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

CLEMENS HEUSON
University of Augsburg$^{\Psi}$ *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 considering the case of a polluting symmetric Cournot oligopoly, this paper shows that Weitzman's (1974) policy rule for choosing emission standards vs. taxes against the background of uncertain abatement costs is biased in the presence of market power. The latter enables the firms to shift a part of the abatement costs to consumers through the output channel, which involves a lower volatility of emissions in the tax regime compared to perfect competition. Taxes are therefore preferable to standards for a larger range of parameters. This shift within the instruments' ranking is strengthened by allowing for asymmetric firms. In each case, adequate policy rules are derived.

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$^{\Psi}$ 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 imposing a direct constraint on emission levels, i.e. implementing emission standards or tradable emission permits, or artificially establishing the non-existent price for pollution, i.e. implementing emission taxes. For a long time, economists have extensively discussed the issue as to which mode of regulation should be favoured in terms of maximising social welfare. They realised at an early stage that the answer might be crucially influenced by the regulator's uncertainty concerning damage and abatement costs, which is, de facto, given in any actual regulation setting. Initially, Weitzman (1974), Fishelson (1976) as well as Adar and Griffin (1976), and later on Stavins (1996) 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,[1] while a congruent shock to the marginal abatement cost function makes their comparative advantage solely dependant on the relative slopes of the two aforesaid marginal cost functions – assuming that the two shocks are uncorrelated.

All these studies implicitly presume that the regulated firms act in perfectly competitive markets. Evidently this 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 (23.5% - 25%) between 1995 and 2005; see 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; see Requate (2005).

It is therefore of vital importance for policy makers to comprehend the market power's impact on the optimal[2] choice of prices vs. quantities under uncertainty. For this purpose, the present paper establishes the missing link between the abovementioned uncertainty literature and the field of environmental policy under imperfect competition, which is based, amongst others, on the contributions of Buchanan (1969), Barnett (1980), Ebert (1992), Requate (1993a and b) and Simpson (1995).[3]

To avoid an unnecessarily complicated presentation, the analysis restricts itself to abatement cost uncertainty, since uncertain damage costs do not affect the firms' behaviour, and are thus 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 truly seem natural to incorporate tradable permits. Given the firms' market power, a realistic modelling of the permit trade would

[1] Amongst others, this equivalence – which is a common insight in environmental economics (see e.g. Baumol and Oates, 1988, p. 58ff) – particularly presumes identical cost functions of the regulated firms; see e.g. Tisato (1994).

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

[3] Requate (2005) provides a comprehensive survey of this field.

[4] As is well-known, quantity based modes of regulation control the firms' behaviour in a direct manner against what price based modes operate indirectly, through the firms' profit maximisation endeavour. Hence, the regulator's uncertainty concerning abatement costs necessarily leads to a differing performance of prices and quantities. On the other hand, damage cost uncertainty indeed affects the emission target level, but it does not hinder the regulator from similarly enforcing the target by prices or quantities (see Weitzman, 1974, p. 485ff, Adar and Griffin, 1976, p. 180ff or Fishelson, 1976, p. 192fff). This well-known result holds for any kind of market structure, since the independence of the firms' profit from damage costs is clearly not tied to the question whether firms possess market power or not.

trade would have to account for strategic effects and thus go 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 through adopting an abatement technology but also via output shortage. The paper shows that the inclusion of the product market does not change Weitzman's (1974) results, provided that there is perfect competition. However, his policy rule is biased when the polluting firms exhibit market power. Based on the case of a symmetric Cournot oligopoly, the paper reveals that firms use their market power to pass a part of the abatement costs on to consumers by rendering – from social perspective – a too high share of their abatement burden through output reduction and a too low share via the abatement technology. Due to the associated rise of the marginal aggregate abatement costs' slope compared to perfect competition, the volatility of total emissions within the tax regime decreases. Hence, standards, which guarantee a deterministic emission level independently of the market form, become relatively less attractive in terms of expected welfare maximisation. This effect is proven to be positively correlated to the degree of market power.

Abolishing the premise of symmetric firms provides further insights. Firstly, the shift in the instruments' ranking in favour of taxes is boosted owing to the standards' well-known drawback with respect to abatement efficiency. Secondly, the extent of uncertainty has to be taken into account for the optimal instrument choice, contrary to the recommendations given by the respective literature so far. Adequate modifications of Weitzman's (1974) policy rule are derived, both for symmetric and asymmetric Cournot oligopoly.

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 symmetric 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

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. Consumers' preferences can be mapped into a quasi-linear utility function which implies a linear inverse demand of the form $p(X) = B - bX$, depending on the aggregate output $X = \sum_i x_i$. Producing one output unit 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 $c_e(a_{ei}, \theta) = (Z + \theta)a_{ei} + (z/2)a_{ei}{}^2$.

The monetary value of the environmental damage emanating from 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.

As the analysis builds upon Weitzman (1974), it is tied to his assumption of quadratic cost and utility functions, which in turn implies to model firms' costs as being additively separable into production and abatement components and therefore allow for zero emissions without ceasing production.[5] After all, both the inputs for 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.

Apart from fading out 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] In the sense of Weitzman (1974, p. 480), θ does not arise from genuine randomness within the firms' abatement process. It rather reflects the regulator's information gap, i.e. the latter perceives $c_e(a_{ei}, \theta)$ as an estimate or approximation. The present paper sticks 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, i.e. $E[\theta] = 0$ 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 paper focuses on that special case in order to present the central point of the uncertainty's and market power's combined impact upon the optimal instrument choice as simply as possible.

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, she implements one of the instruments at choice – uniform emission standards and taxes – to maximise expected welfare. Then, the firms decide upon output and end-of-pipe abatement effort in stage two. Throughout the paper it is assumed that the emissions generated by each firm can be perfectly monitored by the regulator without any costs. Beyond, 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.

Similar to Weitzman (1974) and the associated literature, the analysis restricts itself to the interior solution, i.e. to that subgame perfect equilibrium which 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.

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[5] This approach is rather rare in the respective literature (see e.g. Ebert, 1992, p. 159). Most models rather ground on a non-separable cost function $c(x_i, em_i)$ or $c(x_i, a_{ei})$ respectively, which accounts for the fact that usually total abatement given a positive output level involves prohibitively high costs (see e.g. Requate, 2005, p. 8f). However, this way of modelling is necessarily associated with non-linear marginal costs and thus incompatible with Weitzman's (1974) framework.

[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.

3. Perfect competition

3.1 Optimal instrument choice

Backwards induction starts with the second stage. Facing 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*:[7]

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

Thereby $R^{PC}(x_i) = px_i$ represents the individual revenue. Seeing that profit maximisation requires the constraint to be 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, (2) requires bringing the associated marginal costs in line. The marginal costs of output shortage are simply given by the loss of producing one unit less, i.e. the marginal loss of revenue less the marginal saving of production costs (left hand side of (2)), whereas the marginal costs of the end-of-pipe option on the right hand side of (2) are self-explanatory. Taking additionally into account the demand side gives the equilibrium quantities of output, end-of-pipe abatement and emissions depending on *s*:[8]

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

Standards force the firms to coordinate their output and end-of-pipe decision in order to comply with the (binding) emission constraint in (1), i.e. they fix x_i and a_{ei} simultaneously. As a consequence, the regulator can enforce the designated emission level despite her lack of information. However, she is uncertain about the way firms split their total abatement burden between the two options of reducing emissions, i.e. both equilibrium output and end-of-pipe abatement effort are random from her point of view. 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.

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[7] The modus of a uniform absolute emission standard is chosen for two reasons: Firstly, it is the standards' prototype taken for granted in the respective literature and thus allows for the comparability of results; see Helfand (1991). Secondly, 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 a uniform absolute emission standard, see e.g. Helfand (1991, p. 625).

[8] Since the equilibrium quantities are identical for all the firms, the subscript "*i*" can be omitted. As firms independently decide upon the abatement effort of each option, the latter depend all on *s* in equilibrium. The equilibrium output given in (3) similarly defines the equilibrium abatement effort in terms of output shortage compared to the unregulated equilibrium.

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

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

The profit maximising strategy balances the marginal costs of the each abatement option and the tax rate:

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

Contrary to standards, firms set x_i and a_{ei}, according to (5), independently from each other, 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*.

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

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.

Next, define social welfare as the sum of consumers' surplus and firms' total revenue net of the aggregate costs of production, end-of-pipe abatement and environmental damage:[9]

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

The regulator's problem in stage one is to set *s* and *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 expected sum of the aggregate abatement and damage costs.

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

While the latter 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 social perspective, emission reduction via

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

output shortage causes opportunity or abatement costs respectively according to the related loss of consumers' and producers' surplus – compared to the unregulated equilibrium. The aggregate costs referred to the end-of-pipe option simply correspond to the sum of the firms' respective costs.[10] The equivalence between (7) and (8) turns out to play an essential role for checking whether Weitzman's (1974) 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 used in a way that does not affect social welfare, the optimal tax rate t^{*PC} satisfies

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

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}:

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

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 subsequent policy rule:*

[10] 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 firm and social level; see section 2.

(i) Standards should be preferred to taxes if and only if $\Delta^{PC} > 0 \quad \Leftrightarrow \quad d > \alpha^{PC}$

(ii) Taxes should be preferred to standards if and only if $\Delta^{PC} < 0 \quad \Leftrightarrow \quad d < \alpha^{PC}$

provided that both the optimal standard s^{*PC} *and tax* t^{*PC} *meet the demands of the interior solution, i.e. induce each firm to implement a positive equilibrium output and end-of-pipe abatement level.*

3.2 Examining the coefficient of comparative advantage

First of all, it is important to see that s^{*PC} and t^{*PC} entail the same output, end-of-pipe abatement and emission levels in terms of expectation:[11]

$$E\left[x^{PC}\left(s^{*PC},\theta\right)\right] = x^{PC}\left(t^{*PC}\right), \qquad E\left[a_e^{PC}\left(s^{*PC},\theta\right)\right] = E\left[a_e^{PC}\left(t^{*PC},\theta\right)\right],$$
$$s^{*PC} = E\left[em^{PC}\left(t^{*PC},\theta\right)\right] \tag{12}$$

Hence, there is no mechanism except for the regulator’s uncertainty suspending the basically given equivalence of regulation through prices and quantities. More precisely, (11) arises solely from the fact that the way the random variable θ enters the firms’ equilibrium choices differs between the standard and tax regime, as can be seen from (3) and (6). Now, the related consequences shall be revealed for every single component of Δ^{PC} to gain a deeper insight into the instruments’ comparative advantage.

Components’ general form	specific form	sign
$\Delta_1^{PC} = E\left[\int p\left(X^{PC}\left(s^{*PC},\theta\right)\right)d(\cdot) - \int p\left(X^{PC}\left(t^{*PC}\right)\right)d(\cdot)\right]$	$-\frac{b}{2}Var[\theta]\left(n\frac{\partial x^{PC}(s,\theta)}{\partial\theta}\right)^2$	<0
$\Delta_2^{PC} = nE\left[c_p\left(x^{PC}\left(s^{*PC},\theta\right)\right) - c_p\left(x^{PC}\left(t^{*PC}\right)\right)\right]$	$n\frac{c}{2}Var[\theta]\left(\frac{\partial x^{PC}(s,\theta)}{\partial\theta}\right)^2$	>0
$\Delta_3^{PC} = nE\left[c_e\left(a_e^{PC}\left(s^{*PC},\theta\right),\theta\right) - c_e\left(a_e^{PC}\left(t^{*PC},\theta\right),\theta\right)\right]$	$nVar[\theta]\left(\frac{\partial a_e^{PC}(s,\theta)}{\partial\theta} - \frac{\partial a_e^{PC}(t,\theta)}{\partial\theta} + \frac{z}{2}\left(\left(\frac{\partial a_e^{PC}(s,\theta)}{\partial\theta}\right)^2 - \left(\frac{\partial a_e^{PC}(t,\theta)}{\partial\theta}\right)^2\right)\right)$	>0
$\Delta_4^{PC} = E\left[C_d\left(ns^{*PC}\right) - C_d\left(EM^{PC}\left(t^{*PC},\theta\right)\right)\right]$	$-\frac{d}{2}Var[\theta]\left(n\frac{\partial em^{PC}(t,\theta)}{\partial\theta}\right)^2$	<0
$\Delta^{PC} = \Delta_1^{PC} - \sum_{i=2}^{4}\Delta_i^{PC}$	$= A^{PC2}Var[\theta]\left(\frac{d-\alpha^{PC}}{2\alpha^{PC2}}\right)$	$sgn\{d-\alpha^{PC}\}$

Table 1: Decomposing the coefficient of comparative advantage

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, i.e. $\Delta_1^{PC} < 0$. The taxes’ dominance in this respect increases with the degree of risk aversion (measured by *b)* and uncertainty

[11] Naturally, this is true for any pair of *s* and *t* which enforces an identical overall emission level.

(measured by $Var[\theta]$), as well as the strength of the random variable's impact on the standard regulated output, $\left|\partial x^{PC}(s,\theta)/\partial\theta\right| = \left|-\varepsilon/\left(bn + z\varepsilon^2 + c\right)\right|$. Moreover, the number of firms *n* plays a similar role as $Var[\theta]$. A larger *n* means simply that the amount of uncertain choices, from the regulator's view, 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 to 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, unlike output, the end-of-pipe abatement effort 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: $\left|\partial a_e^{PC}(s,\theta)/\partial\theta\right| = \left|-\varepsilon^2/\left(bn + z\varepsilon^2 + c\right)\right| < \left|\partial a_e^{PC}(t,\theta)/\partial\theta\right| = \left|-1/z\right|$. This is simply for the reason that for taxes the shock fully affects the end-of-pipe effort (firms fix x_i and a_{ei} separately), against what the shock splits between output and end-of-pipe for 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 in case of unexpected high or low costs which favours taxes: $\Delta_3^{PC} > 0$. The gap between the standards' and taxes' expected end-of-pipe costs increases with shrinking curvature of $c_e(a_{ei},\theta)$ (measured by *z*)[12] and with growing $Var[\theta]$, number of firms as well as with growing difference between the standards' and taxes' end-of-pipe abatement sensitivity concerning the shock $\partial a_e^{PC}(s,\theta)/\partial\theta - \partial a_e^{PC}(t,\theta)/\partial\theta = (bn + c)/z\left(bn + z\varepsilon^2 + c\right)$.

While all the components of Δ^{PC} analysed so far favour taxes, standards are superior in terms of expected damage costs: $\Delta_4^{PC} < 0$. Due to the quadratic form of $C_d(EM)$ and the associated risk aversion of consumers regarding the emission level, standards perform better than taxes, as only they ensure a deterministic degree of pollution. The standards' comparative advantage gains weight as the degree of risk aversion (measured by *d*), uncertainty (measured by $Var[\theta]$) and θ's influence on the tax regulated emissions $\partial em^{PC}(t,\theta)/\partial\theta = 1/z$ as well as the number of firms rise.

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 show a better 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 in coping with the consumers' risk aversion as regards environmental damage ($\Delta_4^{PC} < 0$).

[12] This effect is of the same nature as the "curvature effects" related to *b* and *c*.

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 consequently also the level of Δ^{PC}, but not its sign. Hence, the question of optimal instrument choice involves exclusively the proportion of *d* and α^{PC}. The positive correlation between *d* and the performance of standards has already been revealed above. In comparison, 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 as follows: A larger ε implies more emissions per output unit which puts a greater emphasis on the desire of consumers for a deterministic degree of pollution guaranteed by standards. On the one hand, an increasing number of firms *n* implies a higher level of uncertainty (similarly to an increase of $Var[\theta]$) 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 with increasing *n*. As can be seen from 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}, which is why on the whole a larger *n* makes taxes relatively less attractive. The higher the curvature of the utility function, *b*, and the production cost function, *c*, the more detrimental the volatile 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 similar manner like an increase in *n*. Indeed this effect downgrades the taxes' performance as depicted above, but it is weaker than the fist-mentioned curvature effect for which reason the aggregate impact of a growing *b* or *c* on the taxes' performance is positive. 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. There is again a dominant countervailing effect, though, as *z* also reduces the random variable's impact on the tax regulated emission level.

Having revealed the various mechanisms which drive the difference in the instruments' performance, it remains to be clarified whether the result depicted in proposition 1 conforms to Weitzman's (1974) renowned policy rule. 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, i.e. the marginal damage and abatement cost function's slope. As easily can be seen, 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 occurring at the social level (Weitzman, 1974, p. 479f). As he additionally allows for individually set standards in 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. Accordingly, minimising the aggregate abatement costs, comprising the loss of consumers' and producers' surplus, relative to the unregulated aggregate equilibrium output $X^{PC} = n(B-C)/(bn+c)$, as well as total end-of-pipe 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]

$$\min_{\{x,a_e\}} \left(\int_0^{X^{PC}} p(X)dX - nc_p\left(x^{PC}\right) \right) - \left(\int_0^{X} p(X)dX - \sum_i c_p(x_i) \right) + \sum_i c_e(a_{ei}, \theta)$$
$$s.t. \quad EM^{PC} - EM = A \tag{13}$$

and reinserting results into (13) produces $C_A^{min\,PC}(A,\theta)$, which is the equivalent to Weitzman's abatement cost concept. The associated marginal cost function reads

$$MC_A^{min\,PC}(A,\theta) = (Z+\theta)A^{PC} + \alpha^{PC} A \tag{14}$$

As $\partial MC_A^{min\,PC}(A,\theta)/\partial A = \alpha^{PC}$ obviously applies

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

This result stands to reason, as the crux of Weitzman's rule is – beyond the quadratic form of the cost and utility functions, and the additivity of the cost shock – the congruence of the costs occurring at the firm and social level, which is, per definition, fulfilled for perfectly competitive markets. To gain a deeper intuition, restate the regulator's welfare maximisation problem depending on $s(A)$ and $t(A)$ respectively – that standard and tax which enforce an identical (in case of taxes expected) overall abatement effort A.[14] Then the first order condition with respect to A prescribes to balance $MC_A^{min\,PC}(A,\theta)$ and marginal damage costs. So the optimal instrument choice can be reduced to the question of whether standards or taxes produce an overall abatement effort which is closer to first best, or equivalently, whether $d > \alpha^{PC}$ or vice versa.[15] The whole point about this insight is that by using the adequate abatement cost concept, all the aspects of optimally allocating risks and minimising expected costs are captured within the comparison of the marginal damage and abatement cost function's slope. Note that the number of firms n is irrelevant for corollary 1 to hold, as long as they act as price takers.[16]

[13] Of course, the unregulated output and emission level vary with the specific market form.
[14] $s(A)$ and $t(A)$ simply result from solving $A(s) = EM^{PC} - ns$ for s and $A(t) = EM^{PC} - nE\left[em^{PC}(t,\theta)\right]$ for t.
[15] For a graphical illustration see Adar and Griffin (1976).
[16] Indeed, n turns out to be a relevant determinant for the relation between Weitzman's original rule and its modification in case of market power, see section 4.2, corollary 3.

4. Symmetric Cournot oligopoly

4.1 Optimal instrument choice

This section analyses the impact of market power on the optimal instrument choice under uncertainty by considering a symmetric Cournot oligopoly within the output market. Market power means an additional distortion beside the external diseconomies of pollution. Thus, even under uncertainty, a first best solution could only be achieved by flanking standards or taxes with a subsidy on output; see Baumol and Oates (1988). However, this option is ruled out on the grounds that it is politically untenable. The previous model framework is maintained. The same is true for restricting the analysis to the inner solution, which implies the distorting pollution to outweigh the oligopolistic output shortage. In this sense, both the optimal standard and tax induce a decrease of the firms' output compared to the unregulated equilibrium.[17] Otherwise, regulation would probably not be part of the environmental policy's field of duty.

The calculation of the subgame perfect equilibrium ensues perfectly analogously to 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 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 – whose meaning remains unchanged – simultaneously gives the Cournot Nash equilibrium quantities for standards

$$x^{CO}(s,\theta) = \frac{B - C - \varepsilon(Z + \theta - zs)}{b + bn + z\varepsilon^2 + c}, \qquad a_e^{CO}(s,\theta) = \varepsilon x^{CO}(s,\theta) - s\ ,$$
$$em^{CO}(s) = s \tag{15}$$

and taxes

$$x^{CO}(t) = \frac{B - C - \varepsilon t}{b + bn + c}, \qquad a_e^{CO}(t,\theta) = \frac{t - Z - \theta}{z},$$
$$em^{CO}(t,\theta) = \varepsilon x^{CO}(t) - a_e^{CO}(t,\theta) \tag{16}$$

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 (15) and (16) respectively.[18] Their explicit illustration is in turn abandoned for the familiar reasons. The appropriate coefficient of the instruments' comparative advantage reads

$$\Delta^{CO} = E\left[W\left(\boldsymbol{x}^{co}\left(s^{*CO},\theta\right),\boldsymbol{a}_e^{co}\left(s^{*CO},\theta\right),\theta\right) - W\left(\boldsymbol{x}^{co}\left(t^{*CO}\right),\boldsymbol{a}_e^{co}\left(t^{*CO},\theta\right),\theta\right)\right] =$$
$$= A^{CO2} Var[\theta]\left(\frac{d - \alpha^{CO}}{2\alpha^{CO^2}}\right)$$

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

[18] Of course the problem can be restated to minimise total costs like in case of perfect competition; see (8).

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

$$A^{CO} = \frac{b^2(1+n)^2 + c\left(z\varepsilon^2 + c\right) + b\left(nz\varepsilon^2 + 2c(1+n)\right)}{\left(b + bn + z\varepsilon^2 + c\right)^2} \qquad (17)$$

which entails:

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 subsequent policy rule:*

(i) Standards should be preferred to taxes if and only if $\Delta^{CO} > 0 \Leftrightarrow d > \alpha^{CO}$

(ii) Taxes should be preferred to standards if and only if $\Delta^{CO} < 0 \Leftrightarrow d < \alpha^{CO}$

provided that both the optimal standard s^{*CO} *and tax* t^{*CO} *meet the demands of the interior solution, i.e. 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

The minimised aggregate abatement cost function for symmetric Cournot oligopoly $C_A^{min\,CO}(A,\theta)$ results from (13), 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 compared to perfect competition, the related marginal cost function

$$MC_A^{min\,CO}(A,\theta) = (Z+\theta)A^{min\,CO} + \frac{bz\varepsilon(B-C)}{(b+bn+c)\left(bn+z\varepsilon^2+c\right)} + \alpha^{PC}A$$

$$\text{where} \quad A^{min\,CO} = \frac{(bn)^2(1+n) + bnc(1+2n) + nc^2}{n(b+bn+c)\left(bn+z\varepsilon^2+c\right)} \qquad (18)$$

runs at a necessarily higher level than $MC_A^{min\,PC}(A,\theta)$ while exhibiting the same slope. Consequently, Weitzman's rule still prefers 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 comprises the risk of wrongly choosing standards instead of taxes which arises whenever* $\alpha^{CO} > d > \alpha^{PC}$. *An aberrant implementation of taxes is yet impossible because* $\alpha^{CO} > \alpha^{PC}$.

Obviously, the emergence of market power shifts the comparative advantage of instruments in favour of taxes relative to perfect competition. But for what reason? The bias of Weitzman's rule must be attributed to a violation of at least one of its mandatory qualifications listed in section 3.2. Seeing that still all cost and utility functions show a quadratic progress and θ enters the end-of-pipe costs additively, the bias can only be grounded on a deviation between the abatement costs occurring at firm and social level. While market power in the output market evidently does not infringe upon the assumption that $c_e(a_{ei},\theta)$ perfectly captures the social opportunity costs of end-of-pipe abatement, things are different with regard to the option of reducing emissions through output shortage.

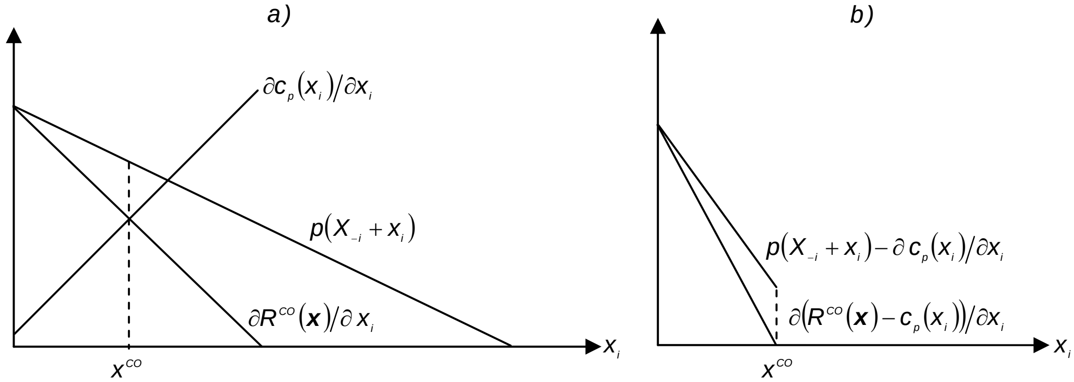

Figure 1: Oligopolist's vs. society's marginal costs of output shortage

First, consider the benchmark set by a price taking firm whose marginal costs of output reduction are $\partial(R^{PC}(x_i)-c_p(x_i))/\partial x_i = p-(C+cx_i)$, the marginal loss of revenue minus the marginal saving of production costs; see (2) or (5). In the case of perfect competition, the former 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 which results from producing one unit less is congruent to the associated social opportunity costs – the marginal decrease of consumers' and producers' surplus.[19] In contrast, an oligopolist aware of her influence on the market price faces marginal output shortage costs of $\partial(R^{CO}(\mathbf{x})-c_p(x_i))/\partial x_i = \partial(p(X_{-i}+x_i)x_i - c_p(x_i))/\partial x_i = = a-bX_{-i}-2bx_i-(C+cx_i)$. As illustrated in figure 1, these only capture the marginal loss of consumers' and producers' surplus in parts.

To understand why this disparity makes taxes relatively more attractive, again decomposing the coefficient of comparative advantage will be helpful. 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 occurring under perfect competition. Figure 1b) demonstrates that the oligopolist's marginal costs of output shortage exhibit a higher absolute slope ($2b+c$) than those of the price taking firm ($b+c$). Consequently, the standard regulated output and end-of-pipe effort respond less sensitively to the shock compared to perfect competition:

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

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

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

Clearly (19a) lowers the standards' drawback vs. the deterministic output provided by taxes in terms of maximising expected utility of consumption and minimising expected production costs. However, since minimising expected end-of-pipe costs benefits from a high volatility 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 volatility. Inevitably, the same applies for tax regulated emissions. Since furthermore 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 the one caused by (19a) since $\alpha^{CO} > \alpha^{PC}$. This is simply because contrary to utility of consumption and production costs, end-of-pipe costs themselves are subject to uncertainty and hence the change in end-of-pipe volatility boosting the taxes' performance carries more weight than the change in output volatility boosting the standards' performance.

The optimal instrument choice can again be merged to the question of which instrument generates an overall abatement effort closer to the desired, here second best, level, i.e. whether aggregate marginal abatement or damage costs run steeper. In doing so, it is important to realise that, in contrast to perfect competition, the aggregate abatement costs which come along with regulation deviate from the minimised aggregate abatement costs on which Weitzman's rule is based. The fact that an oligopolist's marginal output shortage costs fall short of the related marginal costs at social level, see figure 1b), implies an inefficient combination of the two abatement options: Each oligopolist balances her option specific marginal abatement costs and thus renders from a welfare perspective a too large share of the overall abatement burden via output shortage and a too low share via end-of-pipe, i.e. she exploits her market power to pass a part of the abatement costs on to consumers via the output channel.

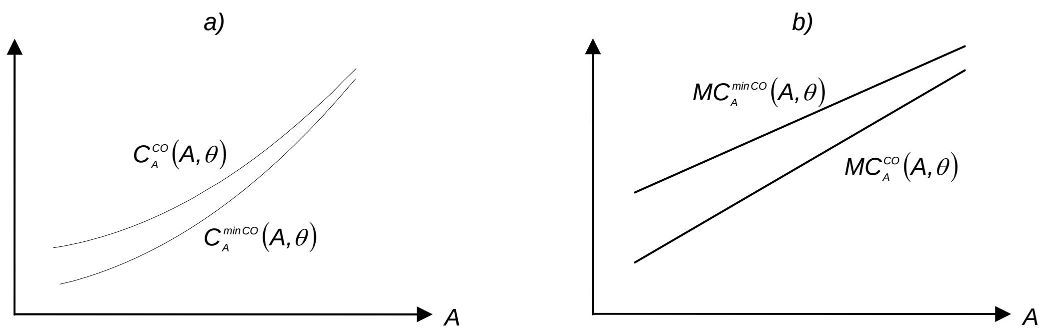

Figure 2: Aggregate (marginal) abatement costs: Efficient abatement vs. Cournot oligopoly

Accordingly, the aggregate abatement costs arising from the standard or tax regulation of the Cournot oligopoly $C_A^{CO}(A,\theta)$ run above the minimised aggregate abatement costs $C_A^{min\,CO}(A,\theta)$.[20] As can be seen in figure 1, the marginal costs of output shortage for the oligopolist and society converge with increasing abatement effort (and hence with decreasing output). Thus, the same must apply for $C_A^{min\,CO}(A,\theta)$ and $C_A^{CO}(A,\theta)$, as well as for the related marginal cost functions $MC_A^{min\,CO}(A,\theta)$ and

$$MC_A^{CO}(A,\theta) = (Z+\theta)A^{CO} + \frac{bz\varepsilon(B-C)}{(b+bn+c)(b+bn+z\varepsilon^2+c)} + \alpha^{CO}A \qquad (20)$$

This in turn implies that $MC_A^{min\,CO}(A,\theta)$ runs at a higher level than $MC_A^{CO}(A,\theta)$,[21] but exhibits a lower slope, i.e. $\alpha^{PC} < \alpha^{CO}$. Hence, opposing the slopes of the marginal damage cost and the adequate marginal aggregate abatement cost function, $MC_A^{CO}(A,\theta)$, suggests that taxes are preferable to standards for a larger range of parameters in comparison with perfect competition.

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*

$$\frac{\partial(\alpha^{CO}-\alpha^{PC})}{\partial n} = -\frac{(bz\varepsilon)^2\left(2b^2n(1+2n)+b(1+5n)(z\varepsilon^2+c)+(z\varepsilon^2+c)^2\right)}{n^2(bn+z\varepsilon^2+c)^2(b+bn+z\varepsilon^2+c)^3} < 0 \qquad (21)$$

a decreasing number of firms, and therefore an increasing degree of market power reinforces the taxes' gain in comparative advantage as against perfect competition.

By the same token, (21) suggests that the risk of a suboptimal instrument choice accompanied with the adaption of Weitzman's rule to a Cournot oligopoly is positively correlated to the firms' concentration in the output market. The cause of this relation is not far to seek. 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 more the difference between the standard regulated equilibrium outcome in case of perfect competition (3) and Cournot oligopoly (15) grows. The same necessarily applies to the volatility of the respective outcomes, which strengthens the force responsible for the gain of taxes. In terms of aggregate abatement costs, a smaller *n* implies the inefficiency of the abatement allocation and thus the gap between $C_A^{CO}(A,\theta)$

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[20] $C_A^{co}(A,\theta)$ can be calculated as follows: First, define $s^{co}(A)$ and $t^{co}(A)$ as that standard and tax which induce the oligopolists to render an (expected) overall abatement effort of *A* by solving $A(s) = EM^{co} - ns$ for *s* and $A(t) = EM^{co} - nE[em^{co}(t,\theta)]$ for *t*. $s^{co}(A)$ and $t^{co}(A)$ combined with (14) and (15) respectively gives the quantities of the standard or tax regulated Cournot Nash equilibrium as functions of *A*. Finally, plugging either of the latter into $\left(\int_0^{X^{co}} p(X)dX - nc_p(x^{co})\right) - \left(\int_0^{X} p(X)dX - \sum_i c_p(x_i)\right) + \sum_i c_e(a_{ei},\theta)$ leads to $C_A^{co}(A,\theta)$, where it is straightforward to show that $C_A^{co}(A,\theta) > C_A^{min\,co}(A,\theta)$ for any *A*.

[21] It is straightforward to prove this relation by using the conditions for the inner solution.

and $C_A^{min\,CO}(A,\theta)$ to rise, since a higher degree of market power enables the oligopolists to shift a larger part of their abatement costs to consumers. For the reasons listed above, this augments the difference between the related marginal cost function slopes. Finally, $\lim_{n\to\infty} \Delta^{PC} = \lim_{n\to\infty} \Delta^{CO} = Var[\theta](d/z^2) > 0$ reveals that the disparity between the instruments' comparative advantage for Cournot and perfect competition completely vanishes as n tends to infinity. Aggregate marginal abatement costs then become constant for both market forms, i.e. $\lim_{n\to\infty} \alpha^{PC} = \lim_{n\to\infty} \alpha^{CO} = 0$, which means standards perform better than taxes for any constellation of parameters.

5. Asymmetric firms

The assumption of symmetric firms means a severe restriction to the previous results as it cancels out the well-known drawback of standards in allocating total abatement efficiently among firms; see e.g. Tisato (1994). Hence, the following slight adjustment of the model is intended for incorporating this major in point in the decision between standards and taxes as simply as possible. Consider two types of Cournot oligopolists $j = h,l$ with production costs $\tilde{c}_p^j(x_i^j) = C^j x_i^j + (c/2)x_i^{j\,2}$, where $C^h > C^l$ – i.e. 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.[22] Thus, it is straightforward to calculate the subgame perfect equilibrium by following the procedure in section 4, which leads to the coefficient of comparative advantage for the asymmetric Cournot oligopoly:[23]

$$\tilde{\Delta}^{CO} = E\left[\tilde{W}\left(\tilde{\boldsymbol{x}}^{co}\left(\tilde{s}^{*CO},\theta\right),\tilde{\boldsymbol{a}}_e^{co}\left(\tilde{s}^{*CO},\theta\right),\theta\right) - \tilde{W}\left(\tilde{\boldsymbol{x}}^{co}\left(\tilde{t}^{*CO}\right),\tilde{\boldsymbol{a}}_e^{co}\left(\tilde{t}^{*CO},\theta\right),\theta\right)\right] =$$

$$= A^{CO2} Var[\theta]\left(\frac{d-\alpha^{CO}}{2\alpha^{CO2}}\right) - \Delta^A$$

$$\text{where} \qquad \Delta^A = \frac{nz\varepsilon^2\left(C^h - C^l\right)^2\left(3b^2 + 2bz\varepsilon^2 + 4bc + z\varepsilon^2 c + c^2\right)}{8(b+c)^2\left(b + z\varepsilon^2 + c\right)^2} \qquad (22)$$

From this follows:

Proposition 3. *Within the model framework depicted in section 2 and 5, the optimal choice between emission standards and taxes for regulating a polluting asymmetric Cournot duopoly with uncertain abatement costs obeys the subsequent policy rule:*

[22] The adherence to the assumption of identical end-of-pipe costs is justified by the fact that the market for end-of-pipe technologies is usually thin.

[23] Note that $\tilde{\boldsymbol{x}}^{co}(\cdot)$ and $\tilde{\boldsymbol{a}}_e^{co}(\cdot)$ comprise the firm specific quantities of the regulated equilibrium for both types.

(i) Standards should be preferred to taxes if and only if

$$\tilde{\Delta}^{CO} > 0 \quad \Leftrightarrow \quad d > \alpha^{CO} + \frac{2\alpha^{CO^2} \Delta^{C_A}}{A^{CO^2} Var[\theta]}$$

(ii) Taxes should be preferred to standards if and only if

$$\tilde{\Delta}^{CO} < 0 \quad \Leftrightarrow \quad d < \alpha^{CO} + \frac{2\alpha^{CO^2} \Delta^{C_A}}{A^{CO^2} Var[\theta]}$$

provided that both the optimal standard $\tilde{s}^{*CO}$ and tax $\tilde{t}^{*CO}$ meet the demands of the interior solution, i.e. induce each duopolist to implement a positive output and end-of-pipe abatement level in the Cournot Nash equilibrium.

To reveal the asymmetry's role for the optimal instrument choice, it is first of all important to see how it affects the firms' marginal output shortage costs. As demonstrated in section 4.2, the latter's absolute slope ($2b + c$) is independent on C^j. Hence, the only difference caused by asymmetry is that the low cost type's marginal costs are defined over a wider range than the high cost type's, since the former produces more in the unregulated equilibrium: $x^{lCO} - x^{hCO} = (C^h - C^l)/(b + c) > 0$. So the marginal abatement costs of the two types exhibit the identical progress for both abatement options, which is why all of them are balanced in the case of taxes. However, uniform standards prescribe the same emission level to both types, thus imposing a higher abatement burden on the low cost type, since the latter, as shown above, produces and therefore emits more in the absence of regulation. This in turn implies that the marginal abatement costs of $j = l$ are higher than those of $j = h$ within the standard regime:

$$\begin{aligned} &\left.\frac{\partial c_e(a_{ei}^j, \theta)}{\partial a_{ei}^j}\right|_{a_{ei}^j = a_e^{lCO}(s,\theta)} - \left.\frac{\partial c_e(a_{ei}^j, \theta)}{\partial a_{ei}^j}\right|_{a_{ei}^j = a_e^{hCO}(s,\theta)} = \\ &= \left.\frac{\partial\left(R^{CO}(\mathbf{x}) - \tilde{c}_p^l(x_i^j)\right)}{\partial x_i}\right|_{\mathbf{x} = \tilde{\mathbf{x}}^{CO}(s,\theta)} - \left.\frac{\partial\left(\tilde{R}^{CO}(\mathbf{x}) - \tilde{c}_p^h(x_i^j)\right)}{\partial x_i}\right|_{\mathbf{x} = \tilde{\mathbf{x}}^{CO}(s,\theta)} = \\ &= \frac{z\varepsilon\left(C^h - C^l\right)}{b + z\varepsilon^2 + c} > 0 \end{aligned} \tag{23}$$

Due to this inefficient allocation of total abatement among firms, the aggregate abatement costs associated with standards run at a higher level than those associated with taxes for any *A*: $\tilde{C}_A^{CO}(\tilde{s}(A), \theta) - \tilde{C}_A^{CO}(\tilde{t}(A), \theta) = \Delta^{C_A} > 0$.[24] Note that the respective marginal cost functions are congruent and identical to the symmetric case. Hence, the gain of taxes over standards evoked by market power spreads one-to-one from the symmetric to the asymmetric setting. Furthermore, the standards' drawback with respect to abatement efficiency amplifies this gain: The equivalence of standards and taxes requires the marginal damage costs to run more steeply than the marginal aggregate

[24] $\tilde{C}_A^{CO}(\tilde{s}(A), \theta)$ and $\tilde{C}_A^{CO}(\tilde{t}(A), \theta)$ can be calculated according to the procedure described in footnote 20. From $\tilde{C}_A^{CO}(\tilde{s}(A), \theta) - \tilde{C}_A^{CO}(\tilde{t}(A), \theta) = \Delta^{C_A} > 0$ follows that taxes strictly dominate standards under certainty.

abatement costs, as can be seen in proposition 3. As a result, the asymmetry increases the risk of erroneously choosing standards which emerges when the regulator grounds her decision on Weitzman's rule and

$$\alpha^{CO} + 2\alpha^{CO^2} \Delta^{C_A} \Big/ A^{CO^2} Var[\theta] > d > \alpha^{PC} \tag{24}$$

Another fundamental consequence is given by the relevance of $Var[\theta]$ for the optimal instrument choice: $Var[\theta]$ weights the instruments' difference ascribed to uncertainty, which has to be traded off against the difference concerning abatement efficiency.
Tisato (1994) achieves similar results by investigating "inefficient standards" within Weitzman's (1974) framework. However, he argues that the standards' abatement efficiency disadvantage involves a steeper marginal aggregate abatement cost function compared to taxes, which is not necessarily true as demonstrated above. Besides, he does not explicitly elaborate on the insight that $Var[\theta]$ becomes a relevant component for choosing the optimal instrument contrary to the conventional analysis of pollution control under uncertainty.

6. Conclusion

By introducing the product market in Weitzman's (1974) stochastic framework, 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, it is biased when the polluting firms possess market power. The paper demonstrates for the case of a symmetric Cournot Oligopoly that firms shift a part of the abatement costs to consumers by choosing a – from social perspective – suboptimal high level of output shortage to reduce their emissions. This behaviour translates into an increase of the marginal aggregate abatement cost function's slope and hence shifts the comparative advantage of instruments in favour of taxes. The taxes' gain is positively correlated to the degree of market power, measured by the number of firms. Abolishing the assumption of symmetric polluters yields further findings. Firstly, the standards' well-known drawback with respect to abatement efficiency becomes evident and strengthens the shift pro taxes. Secondly, the extent of uncertainty, measured by the random variable's variance, turns out to be a relevant criterion for the optimal instrument choice, contrary to the suggestions in conventional uncertainty literature.
These findings are perfectly in line with Quirion (2004). He considers the traditional Weitzman (1974) framework within another second-best setting by introducing a preexisting distortionary tax, which also leads to a greater comparative advantage of taxes over standards.
The major policy implication to be drawn out of the analysis is that the adaption of Weitzman's rule in the presence of market power comprises the risk of a suboptimal instrument choice, or more precisely, to wrongly choose standards instead of taxes, which is the higher the more market power the firms possess. The specificity of the model demands caution in adopting these findings to any actual regulation scenario. However, Weitzman (1974) weakened this caveat by arguing that the assumed quad-

ratic shape of the cost and utility functions 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).

In terms of future research, there is admittedly much scope for checking the robustness of results concerning various types of competition, the modelling of uncertainty, and all the remaining assumptions on which the analysis is grounded. Though, work pointing in that direction would not appear to promise fundamentally new insights. In the light of growing concerns about global pollution and an increasing international interlacing of trade, a much more promising task would be to investigate the question of optimal instrument choice under uncertainty and market power within a setting of an international oligopoly and several rival national regulators. To my knowledge, strategic environmental policy literature has so far made no efforts to account for uncertainty.

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