. Finally, reinserting results into (12) produces $C_A^{min\,PC}(A,\theta)$. The associated marginal cost function reads

$$\partial C_A^{min\,PC}(A,\theta)/\partial A = (Z+\theta)(n\alpha^{PC}/z) + \alpha^{PC} A \qquad (13)$$

From proposition 1 and $\partial^2 C_A^{min\,PC}(A,\theta)/\partial A^2 = \alpha^{PC}$ immediately follows:

Corollary 1. *The inclusion of a perfectly competitive product market does not change policy rule established by Weitzman (1974) for the optimal choice of standards vs. taxes with uncertain abatement costs.*

This result stands to reason, as all the mandatory qualifications of Weitzman's rule are given in the present framework: The quadratic form of the cost and utility functions and the additivity of the shock to marginal abatement costs are met by assumption. Furthermore, the congruence of the costs occurring at the firm and social level is fulfilled for perfectly competitive markets by definition. So by using the adequate abatement cost concept, $C_A^{min\,PC}(A,\theta)$, and utilising the equivalence between maximising the expectation of social welfare (7) and minimising the expectation of total costs (8) (see Section 3.1), the model can be transferred to Weitzman's original framework. Within this framework, the regulator simply uses standards or taxes to enforce that (aggregate) abatement effort, or, in terms of Weitzman, that amount of the environmental commodity, which equalises marginal damage and expected marginal abatement costs, that is, $-\partial C_D(EM^{PC} - A)/\partial A = E[\partial C_A^{min\,PC}(A,\theta)/\partial A]$. Hence, standards should be preferred over taxes when marginal damage costs run steeper than marginal abatement costs ($d > \alpha^{PC}$) for the familiar reasons (see Section 1).[14] Finally, note that the number of firms *n* is irrelevant for corollary 1 to hold, the crucial point is rather that they act as price takers.[15]

Beyond revealing that Weitzman's rule can be generalised for the case of two abatement options, the introduction of the perfectly competitive product market provides some additional insights concerning the instruments' specific features in allocating the various risks that accompany regulation and minimising the different kinds of expected costs. For that purpose, the coefficient of comparative advantage Δ^{PC} can be decomposed into the standards' and taxes' difference with respect to expected utility of consumption (Δ_1^{PC}), expected production costs (Δ_2^{PC}), expected end-of-pipe costs (Δ_3^{PC}) and expected damage costs (Δ_4^{PC}); see Table 1.

[13] Of course, the unregulated output and emission level vary with the specific market form.
[14] For a graphical illustration, see Adar and Griffin (1976).
[15] Indeed, *n* turns out to be a relevant determinant for the relation between Weitzman's original rule and its modification in cases of market power; see Section 4.2, corollary 3.

Components'…		
…general form	…specific form	…sign
$\Delta_1^{PC} = E[\ \int p(X^{PC}(s^{*PC},\theta))d(\cdot) - \int p(X^{PC}(t^{*PC}))d(\cdot)\ ]$	$-\frac{b}{2}Var[\theta]\left(n\frac{\partial x^{PC}(s,\theta)}{\partial\theta}\right)^2$	< 0
$\Delta_2^{PC} = nE[\ c_p(x^{PC}(s^{*PC},\theta)) - c_p(x^{PC}(t^{*PC}))\ ]$	$n\frac{c}{2}Var[\theta]\left(\frac{\partial x^{PC}(s,\theta)}{\partial\theta}\right)^2$	> 0
$\Delta_3^{PC} = nE[\ c_e(a_e^{PC}(s^{*PC},\theta),\theta) - c_e(a_e^{PC}(t^{*PC},\theta),\theta)\ ]$	$nVar[\theta]\left(\begin{array}{l}\frac{\partial a_e^{PC}(s,\theta)}{\partial\theta} - \frac{\partial a_e^{PC}(t,\theta)}{\partial\theta} + \\ +\frac{z}{2}\left(\left(\frac{\partial a_e^{PC}(s,\theta)}{\partial\theta}\right)^2 - \left(\frac{\partial a_e^{PC}(t,\theta)}{\partial\theta}\right)^2\right)\end{array}\right)$	> 0
$\Delta_4^{PC} = E[\ C_D(ns^{*PC}) - C_D(EM^{PC}(t^{*PC},\theta))\ ]$	$-\frac{d}{2}Var[\theta]\left(n\frac{\partial em^{PC}(t,\theta)}{\partial\theta}\right)^2$	< 0
$\Delta^{PC} = \Delta_1^{PC} - \sum_{i=2}^{4}\Delta_i^{PC}$	$= n^2Var[\theta]\left(\frac{d-\alpha^{PC}}{2z^2}\right)$	$sgn\{d-\alpha^{PC}\}$

Table 1: Decomposing the coefficient of comparative advantage

Analysing the comparative advantage of instruments for every single component of Δ^{PC} leads to the following results. Since the quasi-linear utility function reflects consumers' risk aversion, it is obvious that taxes, which guarantee a certain equilibrium output contrary to standards, provide a higher expected utility of consumption, that is, $\Delta_1^{PC} < 0$. The taxes' dominance in this respect increases with the degree of risk aversion (measured by *b*)[16] and uncertainty (measured by $Var[\theta]$), as well as the strength of the random variable's impact on the standard regulated output, $\left|\partial x^{PC}(s,\theta)/\partial\theta\right| = \left|-\varepsilon/(bn + z\varepsilon^2 + c)\right|$. Moreover, the number of firms *n* plays a role similar to that of $Var[\theta]$. A larger *n* simply means that from the regulator's perspective, the amount of uncertain choices increases, and thus the overall level of uncertainty goes up, which raises $\left|\Delta_1^{PC}\right|$ as well.

Due to the quadratic form of $c_p(x_i)$, the certain tax regulated output causes necessarily lower expected production costs than the random standard regulated output: $\Delta_2^{PC} > 0$. Δ_2^{PC} is positively correlated with the curvature of $c_p(x_i)$ (measured by *c*), $Var[\theta]$, *n* and $\left|\partial x^{PC}(s,\theta)/\partial\theta\right|$.

Explaining the sign of the third component turns out to be more complex. At first, note that the end-of-pipe abatement effort, unlike output, is subject to uncertainty for both standards and taxes. However, a shock influences the end-of-pipe effort to a greater extent in the tax regime: $\left|\partial a_e^{PC}(s,\theta)/\partial\theta\right| = \left|-\varepsilon^2/(bn + z\varepsilon^2 + c)\right| < \left|\partial a_e^{PC}(t,\theta)/\partial\theta\right| = \left|-1/z\right|$. This is simply because for taxes, the shock fully affects the end-of-pipe effort (firms fix x_i and a_{ei} separately), whereas the shock splits between output and end-of-pipe for

16 As the Arrow-Pratt coefficient of the consumers' absolute risk aversion reads $r_U(X) = \frac{\partial^2 U(\cdot)/\partial X^2}{\partial U(\cdot)/\partial X} = \frac{b}{B - bX} > 0$ and obviously $\frac{\partial r_U(X)}{\partial b} = \frac{B}{(B - bX)^2} > 0$, the consumers' risk aversion is positively correlated with *b*. For the Arrow-Pratt coefficient, see for example Mas-Colell, Whinston and Green (1995).

standards (here firms fix x_i and a_{ei} simultaneously). In contrast to the utility and production cost function, θ is an argument of the end-of-pipe cost function. It is therefore desirable from the regulator's point of view that firms adjust their end-of-pipe effort to a greater extent if costs are unexpectedly high or low. Hence, taxes are preferable in this regard: $\Delta_3^{PC} > 0$. The gap between the standards' and taxes' expected end-of-pipe costs increases as the curvature of $c_e(a_{ei}, \theta)$ (measured by *z*)[17] shrinks and $Var[\theta]$ grows. Moreover, for familiar reasons $\Delta_3^{PC} > 0$ is positively correlated with the number of firms and to the difference between the standards' and taxes' end-of-pipe abatement sensitivity concerning the shock $\partial a_e^{PC}(s,\theta)/\partial\theta - \partial a_e^{PC}(t,\theta)/\partial\theta = (bn + c)/z(bn + z\varepsilon^2 + c)$.
While all the components of Δ^{PC} analysed so far favour taxes, standards are superior in minimising expected damage costs: $\Delta_4^{PC} < 0$. Due to the quadratic form of $C_D(EM)$ and the associated risk aversion on the part of the victims of pollution regarding the emission level, standards perform better than taxes, as they ensure a deterministic degree of pollution. The advantage for standards gains weight with rising degrees of risk aversion (measured by *d*),[18] uncertainty (measured by $Var[\theta]$) and θ's influence on the tax regulated emissions $\partial em^{PC}(t,\theta)/\partial\theta = 1/z$. The same applies to a growing number of firms *n*.
Naturally, subtracting all the cost components from the utility component must yield the overall difference of the standards' and taxes' expected welfare (see the last row of Table 1).
To summarise the previous analysis, it can be stated that taxes exhibit superior performance in terms of minimising the consumers' risk with respect to consumption ($\Delta_1^{PC} < 0$) as well as in causing a lower level of expected production and end-of-pipe costs ($\Delta_2^{PC} > 0$, $\Delta_3^{PC} > 0$). On the other hand, standards are superior for coping with the pollution victims' risk aversion with regards to environmental damage ($\Delta_4^{PC} < 0$). The single parameters' impact on this trade-off emanates from (11): $Var[\theta]$ determines the level of each component Δ_i^{PC} in equal measure and thus the level of Δ^{PC} as well, but not its sign. Hence, the question of optimal instrument choice depends solely on the proportion of *d* and α^{PC}, the slopes of the marginal damage costs and the minimised marginal aggregate abatement costs. The positive correlation between *d* and the performance of standards has already been shown earlier, while, for familiar reasons, the taxes' relative superiority is boosted as α^{PC} grows. It is straightforward to show that $\partial\alpha^{PC}/\partial\varepsilon < 0$, $\partial\alpha^{PC}/\partial n < 0$ and $\partial\alpha^{PC}/\partial b > 0$, $\partial\alpha^{PC}/\partial c > 0$, $\partial\alpha^{PC}/\partial z > 0$. The explanation of these relations is depicted in Appendix 1.

[17] This effect is of the same nature as the 'curvature effects' related to *b* and *c*.
[18] The positive correlation between the pollution victims' risk aversion and *d* can be proved in a manner similar to the positive correlation between the consumers' risk aversion and *b* (see footnote 16).

4. Cournot oligopoly

While adhering to the previous model framework, this section assumes that the polluting firms compete à la Cournot and thereby reveals the bias of Weitzman's policy rule in the presence of market power. The oligopolistic output shortage constitutes an additional distortion apart from the external diseconomies of pollution. Thus, even under certainty, a first-best solution could only be achieved by flanking standards or taxes with a subsidy on output (Baumol and Oates, 1988). However, this option is ruled out on the grounds that it is politically untenable. Restricting the analysis to the interior solution defined in Section 2 implies that the distorting pollution outweighs the oligopolistic output shortage. In this sense, both the optimal standard and tax induce a decrease in the firms' output compared to the unregulated equilibrium.[19] Otherwise, regulation would most likely not be within the scope of environmental policy.

4.1 Optimal instrument choice

The calculation of the subgame perfect equilibrium follows the approach of Section 3.1, except for one crucial difference. Now that firms are aware of their influence on the market price, and hence fix their output level in a Cournot manner, it is no longer the revenue function $R^{PC}(x_i) = px_i$ but rather $R^{CO}(\boldsymbol{x}) = p(X_{-i} + x_i)x_i$ which becomes part of the firms' profit maximisation problem. Adjusting and solving the respective first order conditions simultaneously gives the Cournot-Nash equilibrium quantities for standards

$$x^{CO}(s,\theta) = \frac{B - C - \varepsilon(Z + \theta - zs)}{b + bn + z\varepsilon^2 + c},\ a_e^{CO}(s,\theta) = \varepsilon x^{CO}(s,\theta) - s,\ em^{CO}(s) = s \tag{14}$$

and taxes

$$x^{CO}(t) = \frac{B - C - \varepsilon t}{b + bn + c},\ a_e^{CO}(t,\theta) = \frac{t - Z - \theta}{z},\ em^{CO}(t,\theta) = \varepsilon x^{CO}(t) - a_e^{CO}(t,\theta) \tag{15}$$

In stage one, the regulator determines the optimal standard s^{*CO} and tax t^{*CO} by maximising the expectation of social welfare (7) subject to (14) and (15), respectively.[20] Their explicit illustration is abandoned for the familiar reasons. The appropriate coefficient of the instruments' comparative advantage can be written as

$$\begin{aligned}\Delta^{CO} &= E\left[W\left(\boldsymbol{x}^{\boldsymbol{co}}(s^{*CO},\theta), \boldsymbol{a}_{\boldsymbol{e}}^{\boldsymbol{co}}(s^{*CO},\theta),\theta\right) - W\left(\boldsymbol{x}^{\boldsymbol{co}}(t^{*CO}), \boldsymbol{a}_{\boldsymbol{e}}^{\boldsymbol{co}}(t^{*CO},\theta),\theta\right)\right] = \\ &= n^2 Var[\theta]\left(\frac{d - \alpha^{CO}}{2z^2}\right)\end{aligned}$$

$$\text{where}\quad \alpha^{CO} = \frac{z\left(b^2(1+n)^2 + bnz\varepsilon^2 + 2bc(1+n) + c(z\varepsilon^2 + c)\right)}{n(b + bn + z\varepsilon^2 + c)^2} \tag{16}$$

[19] Both an optimal standard and an optimal tax meeting the demands of the interior solution – and thus inducing a positive end-of-pipe abatement effort of all the firms – inevitably lead to a decrease in firms' output compared to the unregulated equilibrium.

[20] Of course the problem can be restated to minimise total costs, as in cases of perfect competition; see (8).

which results in:

Proposition 2. *Within the model framework depicted in Section 2, the optimal choice between emission standards and taxes for regulating a polluting symmetric Cournot oligopoly with uncertain abatement costs obeys the following policy rule: Standards should be preferred to taxes if and only if* $\Delta^{CO} > 0 \quad \Leftrightarrow \quad d > \alpha^{CO}$*, and vice versa, provided that both the optimal standard* s^{*CO} *and tax* t^{*CO} *meet the demands of the interior solution; that is, they induce each oligopolist to implement a positive output and end-of-pipe abatement level in the Cournot-Nash equilibrium.*

This rule can be adapted to a monopolistic polluter by simply setting $n = 1$ within Δ^{CO}.

4.2 Examining the coefficient of comparative advantage

Once again, it is first appropriate to check whether proposition 2 is consistent with Weitzman's policy rule. The minimised aggregate abatement cost function for symmetric Cournot oligopoly $C_A^{min\,CO}(A,\theta)$, that is, Weitzman's respective abatement cost concept (see Section 3.2), results from (12), using the appropriate unregulated total output and emission levels $X^{CO} = n(B-C)/(b+bn+c)$ and $EM^{CO} = \varepsilon X^{CO}$. As these are smaller than in the perfectly competitive setting, the related marginal cost function

$$\frac{\partial C_A^{min\,CO}(A,\theta)}{\partial A} = (Z+\theta)(n\alpha^{PC}/z) + \frac{bz\varepsilon(B-C)}{(b+bn+c)(bn+z\varepsilon^2+c)} + \alpha^{PC}A \qquad (17)$$

is necessarily at a higher level than its counterpart under perfect competition, $\partial C_A^{min\,PC}(A,\theta)/\partial A$, but exhibits the same slope. Consequently, Weitzman's rule still tends to prefer standards over of taxes for $d > \alpha^{PC}$, and vice versa. Since it is straightforward to show that $\alpha^{CO} > \alpha^{PC}$, this suggestion differs from the proper criterion for the optimal instrument choice stated in proposition 2, which gives rise to:

Corollary 2. *Applying Weitzman's rule to a symmetric Cournot oligopoly runs the risk of wrongly choosing standards instead of taxes whenever* $\alpha^{CO} > d > \alpha^{PC}$*. An aberrant implementation of taxes is once again impossible since* $\alpha^{CO} > \alpha^{PC}$*.*

Obviously, the emergence of market power shifts the comparative advantage of instruments in favour of taxes relative to perfect competition. Why is this true? The fact that Cournot oligopolists take into account the influence of their output decision on the equilibrium price annihilates the congruence between the firms' and society's marginal costs of output shortage, which is given in the perfectly competitive setting and implicitly assumed by Weitzman (1974), in the following way:

First, a Cournot oligopolist's marginal costs of output shortage – contrary to a price-taking firm – only cover a portion of the associated costs at the social level. To clarify that point, first consider the benchmark set by a price-taking firm with marginal costs of output reduction $\partial(R^{PC}(x_i) - c_p(x_i))/\partial x_i = p - (C + cx_i)$, the marginal loss of revenue minus the marginal saving of production costs (see (2) or (5)). Under perfect competition, the marginal (loss of) revenue just corresponds to the equilibrium price – tantamount to the firm's residual inverse demand $p(X_{-i}+x_i)=a-bX_{-i}-bx_i$. For that reason, the firm's loss resulting from one less unit being produced is congruent to the associated social opportunity costs – the marginal decrease of consumers' and producers' surplus.[21] Since an oligopolist, in contrast, is aware of her influence on the market price, she faces marginal output shortage costs of $\partial\left(R^{CO}(\boldsymbol{x})-c_p(x_i)\right)/\partial x_i =$ $=\partial\left(p(X_{-i}+x_i)x_i-c_p(x_i)\right)/\partial x_i = a-bX_{-i}-2bx_i-(C+cx_i)$. As illustrated in Figure 1, these only capture the marginal loss of consumers' and producers' surplus in parts.

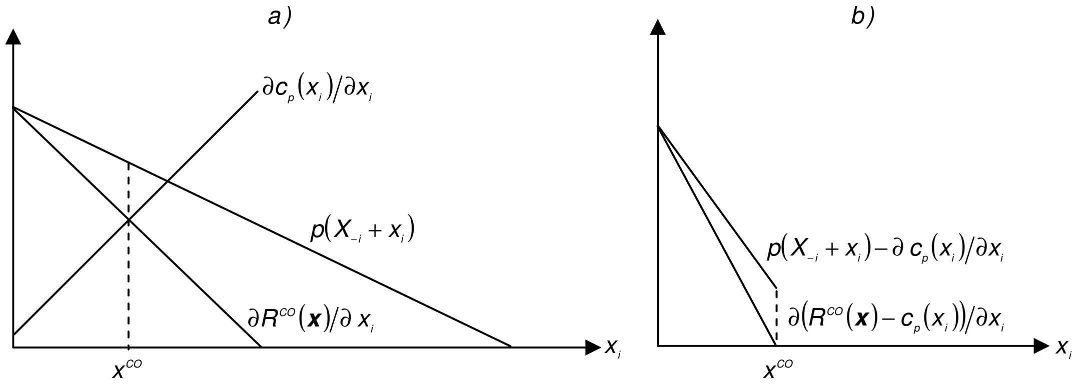

Figure 1: Oligopolist's vs. society's marginal costs of output shortage

This necessarily implies an inefficient combination of the two abatement options; each oligopolist balances her option-specific marginal abatement costs, and thus from a welfare perspective renders a too large share of the overall abatement burden via output shortage and a too low share via end-of-pipe. That is, she exploits her market power to pass a part of the abatement costs on to consumers through the output channel. However, this inefficiency is irrelevant to the optimal instrument choice as it effects standards and taxes equally.[22] Both instruments produce the same aggregate abatement cost function $C_A^{CO}(A,\theta)$ which consequently runs above the minimised aggregate abatement cost function $C_A^{min\,CO}(A,\theta)$; see Figure 2a below.[23]

Second, the Cournot behaviour of firms makes their marginal output shortage costs react more sensitively to changes in the production level than would otherwise be the case under perfect competition. Hence, the oligopolist's marginal costs exhibit a higher absolute slope ($2b+c$) than those of the price-taking firm ($b+c$); see Figure 1b. Naturally, this relation carries over to the aggregate marginal abatement costs; the realisable function in the case of Cournot oligopoly runs steeper than the minimised function

[21] Remember that the input needed for production is assumed to be produced in a perfectly competitive market as well.

[22] See Appendix 2 for the proof.

[23] $C_A^{co}(A,\theta)$ can be easily calculated by plugging the quantities of the standard or tax regulated Cournot-Nash equilibrium, stated as functions of the aggregate abatement effort A, $\boldsymbol{x}^{co}(s^{co}(A),\theta)=\boldsymbol{x}^{co}(t^{co}(A,\theta))$ and $\boldsymbol{a}_e^{co}(s^{co}(A),\theta)=\boldsymbol{a}_e^{co}(t^{co}(A,\theta),\theta)$, see Appendix 2, into the equation of aggregate abatement costs defined by (12) – of course using the appropriate unregulated output level for the case of Cournot oligopoly, X^{co}. It is straightforward to show that $C_A^{co}(A,\theta)>C_A^{min\,co}(A,\theta)$ for any A satisfying the interior solution.

given under perfect competition. Thus $\partial^2 C_A^{CO}(A,\theta)/\partial A^2 = \alpha^{CO} > \partial^2 C_A^{min\,CO}(A,\theta)/\partial A^2 = \partial^2 C_A^{min\,PC}(A,\theta)/\partial A^2 = \alpha^{PC}$ (see Figure 2b).[24]

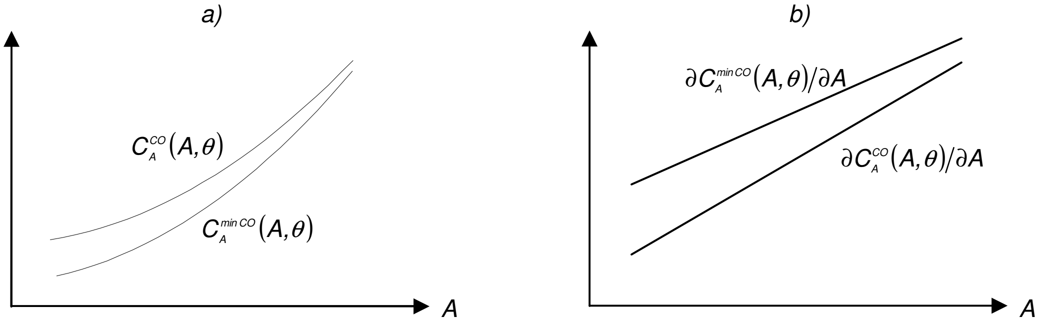

Figure 2: Aggregate (marginal) abatement costs: Efficient abatement vs. Cournot oligopoly

As stated in proposition 2, the optimal instrument choice depends on the relation *d* vs. α^{CO}, contrary to perfect competition and the suggestion of Weitzman's rule (*d* vs. α^{PC}), which reflects the taxes' increased comparative advantage vs. standards due to market power. This shift in favour of taxes can be explained from two different points of view. On the one hand, the increased slope of the aggregate marginal abatement cost function suggests that the overall tax regulated abatement effort and similarly the emission level in cases of Cournot competition is more rigid with respect to changes in the tax rate and hence less vulnerable to miscalculations of the tax rate due to the regulator's information problem:

$$\left|\partial EM^{PC}(t,\theta)/\partial t\right| - \left|\partial EM^{CO}(t,\theta)/\partial t\right| = nb\varepsilon^2/(bn+c)(b+bn+c) > 0 \qquad (18)$$

On the other hand the aforementioned increased slope signals that in the presence of the oligopolistic output shortage, standards which ex post turn out to be suboptimally low lead to a more severe increase in aggregate abatement costs, including the loss of consumers' and producers' surplus. Consequently, the taxes' ability to provide a cap on abatement costs takes on greater significance.

Further insights can be attained by decomposing the coefficient of comparative advantage Δ^{CO} similarly to the manner used in Section 3.2 and thereby studying the market power's impact on the instrument specific characteristics concerning the allocation of risks and the minimisation of the various types of expected costs. The single components of Δ^{CO} necessarily coincide with those of Δ^{PC} depicted in Table 1, apart from the fact that the Cournot-Nash equilibrium quantities replace their counterparts that occur under perfect competition. Since the oligopolist's marginal costs of output shortage exhibit a higher absolute slope than those of the price taking-firm, the standard regu-

---

[24] $\partial C_A^{min\,CO}(A,\theta)/\partial A$ necessarily runs on a higher level than $\partial C_A^{CO}(A,\theta)/\partial A$ for the reason that the gap between the firms' and society's marginal output shortage costs and thus as well the gap between $C_A^{min\,CO}(A,\theta)$ and $C_A^{CO}(A,\theta)$ converges with decreasing output and increasing *A*, respectively; see Figure 1a and 2a.

lated output and end-of-pipe effort respond less sensitively to the shock compared to perfect competition:

$$\left|\partial x^{CO}(s,\theta)/\partial\theta\right| = \left|-\varepsilon/\left(b+bn+z\varepsilon^2+c\right)\right| < \left|\partial x^{PC}(s,\theta)/\partial\theta\right| = \left|-\varepsilon/\left(bn+z\varepsilon^2+c\right)\right| \quad (19a)$$

$$\left|\partial a_e^{CO}(s,\theta)/\partial\theta\right| = \left|-\varepsilon^2/\left(b+bn+z\varepsilon^2+c\right)\right| < \left|\partial a_e^{PC}(s,\theta)/\partial\theta\right| = \left|-\varepsilon^2/\left(bn+z\varepsilon^2+c\right)\right| \quad (19b)$$

Clearly, (19a) lowers the standards' drawback vs. the deterministic output provided by taxes in terms of maximising the expected utility of consumption and minimising the expected production costs. However, since minimising the expected end-of-pipe costs benefits from a high shock sensitivity of the end-of-pipe effort, (19b) shifts the instruments' comparative advantage in favour of taxes. Bear in mind that in the tax regime, the end-of-pipe choice is detached from the output choice, which is why market power does not influence the former's shock sensitivity. Inevitably, the same applies for tax regulated emissions.[25] Since moreover standards guarantee a certain emission level independently of market power, the instruments' relative performance in minimising expected damage costs remains unchanged. Adding up the market power's impact on all four components of Δ^{CO} shows that the shift caused by (19b) must outweigh that caused by (19a) since $\alpha^{CO} > \alpha^{PC}$. This is simply because, contrary to utility of consumption and production costs, end-of-pipe costs are themselves subject to uncertainty. Hence, the change in the end-of-pipe effort's shock sensitivity boosting the taxes' performance carries more weight than the change in the output's shock sensitivity boosting the standards' performance.

In the end, it is of vital interest for the regulator to see how the degree of market power affects the optimal instrument choice.

Corollary 3. *Since*

$$\frac{\partial\left(\alpha^{CO}-\alpha^{PC}\right)}{\partial n} = -\frac{(bz\varepsilon)^2\left(2b^2n(1+2n)+b(1+5n)\left(z\varepsilon^2+c\right)+\left(z\varepsilon^2+c\right)^2\right)}{n^2\left(bn+z\varepsilon^2+c\right)^2\left(b+bn+z\varepsilon^2+c\right)^3} < 0 \quad (20)$$

a decreasing number of firms, and therefore an increasing degree of market power reinforces the taxes' gain in comparative advantage compared to the perfectly competitive setting.

By the same token, (20) suggests that the risk of a suboptimal instrument choice, accompanied by the adaption of Weitzman's rule to a Cournot oligopoly, is positively correlated with the firms' concentration in the output market. The cause of this relation is not obscure; the fewer firms there are in the market, the stronger the oligopolist's influence is on the equilibrium price. As a result, the difference between the individual marginal output shortage costs' slope in cases of Cournot oligopoly and perfect competition increases as *n* decreases. The same is necessarily true for the aggregate marginal abatement cost function realisable under Cournot competition and the respective mini-

[25] Nevertheless, emissions become less vulnerable to miscalculations of the tax rate due to the regulator's information problem, as shown in (18).

mised function, as can be seen from (20), which reinforces the mechanisms supporting the taxes' comparative advantage.[26]

The impact of a decrease in n can in turn be broken down into the single components of the coefficient of comparative advantage. In this context, as mentioned above, the driving force of the shift in favour of taxes associated with the emergence of market power is the decrease in the standard regulated output and end-of-pipe effort sensitivity concerning the shock. The more n declines, the greater the difference between the shock sensitivity of the standard regulated equilibrium outcome in case of perfect competition and Cournot oligopoly, which strengthens the force responsible for the gain of taxes.

Furthermore, $\lim_{n\to\infty}\Delta^{PC} = \lim_{n\to\infty}\Delta^{CO} = Var[\theta](d/z^2) > 0$ reveals that the disparity between the instruments' comparative advantage for Cournot and perfect competition completely vanishes as n approaches infinity. Aggregate marginal abatement costs then become constant for both market forms, that is, $\lim_{n\to\infty}\alpha^{PC} = \lim_{n\to\infty}\alpha^{CO} = 0$. This indicates that standards perform better than taxes for any constellation of parameters.

Finally, note that the single parameters' impacts on the coefficient of comparative advantage perfectly correspond to the case of perfect competition (see Section 3.2 and Appendix 1).

5. Asymmetric firms

So far, the analysis has operated on the assumption that firms are symmetric, a severe restriction to the previous results as it cancels out the well known drawback of standards in allocating total abatement efficiently among firms. Clearly, the presumed uniform absolute standards, unlike taxes, fail to equalise the firms' marginal abatement costs and thus generate a higher level of aggregate abatement costs independent of the market structure. Weitzman (1974) removes this issue by taking for granted the rather unrealistic possibility of setting firm-specific standards that reproduce the taxes' abatement allocation.[27]

Thus, in optimally choosing between uniform standards and taxes, the regulator faces a trade off between the instruments' abatement cost difference and their expected welfare difference ascribed to uncertainty, reflected so far by Δ^{PC} and Δ^{CO}, respectively. Accordingly, the absolute value of the latter, which is positively correlated with the variance of the stochastic element $Var[\theta]$, becomes a determinant of the coefficient of comparative advantage. This indicates a fundamental difference from Weitzman (1974), who argues that the degree of the regulator's uncertainty is completely irrelevant to the optimal instrument choice. Furthermore, introducing asymmetric firms combined with uniform standards apparently shifts the comparative advantage of instruments in favour of taxes under both perfect and Cournot competition. Tisato (1994) achieves similar results by investigating 'inefficient standards' within the framework

[26] Clearly, a decrease in n also aggravates the instruments' inefficiency in combining abatement options, as it enables the firms to shift a larger part of their abatement costs to consumers. However, this effect applies to both standards and taxes and is consequently irrelevant to the optimal instrument choice.

[27] This is possible despite the regulator's lack of information because of the assumption that the cost shocks are perfectly correlated among the firms.

established by Weitzman (1974). However, he does not explicitly elaborate on the insight that $Var[\theta]$ enters the adjusted policy rule.

Appendix 3 provides formal evidence for the above findings by a simple modification of the previous model framework that allows for asymmetric firms.

6. Conclusion

By introducing the product market into the stochastic framework of Weitzman (1974), the present paper provides new insights into the comparative advantage of emission standards over taxes. In the absence of market power, Weitzman's policy rule is still the proper criterion for the optimal instrument choice. However, the present study demonstrates for the case of a symmetric Cournot oligopoly that his rule is biased when the polluting firms possess market power. Due to the associated output shortage, standards which ex post turn out to be too low raise the aggregate abatement costs, including the loss of consumers' and producers' surplus, to a greater extent than in the case of perfect competition. Hence, the taxes' ability to restrict the level of abatement costs takes on greater significance, which explains why they are preferable to standards for a larger range of parameters. Similarly, the adaption of Weitzman's rule in the presence of market power runs the risk of a suboptimal instrument choice – specifically, wrongly choosing standards instead of taxes. The taxes' gain and hence the aforesaid risk are positively correlated with the degree of market power.

These results are perfectly in line with Quirion (2004). He considers the traditional Weitzman (1974) framework within another second-best setting by introducing a pre-existing distortionary tax, which also leads to a greater comparative advantage of taxes over standards.

Abolishing the assumption of symmetric polluters yields further insights. First, the standards' well known drawback with respect to abatement efficiency becomes evident and shifts the instruments' comparative advantage in favour of taxes under both perfect and Cournot competition. Second, the extent of uncertainty, measured by the random variable's variance, turns out to be a relevant criterion for the optimal instrument choice. These effects are ruled out by the conventional uncertainty literature since the latter allows for firm-specific standards satisfying the abatement efficiency, instead of the more realistic case of uniform standards, on which the present paper is grounded.

The specificity of the model demands caution in adopting these findings to any real world regulation scenario. However, Weitzman (1974) weakened this caveat by arguing that the assumed quadratic shape of the cost and utility functions allows for an interpretation of the results as an approximation for more general functions, provided that the feasible value range of the random variable is sufficiently small.[28] Nevertheless, the most salient point for the policy maker to take away from this analysis is that in cases of abatement cost uncertainty, which is omnipresent in any pollution problem, the polluters' market power not only affects the optimal design of environmental policy instruments, but also their comparative advantage.

In terms of future research, it is clearly important to extend the analysis of the instrument of tradable emission permits. This instrument has attracted more and more atten-

[28] For a critical discussion of this point see Malcomson (1978) and Weitzman (1978).

tion in contemporary environmental policy making, as can be seen most notably in the implementation of the European Union Greenhouse Gas Emission Trading System in 2005. Since the regulation of greenhouse gases is, like many other serious pollution problems, inevitably subject to the market power of the polluting firms and cost uncertainty on the part of the policy maker, this project promises some highly relevant policy recommendations.

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.

European Environment Agency (2007), *Europe's Environment. The fourth assessment*. Online available at http://reports.eea.europa.eu/state_of_environment_report_2007_1/en/Belgrade_EN_all_chapters_incl_cover.pdf. Cited 20 Sept 2008.

Fishelson, G. (1976), 'Emission control policies under uncertainty', *Journal of Environmental Economics and Management* **3**, 189-197.

Glachant, M. (1998), 'The use of regulatory mechanism design in environmental policy: a theoretical critique'. In: Faucheux, S. et al.: *Sustainability and firms: technological change and the changing regulatory environment*. Cheltenham: Edward Elgar, 179-188.

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.

Montero, J.-P. (2002), 'Prices versus quantities with incomplete enforcement', *Journal of Public Economics* **85**, 435-454.

Quirion, P. (2004), 'Prices versus quantities in second-best setting', *Environmental and Resource Economics* **29**, 337-359.

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, R. D. (1995), 'Optimal pollution taxation in a Cournot duopoly', *Environmental and Resource Economics* **6**, 359-369.

Stavins, R. (1996), 'Correlated uncertainty and policy instrument choice', *Journal of Environmental Economics and Management* **30**, 218-232.

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.

Appendix 1

$\partial\alpha^{PC}/\partial\varepsilon < 0$: A larger ε implies more emissions per unit of output, which puts a greater emphasis on the desire of consumers for a deterministic degree of pollution guaranteed by standards.

$\partial\alpha^{PC}/\partial n < 0$: On the one hand, an increasing number of firms *n* implies a higher level of uncertainty (similarly to an increase in $Var[\theta]$), which does not impinge on the instruments' comparative advantage. On the other hand, the sensitivity of the standard regulated output and end-of-pipe effort with respect to θ declines as *n* increases. As can be seen in Table 1, the output effect benefits standards by Δ_1^{PC} and Δ_2^{PC} while the end-of-pipe effect benefits taxes, but only by Δ_3^{PC}. This is why on the whole a larger *n* makes taxes relatively less attractive.

$\partial\alpha^{PC}/\partial b > 0$, $\partial\alpha^{PC}/\partial c > 0$: The higher the curvature of the utility function, *b*, and the production cost function, *c*, the more detrimental the stochastic output level emerging in the standard regime is. Moreover, an increase in *b* or *c* reduces θ's influence on $x^{PC}(s,\theta)$ and $a_e^{PC}(s,\theta)$ in a manner similar to the reduction caused by an increase in *n*. Indeed, this effect downgrades the taxes' performance as depicted above, but it is weaker than the fist-mentioned curvature effect, which explains why the aggregate impact of a growing *b* or *c* on the taxes' performance is positive.

$\partial\alpha^{PC}/\partial z > 0$: Finally, *z* increases the end-of-pipe costs' curvature and decreases the difference between the standards' and taxes' end-of-pipe abatement sensitivity concerning the shock, which in each case suggests that standards should be chosen more often. However, there is again a dominant countervailing effect as *z* also reduces the random variable's impact on the tax-regulated emission level.

Appendix 2

To ensure that the considered instruments are comparable with respect to the efficiency of the abatement options' allocation within each firm, define

$$s^{co}(A) \quad \text{and} \tag{A2.1}$$

$$t^{co}(A) \tag{A2.2}$$

as the standard and tax that induce the oligopolists to render a given abatement effort *A* by solving $A^{co}(s) = EM^{co} - ns$ for *s* and $A^{co}(t,\theta) = EM^{co} - nem^{co}(t,\theta)$ for *t*, respectively. $s^{co}(A)$ and $t^{co}(A)$ necessarily produce exactly the same Cournot-Nash equilibrium outcome:

$$\mathbf{x}^{co}(s^{co}(A),\theta) = \mathbf{x}^{co}(t^{co}(A,\theta)) \tag{A2.3}$$

$$\mathbf{a}_e^{co}(s^{co}(A),\theta) = \mathbf{a}_e^{co}(t^{co}(A,\theta),\theta) \tag{A2.4}$$

Comparing the marginal abatement costs of output reduction and end-of-pipe, each with occurring at social level, in consideration of (A2.1) - (A2.4) yields

$$\left(\frac{1}{\varepsilon}\left(p(X) - \frac{\partial c_p(x_i)}{\partial x_i}\right) - \frac{\partial c_e(a_{ei},\theta)}{\partial a_{ei}}\right)\Bigg|_{\mathbf{x}=\mathbf{x}^{co}(s^{co}(A),\theta),\mathbf{a}_e=\mathbf{a}_e^{co}(s^{co}(A),\theta)} =$$

$$= \frac{b(B-C)}{\varepsilon(b+bn+c)} - \frac{b(n(Z+\theta)+zA)}{n(b+bn+z\varepsilon^2+c)} > 0 \tag{A2.5}$$

(A2.5) shows that the marginal abatement costs of output reduction exhibit a higher level, proving the fact that from the social perspective, each oligopolist abates too much via output shortage and too little via end-of-pipe, which applies equally to standards and taxes, given a specific overall abatement effort *A*.

To see that (A2.5) is strictly larger than zero, note the following. First, the existence of the interior solution defined in Section 2 clearly requires the reservation price, *B*, to be higher than the marginal production costs at the output level of zero, *C*. Second, (A2.5) necessarily decreases in *A*, as the gap between the social and firm-specific marginal output shortage costs shrinks as the output decreases and thus as *A* increases (see Figure 1b). However, due to the interior solution the equilibrium output is always strictly positive, which implies that the same is true for the aforementioned gap as well as for (A2.5).

Appendix 3

Consider the following slight adjustment to the model, which is intended to incorporate the uniform standards' drawback with respect to abatement efficiency as simply as possible. There are two types of firms $j = h, l$ with production costs $\tilde{c}_p^j(x_i) = C^j x_i + (c/2)x_i^2$, where $C^h > C^l$. The marginal production costs of the 'high-cost' type $j = h$ run parallel above those of the 'low-cost' type $j = l$. Assume that the types are equally distributed, implying $n/2$ firms of each type. The rest of the model framework remains unchanged. Thus, it is straightforward to calculate the subgame perfect equilibrium for the asymmetric polypoly by following the procedure in Section 3.1, which leads to the instruments' ex ante expected welfare difference

$$\tilde{\Delta}^{PC} = E\left[\tilde{W}\left(\tilde{\mathbf{x}}^{PC}\left(\tilde{s}^{*PC}, \theta\right), \tilde{\mathbf{a}}_e^{PC}\left(\tilde{s}^{*PC}, \theta\right), \theta\right) - \tilde{W}\left(\tilde{\mathbf{x}}^{PC}\left(\tilde{t}^{*PC}\right), \tilde{\mathbf{a}}_e^{PC}\left(\tilde{t}^{*PC}, \theta\right), \theta\right)\right] = \tag{A3.1}$$
$$\Delta^{PC} - \tilde{\Delta}C_A^{PC} = n^2 Var[\theta]\left(\frac{d - \alpha^{PC}}{2z^2}\right) - \tilde{\Delta}C_A^{PC}$$

where '~' marks the specific form of functions and variables which is due to the asymmetry of firms. Moreover, $\tilde{\Delta}C_A^{PC} = nz\varepsilon^2\left(C^h - C^l\right)^2 / 8c\left(z\varepsilon^2 + c\right) > 0$ denotes the difference of the standards' and taxes' aggregate abatement costs. Note that the instrument-specific aggregate abatement costs can be derived by using the same procedure as described in footnote 23, Section 4.2.

(A3.1) reveals immediately that $\tilde{\Delta}C_A^{PC}$ enters the coefficient of comparative advantage and must be traded off against the instruments' expected welfare difference ascribed to uncertainty Δ^{PC}. As the absolute value of Δ^{PC} depends on $Var[\theta]$, the degree of the regulator's uncertainty becomes a relevant factor for the optimal instrument choice, contrary to Weitzman (1974). Clearly, abolishing the assumption of symmetric firms shifts the comparative advantage of instruments in favour of taxes (given uniform standards). For the case in which marginal damage and abatement costs exhibit the same slope in absolute terms ($d = \alpha^{PC}$), the instruments are no longer equivalent, and taxes should in fact be preferred due to their advantage concerning abatement efficiency ($\tilde{\Delta}^{PC} = -\tilde{\Delta}C_A^{PC} < 0$).

The coefficient of comparative advantage for the asymmetric Cournot oligopoly can be calculated in similar manner as in the case of the asymmetric polypoly:

$$\tilde{\Delta}^{CO} = E\left[\tilde{W}\left(\tilde{\mathbf{x}}^{CO}\left(\tilde{s}^{*CO}, \theta\right), \tilde{\mathbf{a}}_e^{CO}\left(\tilde{s}^{*CO}, \theta\right), \theta\right) - \tilde{W}\left(\tilde{\mathbf{x}}^{CO}\left(\tilde{t}^{*CO}\right), \tilde{\mathbf{a}}_e^{CO}\left(\tilde{t}^{*CO}, \theta\right), \theta\right)\right] = \tag{A3.2}$$
$$\Delta^{CO} - \tilde{\Delta}C_A^{CO} = n^2 Var[\theta]\left(\frac{d - \alpha^{CO}}{2z^2}\right) - \tilde{\Delta}C_A^{CO}$$

where $\tilde{\Delta}C_A^{CO} = nz\varepsilon^2\left(C^h - C^l\right)^2\left(3b^2 + 2bz\varepsilon^2 + 4bc + z\varepsilon^2 c + c^2\right) / 8(b + c)^2\left(b + z\varepsilon^2 + c\right)^2 > 0$ represents the respective abatement cost difference between standards and taxes. The implications of introducing asymmetry are exactly the same as for the polypolistic market, that is, the taxes' gain due to market power is boosted.