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Environmental Policy under Imperfect Competition - A Survey

by Till Requate

CAU
Christian-Albrechts-Universität Kiel
Department of Economics

Economics Working Paper

No 2005-12

Environmental Policy under Imperfect Competition -
A Survey [1]

by

Till Requate[2]

Abstract

In this article I survey the theoretical literature on environmental policy in the presence of imperfect competition, ranging from early contributions in the 1960s to the present. I cover the following market structures when polluting firms have market power in the output market: monopoly, Cournot oligopoly, Bertrand duopoly with homogeneous products, price-setting duopoly with differentiating commodities, and models of monopolistic competition. Among the latter I consider Cournot oligopoly with free entry, the Dixit-Stiglitz model, and Salop's model of the circular city with polluting firms. The regulation instruments I concentrate on are emission taxes, tradable permits, and both absolute and relative standards. I also discuss taxation when firms have market power in the input market, and I study models where firms exercise market power in the market of tradable permits. In the latter case I also survey some recent results from the literature on experimental economics. Finally, I briefly discuss environmental policy in open economies when firms have market power in international markets. Here I suggest different decompositions of the unilateral second-best optimal tax rate, thus attempting to unify alternative interpretations of these decompositions in the literature.

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1 Introduction

It is well known that due to their static efficiency economists prefer market-based instruments of environmental policy such as emission taxes and tradable permits, to command and control. According to the Pigouvian rule, the optimal price of pollution should be equal to marginal social damage. Thus, since competitive firms equalize their marginal abatement costs to the price of pollution, notably an emission tax rate or a price for tradable permits, a socially optimal allocation can be decentralized. This is because (a) marginal abatement costs are levelled out among all the polluters, and (b) marginal abatement costs are equalized to marginal damage.

At an early stage, Buchanan & Stubblebine [1962] and Buchanan [1969] challenged the Pigouvian paradigm by pointing out that a monopolist distorts the market allocation by holding down output. Therefore, a Pigouvian tax established to regulate emissions by a polluting monopolist, would exacerbate the distortion. Starting from this observation, Buchanan [1969] rides a general attack against emission taxes in imperfectly competitive markets. He writes "*This note is presented as a contribution to the continuing dismantling of the Pigouvian tradition in applied economics*" and "*... the whole approach of the Pigouvian tradition is responsible for many confusions in applied economics that are slowly to be clarified ... making the marginal private cost as faced by the decision–taking unit equal to marginal social cost does not provide the Aladdin's Lamp for the applied welfare theorist, and the sooner he recognizes this the better.*" Finally, on the relationship of Pigouvian taxes and market structure he writes: "*It is necessary to distinguish, however, between the relevance of market structure for the emergence of externality and the relevance of market structure for the application of Pigouvian norms ... it is necessary, to limit the Pigouvian correctives on the tax side to situations of competition.*" This statement certainly over-shoots the mark with regard to the problem of regulating a polluting monopolist, because when environmental damage is large, a zero tax (or the absence of any other kind of regulation) may be much worse than setting the Pigouvian level of a tax (equal to marginal damage), even if the market structure is monopolistic. D.R. Lee [1975] supports Buchanan's view in principle but does not reject emission taxes outright as a means of mitigating the externality. He was the first to point out that, compared to the tax rate to be imposed on a competitive firm, a tax charged on a firm exercising market power has to be reduced by a term including $P'(Q)q_i$, where P and q_i denote the inverse demand function and firm i's output, respectively. As is well known, $P'(Q)q_i$ represents the difference in marginal revenues between a competitive and an oligopolistic (or monopolistic) firm.

While Lee concentrated on a standard-and-charges approach where the emission target is assumed to be given, Barnett [1980] was the first to rigorously solve the problem of determining the second-best optimal emission level and the corresponding second-best optimal emission tax to be imposed on a monopolist when pollution is evaluated with reference to a social damage function. Barnett's article was a milestone in the theory of pollution regulation under imperfect competition and opened up a new avenue for research. There is hardly any paper on the theory of pollution control on imperfectly competitive firms that does not refer to Barnett's contribution.

In this chapter I survey the theory of pollution control on firms exercising market power at some point in the market process. For this purpose I set up a general model where the firms' technologies, including abatement opportunities, are represented by their cost functions. I distinguish two cases. In the first case, pollution is proportional to output and firms have no opportunity to reduce pollution other than by reducing output. In the second case, firms can in principle decide independently on output and emissions. In this case I write a typical firm's cost function as $C(q, e)$, which is interpreted as the cost incurred by the firm for producing q units of output with no more than e units of emissions. This representation of the firms' technologies is used throughout the whole chapter, except when I focus on pure market power in a market of tradable permits. Here the firms' technologies are simply represented by their abatement cost functions.

For the greater part of this chapter, I will discuss both the comparative static effects of different pollution control instruments and the rules for determining the first- or second-best optimal levels of certain policy instruments, in particular emission taxes. I start with the case of pure monopoly; besides taxes I also study other instruments such as absolute and relative standards. Next I summarize pollution control policies in the standard types of oligopoly model: Cournot competition, Bertrand competition with homogeneous goods, price competition with differentiated commodities, Cournot competition with free entry, and finally, monopolistic competition. Then I turn to permit trading when only two or a small number of firms engage in imperfect competition on the output market. In a further section I consider market power on some input market and investigate the consequences for optimal or second-best optimal policy setting.

An assumption frequently made in all these models is that the regulator can only use environmental policy to combat two or at best three market imperfections: The firms create an externality, they keep up prices (or hold down output) by virtue of exercising market power, and finally, in models with free entry, a non-optimal number of firms enter the market. The main conclusion in all this literature is that with both types of market power, in the output or in an input market, second-best optimal policies lead to allocations where the firms' marginal abatement costs fall short of marginal damage. This implies that, under a tax policy, the second-best optimal tax rate is smaller than marginal damage. There are two exceptions to this rule. The first is the case of Cournot competition with free entry, in which the second-best optimal tax may exceed marginal damage to mitigate excessive market entry. The second is where a monopolist has market power over an abating input or an advanced abatement technology. In a scenario like this, a regulator can raise the demand for abating inputs or advanced abatement technology by raising the tax rate.

Further, I study monopoly power on the market for tradable permits. For this purpose I elaborate a generalized version of Hahn's influential model [1984]. Hahn presented a simple set-up for a permit market with one large price-setting firm and several small price-taking firms. This model has been extended in several directions: market power on both the permit and the output market, non-compliance by either the small firms or the large firm, etc.. The Hahn model has also been subjected to a number of experimental investigations which I briefly summarize.

All the models mentioned so far rely on the assumption that market power is exercised in a closed domestic market. Since the literature on environmental policy in open economies has been treated in detail elsewhere, in particular by Ulph [1997] in this series, I will not attempt to present a complete survey on this large sector of the literature. However, I would like to highlight the link between the theories of *environmental policy under imperfect competition* and *environmental policy as trade policy.* Several environmental and trade theorists have pointed out that in the absence of trade policy environmental policy instruments can be (ab)used as trade policy since they can have an impact on the terms of trade when the country applying those instruments is large (see Markusen 1975). In particular, a country hosting large firms with market power in international markets has to take account of several offsetting effects when calculating the unilaterally optimal emission tax rate. If domestic consumers are also served by domestic firms engaging in imperfect competition on international markets, the regulator has to take account of domestic consumer surplus and weigh this either against the terms-of-trade or against the rent-shifting effect. Due to these offsetting aspects caution is required in talking about *eco-dumping* whenever a government sets a domestic tax rate below marginal damage. The point is that in the pure model of a polluting monopolist, where pollution is proportional to output, the regulator can even implement the first-best allocation by choosing the appropriate tax rate. In this case, the regulator *must* set the tax rate *below* marginal damage since he has to take into consideration the monopolistic behavior of the firm. Hence, in an international trade model with imperfect competition, the regulator must take account of the dead weight loss generated at home. Accordingly, as Duval and Hamilton [2002] have pointed out, not every issue that makes the tax rate lower than marginal damage, is to be interpreted as eco-dumping. To highlight these issues I extend the basic model used in this survey to the case of international trade, I suggest alternative decompositions of the unilateral optimal emission tax, and I discuss rival interpretations of such decompositions with respect to terms-of-trade versus the rent-shifting effect.

In discussing important results from the literature in detail, I shall usually adapt the models of other authors to my notation and assumptions, in order to present an integrated treatment of all the different cases. I will also add some new material, in cases where I have found a gap in the literature that needs to be closed. Two such cases are optimal standards in Cournot oligopoly with free entry and market power on factor markets. Needless to say, there are many other gaps in the literature that need to be closed.

The remainder of this chapter is organized as follows: In the next section I set up some general assumptions on the firms' cost functions, market demand, and the social damage function that will be used throughout this chapter. In Section 3 I treat the pure regulation of a monopolist. Besides the tax instrument I also study absolute standards, relative standards, and tax/subsidy schemes. Further, I summarize several extensions of that basic model taken from the literature. Since there are so many contributions on the regulation of polluting oligopolies, I have decided to split up the treatment of oligopoly into several sections. In Section 4 I investigate emission taxes in the classical Cournot model, i.e. *quantity-setting* oligopoly with a fixed number of firms. I extend that model to tax/subsidy schemes, and at the end of the section I summarize several extensions taken from the literature, such as pre-investment, ecological tax reform, and other issues. In Section 5

I study emission taxes in *price-setting oligopoly*, where I treat both cases, i.e. genuine Bertrand competition with homogeneous commodities and the case of differentiated commodities. Section 6 deals with environmental policy in models with market entry. Besides the classical Cournot model with free entry, I also present a version of the Dixit-Stiglitz model and briefly summarize results from emission taxes in Salop's model of the circular city. In Section 7 I present a model for an output duopoly with permit trading and briefly discuss extensions to the case of more than two firms. In Section 8 I treat models with market power on an input market, considering the cases of pure monopsony and Cournot oligopsony. In subsection 8.5 I briefly summarize some results on models of market power for a clean input. Though brief, this section is important because it yields results where the second-best optimal emission tax may exceed marginal damage. In Section 9 I study models involving market power in the permit market. The section presents a model that generalizes the seminal model suggested by Hahn [1984] to cover the case of several firms with market power. I survey the numerous extensions of the Hahn model, including experimental evidence. In Section 10 I deal with the regulation of market power in models of international trade. Section 11 provides a summing-up, indicates some gaps in the literature and suggests directions for further research.

2 Some Basic Assumptions

For most of this chapter I intend to discuss partial equilibrium models with one consumption good and one pollutant. In sections 5.2 and 6.3 I will also consider models with several private commodities, modifying assumptions on preferences and demand accordingly.

There are $n \geq 1$ firms producing a homogenous commodity. In the production process the firms generate a pollutant emitted into the environment. Most of the time I will assume that the pollutant is generated in this industry only (i.e., by the n firms under consideration). This assumption does not hold in *all* industries, of course. CO_2, for example, is generated by many different industries. In the chemical industry, by contrast, several hazardous pollutants are generated by the production of one commodity only. In our framework, notably when considering *imperfect* competition, assuming the pollutant to be industry-specific makes the analysis more interesting and is of greater empirical relevance.

As a welfare measure I will adopt the standard cost/surplus concept employed throughout the literature on industrial organization. Thus welfare is defined as gross consumer benefit minus production costs minus the monetarized damage from pollution, to be defined more precisely below. For $i = 1, \dots, n$ I will use q_i and e_i to denote the quantity produced and supplied on the commodity market and the emissions dumped into the environment by firm i, respectively. Aggregate (or industry) output and total emissions are denoted by $Q := \sum_{i=1}^{n} q_i$ and $E := \sum_{i=1}^{n} e_i$, respectively.

2.1 Preferences

Preferences on the part of the consumers (or society) are represented by an inverse demand function P and a social damage function D, where the latter captures both the disutility that consumers suffer and the economic damage that other industries suffer from the pollution generated by the n firms under consideration. I make the following assumption about demand:

Assumption 1 *The inverse demand function* $P : \mathbb{R}_+ \rightarrow \mathbb{R}_+$ *depends on aggregate industry output* Q *only. Moreover,*

i) it is twice continuously differentiable for all $Q \in \{\tilde{Q} > 0 | \text{ with } P(\tilde{Q}) > 0\}$.

ii) P' *is strictly decreasing, and* P'' *is sufficiently bounded; in particular, for all* $Q > 0$ *we have*:

$$\frac{P''(Q)}{P'(Q)} Q > -1 \quad . \tag{1}$$

(1) says that P is not too convex. This is sufficient to guarantee the second-order conditions for several maximization problems, in particular for social optimum, profit maximization of monopoly and, for the oligopolistic firm in Cournot–Nash equilibrium. It is also sufficient to guarantee the stability and uniqueness of Nash equilibrium when we consider the Cournot game in Section 4.

For the damage function I adopt the following assumption from the literature:

Assumption 2 *The damage from pollution depends on total pollution E only. The social damage function $D(E)$ is twice continuously differentiable, increasing and (weakly) convex, i.e.* $D''(E) \geq 0$.

Where certain results require strict convexity, I will make explicit mention of this fact.

2.2 Technologies

The firms' technologies are represented by their reduced cost functions. This assumes that all factor markets are perfectly competitive and — both here and in the models of imperfect competition in the output market — are not influenced by any strategic behavior of the firms in other markets.

We will make alternative assumptions about those technologies. In the first assumption, pollution is proportional to output and firms do not have any further abatement technologies:

Assumption 3 *Each firms' cost function* $C_i : \mathbb{R}_+ \to \mathbb{R}_+$ *is*

i) twice continuously differentiable for $q_i > 0$.

ii) Moreover, $C_i'(q_i) > 0$ *and* $C_i''(q_i) \geq 0$. *(If* $C_i''(q_i) > 0$ *is required, this will be explicitly mentioned.)*

iii) Pollution is proportional to output, i.e. $e_i = \delta_i q_i$, *with* $\delta_i > 0$, *for all* $i = 1, ..., n$.

Alternatively, I assume that firms have technologies where pollution can be substituted for by using more of other abating inputs, which in turn incurs higher costs. I assume that those abatement opportunities are already incorporated in the reduced cost function written as $C^i(q_i, e_i)$, i.e., the cost depends on both firm i's output q_i and its emissions e_i, thus satisfying the following assumption:

Assumption 4 *For each firm* $i \in \{1, ..., n\}$ *its cost function* $C^i : \mathbb{R}_+^2 \to \mathbb{R}$ *is twice continuously differentiable and satisfies the following properties (we omit the superscript* i*):*

i) $C_q > 0$, $C_{qq} > 0$, $C_{ee} > 0$, $C_{qe} < 0$.

ii) For all q there exists an emission level $e(q)$ such that $C_e(q, e(q)) = 0$, and $C_e(q, e) < 0$ if $e < e(q)$, and $C_e(q, e) \geq 0$ if $e > e(q)$.

iii) The Hessian of C is positive definite. In particular, C satisfies

$$C_{qq}C_{ee} - [C_{qe}]^2 > 0 \quad . \tag{2}$$

This assumption implies that the *variable* cost function is strictly convex. In particular, we have increasing marginal costs for fixed emission levels, abatement costs are convex for each fixed output, and output and emissions are complements ($C_{qe} < 0$), which implies that the marginal abatement cost increases with more output ($-C_{eq} > 0$). Moreover, for each output level there is a cost-minimizing emission level $e(q)$ that would be chosen by the firms in the absence of regulation (i.e. $C_e(q, e(q)) = 0$). In such a case, we can define a further reduced cost function by $\widetilde{C}(q) := C(q, e(q))$. In principle the cost function could in principle contain fixed costs. Where these are important, for example in models with free entry, we will also explicitly mention the fact.

Note: Some authors, such as Barnett [1980], Conrad [1993], and Duval & Hamilton [2002], specify certain inputs that can be used to reduce pollution. These authors write the cost function as $C(q, w(\tau))$, where $w(\tau)$ is the price of a polluting input including a tax rate τ (or a corresponding permit price). Using Shepard's Lemma it is possible to recover each firm's level of emissions, which are assumed to be proportional to the polluting input x, by the relationship $e = \delta C_w(q, w(\tau))$, where δ is an emission coefficient.

2.3 Welfare and First-Best Allocations

To evaluate the utility and the harm of a given allocation $(q_1, \ldots, q_n, e_1, \ldots, e_n)$ for society, we define a social welfare function W, which is additively separable into consumers' gross benefit, production cost, and the social damage caused by the pollution:

$$W(q_1, \ldots, q_n, e_1, \ldots, e_n) := \int_0^Q P(z)dz - \sum_{i=1}^{n} C^i(q_i, e_i) - D(E) \tag{3}$$

where $Q = \sum_{i=1}^n q_i$ and $E = \sum_{i=1}^n e_i$. If there are no abatement technologies we simply obtain

$$W(q_1, \ldots, q_n) := \int_0^Q P(z)dz - \sum_{i=1}^{n} C_i(q_i) - D(E) \tag{4}$$

where total emissions are now determined by $E = \sum_{i=1}^{n} \delta_i q_i$.

Under Assumption 3, and if the firms' cost functions are strictly convex, the socially optimal allocation is characterized by the following set of first order conditions:[3]

$$P(Q) = C_i'(q_i) + \delta_i D'(E) \qquad \forall i = 1, \ldots, n$$

Thus the marginal willingness to pay equals marginal production costs plus marginal social damage times the emission coefficient of the respective firm.

Under Assumption 4, the social optimum is characterized by the following alternative set of first-order conditions:

$$\begin{aligned} C_q^i(q_i, e_i) &= P(Q) \qquad i = 1, \ldots, n && (5) \\ -C_e^i(q_i, e_i) &= D'(E) \qquad i = 1, \ldots, n && (6) \end{aligned}$$

This means that the firms' marginal cost of producing a further unit of the marketable commodity equals the consumers' marginal willingness to pay, and the marginal abatement costs $-C_e^i(q_i, e_i)$ are equal to the marginal social damage. In particular, marginal costs and marginal abatement costs are equal across all the firms.

We use $(q_i^*, e_i^*)_{i=1,\ldots,n}$ to denote the socially optimal allocation and Q^* for the corresponding aggregate output. The corresponding total emissions are denoted by E^*.

2.4 Decentralization under Perfect Competition

It is easy to see that under perfect competition the social optimum can be implemented by charging a tax rate that satisfies the Pigouvian rule, i.e. equals the marginal damage resulting from the socially optimal allocation. This can be seen as follows. The firms take the price for the output commodity as given and maximize

$$\pi_i(q_i, e_i) = pq_i - C^i(q_i, e_i) - \tau e_i$$

---

[3] If firms have constant marginal costs, it is socially optimal that only those firms with the lowest marginal social cost (including marginal social damage) produce.

which leads to the following first-order conditions:

$$\begin{aligned} C_q^i(q_i, e_i) &= p = P(Q) \qquad i = 1, \ldots, n & (7) \\ -C_e^i(q_i, e_i) &= \tau \qquad i = 1, \ldots, n & (8) \end{aligned}$$

If the regulator sets

$$\tau = D'(E^*) \quad , \tag{9}$$

we see that (7) and (8) imply (5) and (6). Thus the socially optimal allocation results if the market equilibrium is unique, which is guaranteed by our assumptions. Alternatively, the regulator could issue an amount of tradable permits L equal to the socially optimal total emission level E^*.[4] In the latter case, it does not matter whether the permits are auctioned off or issued for free (grandfathered).

I assume throughout this chapter that the society is indifferent about the redistribution of tax revenues. This implies that collecting tax revenues in this industrial sector is not a government objective. This in its own is tantamount to assuming that no other distortionary taxes (and hence no marginal costs of public funds) exist, and that there is no additional technology that the government can buy in order to reduce the aggregate emissions E once these have been dumped into the environment by the firms. Thus collected taxes will be redistributed to the consumers in a lump-sum way. Only in Sections 3.5.8 and 4.6.6, where I briefly discuss ecological tax reforms in the presence of imperfect competition, do I deviate from this assumption.

Further, I assume that the emissions generated by each firm can be perfectly monitored without cost by the regulatory authorities. Accordingly, the firms will pay a tax bill that is exactly equivalent to the amount of pollutants they emit. In the case of permits, firms cannot emit more than the number of permits allows them to. Otherwise I assume that a high penalty has to be paid (boiling–in–oil policy). Thus there is no room for moral hazard. One departure from this assumption is the summary of models with non-compliance in permit markets in Section 9.

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[4] In this case, the first-order condition (8) is substituted by $-C_e^i(q_i, e_i) = \sigma$ where σ is the competitive price for tradable permits.

3 Imperfect Competition in the Output Market: Monopoly

In this section and the following I study models of imperfect competition in the output market, starting with monopoly. I assume that a single firm operates in the output market and generates a pollutant that is industry-specific (or a local pollutant). Thus regulation refers to this single firm only and does not affect other industries. A real situation represented by such a model is a chemical or pharmaceutical firm specializing on the production of a certain output and generating either a specific or a local pollutant.

3.1 Taxation of Monopoly when there is no Abatement Technology

If the monopolist's technology satisfies Assumption 3 and it is subject to an emission tax τ, its profit depends on output only and can be written as

$$\Pi(q) = P(q)q - C(q) - \tau\delta q$$

The first-order condition for profit maximization is then given by

$$P'(q)q + P(q) - C'(q) - \tau\delta = 0 \tag{10}$$

The solution is denoted by $q^M(\tau)$. Setting $n = 1$ in (4), and writing welfare as a function of the tax rate we obtain:

$$W(\tau) := \int_0^{q^M(\tau)} P(z)dz - C(q^M(\tau)) - D(\delta q^M(\tau)) \tag{11}$$

Differentiating (11), with respect to τ, we obtain

$$[P(q^M(\tau)) - C'(q^M(\tau)) - \delta D'(\delta q^M(\tau))]\frac{dq^M(\tau)}{d\tau} = 0 \tag{12}$$

Using (10) by substituting for $P(q) - C'(q) = -P'(q)q + \tau\delta$ and "solving" (12) for the tax rate[5], we get

$$\tau = D'(\delta q^M(\tau)) + \frac{P'(q^M(\tau))q^M(\tau)}{\delta} \tag{13}$$

---

[5] Note that we do not properly solve for τ since the right hand side of (13) also depends on τ.

which can also be rewritten as

$$\tau = D'(\delta q^M(\tau)) + \frac{P(q^M(\tau))}{\epsilon \cdot \delta} \tag{14}$$

where $\epsilon = P(q^M(\tau)) \cdot q^M(\tau)/P'(q^M(\tau))$ is demand elasticity. By substituting (14) into (10), we immediately see that in this case the optimal emission tax rate leads to the first-best outcome. The simple reason for this is that the regulator has direct control over output by virtue of $q = e/\delta$, and since $q^M(\tau)$ is decreasing in τ.[6] Thus the regulator can induce the firm to produce the socially optimal outcome, i.e. $q^M(\tau) = q^*$. We summarize this as

Proposition 1 *If emissions are proportional to output (or a monotonic function of output) and there is no abatement technology, there exists an emission tax rate that implements the social optimum. The optimal tax rate is lower than marginal damage.*

Note that the tax rate can also be negative because the monopolist creates two market imperfections by holding down output and generating a negative externality through pollution. If the tax rate is negative, the first imperfection dominates the second, and the regulator mitigates underprovision of the output market by subsidizing pollution, which seems to be more a theoretical option rather than a real one.[7]

3.2 Taxation of a Monopolist with Abatement Technology

I now consider the case where the monopolist's cost function satisfies Assumption 4. Again, the monopolist is subject to an *emission tax,* its profit is given by

$$\Pi(q,e) = P(q)q - C(q,e) - \tau e$$

Profit maximization then leads to the following first-order conditions:

$$\begin{aligned} P'(q)q + P(q) - C_q(q,e) &= 0 \qquad (15) \\ -C_e(q,e) &= \tau \qquad (16) \end{aligned}$$

---

[6] This can be seen easily by differentiating (10) with respect to τ. Solving for $dq^M(\tau)/d\tau$ yields: $dq^M(\tau)/d\tau = \delta/[P''q + 2P' - C''] < 0$ by Assumptions 1 and 3.

[7] Of course he can also tax or subsidize output with the same effect.

This means that marginal revenue equals the marginal cost for producing one more unit of output, and marginal abatement cost is equal to the tax rate. I use $q(\tau)$ and $e(\tau)$ to denote the solution to (15) and (16).

The environmental authority then seeks to maximize welfare as a function of the tax rate:

$$W(\tau) := \int_0^{q(\tau)} P(z)dz - D(e(\tau)) - C(q(\tau), e(\tau)) \tag{17}$$

leading to the first-order condition

$$\begin{aligned} W'(\tau) &= [P(q(\tau)) - C_q(q(\tau), e(\tau))]q'(\tau) & (18) \\ &\quad -[C_e(q(\tau), e(\tau)) + D'(e(\tau))]e'(\tau) = 0 & (19) \end{aligned}$$

where again for convenience I have written $q'(\tau) := dq/d\tau$ and so on. Employing (15) and (16) and "solving" for the tax rate gives us the following optimality condition for the second-best optimal emission tax:

$$\begin{aligned} \tau &= D'(e(\tau)) + P'(q(\tau))q(\tau)\frac{q'(\tau)}{e'(\tau)} & (20) \\ &= D'(e(\tau)) + \frac{P(q(\tau))}{\epsilon}\frac{\partial q}{\partial e} & (21) \end{aligned}$$

where $\partial q/\partial e$ is the reaction of output to the relaxation of an emission standard and ϵ is the price elasticity. To determine the signs of q' and e', we differentiate (15) and (16) with respect to τ, yielding

$$q' = \frac{-C_{qe}}{C_{ee}(P'' + 2P') - (C_{qq}C_{ee} - [C_{qe}]^2)} < 0$$

and

$$e' = -\frac{1}{C_{ee}} + \frac{[C_{qe}]^2}{[C_{ee}]^2(P'' + 2P') - C_{ee}(C_{qq}C_{ee} - [C_{qe}]^2)} < 0$$

where we have made use of Assumptions 1 and 4, in particular $C_{qe} < 0$, to sign the expressions.

In this case, the second-best optimal tax rate does not lead to the first-best allocation, as can be seen from substituting (20) into the monopolist's first-order conditions of profit maximization. The reason for this result is that the monopolist can now independently decide on output and emissions, while the regulator has only one instrument available. This result was first established by Barnett [1980]. Again, the second-best tax rate falls short of marginal damage, as can be seen from (20), and it can be even negative. Note that the second-best optimal emission level can exceed the first-best level. This is due to the two market imperfections and the lack of a sufficient number of instruments. A phenomenon like this should not be confused with (environmental or) eco-dumping.[8] It is merely a consequence of an insufficient number of instruments and hence of a second-best optimal setting.

As a special instance, we may briefly consider the case where $C(q, e)$ is additively separable into the cost of production and abatement, i.e. $C(q, e) \equiv C_P(q) + C_A(e)$. Since $C_{qe} = 0$, we obtain

$$\tau = D'(e(\tau)) \quad , \tag{22}$$

and the second-best optimal tax rate equals marginal damage, as is also optimal under perfect competition. We can summarize this result as follows:

Proposition 2 *If $C(q, e)$ is additively separable, the optimal emission tax rate is independent of the commodity market structure and equal to marginal damage, thus satisfying the Pigouvian rule.*

3.3 Emission Standards

Absolute Emission Standard As an alternative to charging a price for emissions, the regulator can set an (absolute) emission standard. If the unregulated monopolist's emission level exceeds the optimal emission level, an emission standard is equivalent to an emission tax. Conversely, if the unregulated emission level falls short of the optimal level of pollution, which is the case when the distortion from the monopolist's market power exceeds the distortion resulting from pollution, the shadow price of pollution is negative, and thus the first-best allocation (in the case where no abatement technology exists) cannot be implemented by a standard. The reason is simply that the regulator cannot induce the monopolist to increase output by setting an emission standard that does not bite.

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[8] Although there is no unique definition in the literature, eco-dumping usually refers to underinternalizing the social damage of pollution. See Rauscher [1994] for a careful discussion of the concept.

Emission Permits Grandfathering a quota of emission permits is clearly equivalent to setting an absolute emission standard. The same applies to auctioning off such a quota of permits. The monopolist would bid zero (or epsilon) and obtain all the permits.

Relative Emission Standard In reality, *relative emission standards* are more common than absolute standards. Under this kind of standard, a firm is restricted with respect to its emissions per unit of output: $e \leq \alpha q$ for some number $\alpha > 0$. If emissions are proportional to output, i.e. $e = \delta q$, either the standard is not binding (i.e. $\delta . < \alpha$) or the firm cannot meet the standard and has to terminate production in the short run. If the firm's technology satisfies Assumption 4 and the standard is binding, the firm's cost function can be written as $C(q, \alpha q)$.

The monopolist's first-order condition is then represented by

$$P(q) + P'(q)q - C_q(q, \alpha q) - \alpha C_e(q, \alpha q) = 0 \tag{23}$$

The comparative static effect of relaxing the standard is now given by

$$\frac{dq}{d\alpha} = \frac{C_e + q[C_{qe} + \alpha C_{ee}]}{P''(q)q + 2P'(q) - [C_{qq} + 2\alpha C_{qe} + \alpha^2 C_{ee}]}$$

We see that the sign depends on the shape of the cost function. The denominator is negative, while the sign of the numerator is ambiguous.

With a similar welfare-maximizing procedure to the one above, we find that the second-best optimal standard is now characterized by the following relationship:

$$C_e(q, \alpha q) = D'(\alpha q)\left[1 + \frac{\alpha}{q}\frac{dq}{d\alpha}\right] + P'(q)\frac{dq}{d\alpha} \tag{24}$$

(24) implicitly defines the second best optimal standard, denoted by α^*. We see that the two terms $\frac{\alpha}{q}\frac{dq}{d\alpha}D'(E)$ and $P'(q)\frac{dq}{d\alpha}$ offset each other, no matter what the sign of $dq/d\alpha$ is. In general the sign of $dq/d\alpha$ is ambiguous. In the *normal case,* however, we would expect $dq/d\alpha > 0$ to hold. In this case we see, as usual, that the term accounting for monopoly power is negative, whereas the multiplier $1 + \frac{\alpha}{q}\frac{dq}{d\alpha}$ exceeds one. Thus the imperfect instrument represented by a relative standard causes the regulator to set the emission target at a stricter level compared to the second-best optimal emission level, resulting from a second-best optimal emission cap or a second-best optimal

emission tax. The reason is that the polluting firm can comply to the standard not only by reducing emissions but also by increasing output.

3.4 Regulating Emissions and Output Simultaneously

It can easily be seen that if the regulator has two regulation instruments, namely an emission tax τ and a subsidy on output ζ, the first-best allocation can be achieved by setting the tax rate equal to the Pigouvian level and the subsidy equal to $\zeta = P(q^*)/\epsilon(q^*)$, where $\epsilon(q^*)$ is again demand elasticity at the optimal output quantity q^*. This policy mix seems to be more of a theoretical possibility than a real option, since subsidies are frequently not feasible or are simply not allowed due to free trade treaties or other agreements. In Section 4.4, where we discuss tax-subsidy schemes for oligopolistic competition, we will see, however, that a tax-subsidy scheme can be mimicked by a tax/tax-refunding scheme as exemplified by the NO_X tax system in Sweden.

3.5 Extensions

3.5.1 Some Remarks on Previous Work

As mentioned in the introduction, Buchanan [1969] refuses to apply emission taxes to the case of a monopolistic polluter. Siebert [1976] criticizes Buchanan's conclusions by setting up a formal model where emissions are initially proportional to output but can be reduced separately by an abatement technology. Siebert indicates that under such a technology both the competitive and the monopolistic firm will choose the same level of abatement activity if they are subject to the same tax rates. However, this does not imply, as Siebert claims, that the second-best optimal tax rate is equal to the Pigouvian level.

Prior to Barnett, Asch & Seneca [1976] and Smith [1976] had also arrived at what is basically the same conclusion, i.e. that taxing emissions by a monopolist requires setting the tax rate below marginal social damage. Parallel to Barnett, Misiolek [1980] generalizes the ideas of both Asch & Seneca and Smith. Oates and Strassmann [1984] extend Barnett's conclusions to other forms of market structure.

3.5.2 Simultaneous Regulation of Monopoly and Competitive Firms

Innes et al. [1991] study a situation where one firm, which is a monopolist in a given commodity market, and other firms, engaging in perfect competition on different output markets, emit the same pollutant. This is certainly a realistic scenario for major pollutants such SO_2 and NO_X or greenhouse gases such as CO_2. The authors study the structure of the second-best optimal tax rate when both industries can only be regulated by a uniform tax. If we use $e^C(\tau)$ and $q^C(\tau)$ to denote emissions and output and $C^C(\cdot,\cdot)$ to denote the aggregate cost function of the competitive sector and $e^M(\tau)$, $q^M(\tau)$, and $C^M(\cdot,\cdot)$ to denote emissions, output and cost function of the monopolist, respectively, we can write welfare as:

$$\begin{aligned} W(\tau) &= \int_0^{q^M(\tau)+q^C(\tau)} P(z)dz - C^M(q^M(\tau), e^M(\tau)) \\ &\quad -C^C(q^C(\tau), e^C(\tau)) - D(e^M(\tau) + e^C(\tau)) \end{aligned}$$

Maximizing welfare with respect to the uniform emission tax the second-best optimal tax rate is characterized by the following formula:

$$\tau = D'(e^M(\tau)) + P'(q^M(\tau))q^M(\tau)\frac{dq^M(\tau)/d\tau}{de^M(\tau)/d\tau + de^C(\tau)/d\tau} \tag{25}$$

The intuition for this result is as follows: We would expect the second-best optimal tax rate to be determined by the benefits from production in both the monopoly and the competitive sector and to be a weighted sum from the pure second-best optimal monopoly tax and the Pigouvian tax resulting from regulating the competitive sectors. This is indeed the case through the multiplier $[dq^M(\tau)/d\tau]/[de^M(\tau)/d\tau + de^C(\tau)/d\tau]$. If the reaction of the competitive sector on a tax increase is small, i.e. $de^C(\tau)/d\tau$ is small, the multiplier will be close to $[dq^M(\tau)/d\tau]/[de^M(\tau)/d\tau]$. In that case the regulator can neglect the competitive sector, and (25) will be approximately represented by (20). If the reaction of the competitive sector on a tax increase is large compared to the reaction of the monopolist, the multiplier will be small and (25) will be close to the Pigouvian rule.

Furthermore, the authors show that a discriminating tax system would be better than a uniform tax. They also show that a system of tradable permits outperforms the uniform tax if the initial allocation of permits is chosen appropriately. We will return to this issue in Section 9, where we study models of market power in markets for tradable permits.

3.5.3 Several Local Monopolies

Requate [1993b] considers the case of regulating several local monopolists. Under pure monopoly, a market for permits does not make much sense since there is only one firm on the demand side for permits. It often happens, however, that there are several firms, each of which exercises monopoly power in a local commodity market and generates the same kind of pollution. The sum of emissions caused by all the firms generates a negative externality for an extensive region, a country, or even the whole world. Typical and highly relevant examples of this kind of market structure are the utility industries, especially in Europe, where the firms have had (and in some regions still have) local monopoly power, and each firm emits pollutants such as SO_2 and NO_X, or CO_2 as a greenhouse gas. If several monopolists are subject to regulation, issuing permits does make sense. Requate [1993b] shows that a suitable Pigouvian tax or a suitable number of tradable permits are equivalent tools for maintaining an aggregate pollution level below the unregulated *laissez–faire* level. This corresponds to a charges-and-standards approach. As with perfect competition, both policies lead to the same allocation. This will not be surprising if the permit market is competitive. However, the result still holds if the number of firms is small so that price-taking behavior on the permit market cannot be expected. In this case Requate assumes that the firms negotiate about both the allocation of permits and transaction prices. Since there is no strategic interaction on any commodity market, the firms have an incentive to achieve a cost-efficient allocation of permits amongst themselves, leading to equal marginal abatement costs across firms. This does not hold in general for firms interacting in the output market, as we will see in Section 7.

Requate also studies the second-best optimal uniform tax and the second best optimal discriminating taxes. The latter case is equivalent to several single monopolists. In the first case, the second-best optimal tax rate is given by

$$\tau = D'(E) + \frac{\sum_{i=1}^{n} P_i'(q_i) q_i (\partial q_i / \partial \tau)}{\partial E / \partial \tau} \tag{26}$$

where $P_i(q_i)$ represents the inverse demand function in market i. The optimal number of permits leads to a market price for permits that is equal to the second-best optimal tax rate determined by (26). Moreover, if the regulator can pay discriminatory subsidies, he can implement the first-best outcome by charging the Pigouvian tax. If discriminatory subsidies are not legally feasible, we are back in the world of second-best.

3.5.4 Rent-Seeking

Misiolek [1988] points out that prior to production a monopolist tends to expend considerable resources to establish its monopoly position. This kind of behavior is also referred to as *rent-seeking.* A considerable share of these resources are usually a waste in social terms. Misiolek argues that the regulator should account for such rent-seeking behavior. In order to lower the incentives for rent-seeking, the second-best tax rate should be higher than the optimal tax rate in cases where the monopolist just arrives out of the blue. Misiolek shows that if we take rent-seeking into account, the second-best optimal emission tax rate can be higher, lower or equal to marginal damage.

3.5.5 When Emissions Influence Consumer Demand

Ebert and von dem Hagen [1998] extend Barnett's [1980] basic model by assuming that both consumer demand and production costs are affected in a negative way by pollution. This can be simply modelled by writing inverse demand and cost functions as $P(Q, E)$ and $C(Q, E)$, respectively. Whereas consumers have less benefit from the output good in a more heavily polluted environment, reflected by $P_E < 0$, the effect on cost and marginal cost may go in opposite directions. In my view, only $C_E < 0$, $C_{XE} < 0$ is relevant, reflecting the fact that the firm faces positive marginal abatement costs. In the opposite case, the firm would have an incentive to internalize the "externality" of pollution on itself since the firm is the only polluter (this is the Coase Theorem applied to a single agent). Moreover, the authors allow for two policy instruments, an output tax and an emission tax. Not surprisingly, if both instruments are available, the first-best allocation can be implemented where both tax rates satisfy the Pigouvian rule (being equal to total marginal social damage). If either the emission tax or the output tax is the only instrument, the second best optimal tax rates may exceed or fall short of marginal damage if $C_{XE} < 0$ holds, and, surprisingly, will otherwise exceed marginal damage.

3.5.6 Taxation of a Durable Goods Monopolist

Runkel [2004] extends Barnett's model to the case of a durable goods monopolist, as developed by Bulow [1986]. However, Barnett's rule still holds: the second-best optimal tax rate falls short of marginal damage.

3.5.7 Overall Regulation

Laffont [1994] considers the overall regulation of a monopolist. Alongside an emission tax and a subsidy on output he also suggests a lump-sum tax for the extraction of the monopoly rent. This is especially important in the presence of existing distortionary taxes. Laffont also studies regulation under asymmetric information. Following the methodology of adverse selection applied to regulating a monopolist with unknown costs, as suggested by Baron and Myerson [1982], Laffont describes the second-best optimal policy scheme that induces the monopolist to produce second-best optimal output combined with the second-best optimal pollution level.

3.5.8 Environmental Tax Reform

Bayindir-Upmann [2000] studies the effects of an ecological tax reform in the case of monopoly. In his model the monopolist produces an output by means of two inputs: capital and emissions (or a polluting input). The government can levy both capital taxes and emission taxes. Bayindir-Upmann finds that if the initial tax rate on the non-polluting input (in his model: capital) is low, an environmental tax reform yields a triple dividend: it leads to a decrease of emissions, raises demand for non-polluting inputs, and raises the firms' profits. If the initial capital tax is extremely high, a double dividend does not exist. Here, it is the environmental dividend that fails to materialize. In other words, a tax shift from the non-polluting to the polluting input, increases pollution while keeping revenues constant. High initial tax rates hamper economic activities and, thereby, induce the side effect of low demand for environmentally harmful production factors. If such a tax is lowered, the total distortion on the economy decreases and demand for *all* goods and production factors increases. This occurs even when the tax on the environmentally harmful factor increases. In this case, an ecological tax reform stimulates production and thus increases profits. This emerges, however, at the expense of environmental quality.

By contrast, Fullerton and Metcalf [2002], who consider a similar model with labor and emissions, come to the opposite conclusion. The existence of monopoly power has two offsetting effects on welfare. On the one hand, a revenue-neutral tax reform that lowers the labor tax and increases the tax on the polluting input (or emissions) lowers the monopolist's profit which, however, leads to an increase of labor supply. This partially offsets pre-existing labor supply distortion. On the other hand, the ecological tax reform raises output prices, and this, together with the pre-existing monopoly distortion, further exacerbates the labor supply distortion. The authors show that for empirically relevant parameters the second effect dominates the first. Thus, monopoly power does not raise the probability of achieving a double dividend from a revenue-neutral ecological tax reform. The more optimistic result in Bayindir-Upmann [2000] may be is driven by both the inelastic supply of capital and the initially low tax rate on capital. Thus, in contrast to a labor market, there is no distortion resulting from the supply of capital. We will return to ecological tax reforms and the double dividend hypothesis in Section 4.6.6.

4 Environmental Policy for Cournot Oligopoly

After this discussion of the polar cases of market structure, namely perfect competition and monopoly, I now turn my attention to the wide array of oligopoly models. Of those the one discussed in the literature in most detail is the Cournot model, where firms use quantities as strategic variables. Accordingly, I shall be giving this model a relatively large amount of space in this survey. The Cournot model also links the perfect competition and monopoly models in a very natural way.

The most relevant example of this kind of market structure with pollution regulation is the energy sector, where a homogeneous product, electricity, is produced and firms compete (at least locally) à la Cournot. Other examples are salt effluents from salt mining, where a small number of firms pollute a river. This was the case with the river Rhine at the border between France and Germany, or with the rivers Elbe and Werra in former Eastern Germany. There are many other examples involving near-homogeneous products.

In this section I start the analysis by studying the tax instrument and I also briefly discuss standards. Since in oligopoly models the analysis of permits is more complicated than in other models, I treat that instrument in a separate section (7). The first researcher to investigate emission taxes for Cournot oligopoly was Levin [1985], who mainly studies the comparative statics effects of increasing an emission tax in an asymmetric Cournot oligopoly. However, Levin does not take damage from pollution into account and so he does not discuss the structure of the (second-best) optimal tax rate. To the best of my knowledge, Ebert [1992] was the first to present a second-best analysis for Cournot oligopoly, restricting his attention, however, to the case of symmetric firms. Later, Simpson [1996] also discusses the case of asymmetric duopoly. I begin with a more general model and derive the main results produced by Levin, Ebert, and Simpson as special cases.

Unless otherwise stated, I assume in this section that an environmental authority can set a uniform emission tax rate per unit of effluent only. Here, the authority neither has the power to regulate output distortions, say, by subsidizing output (cf. Cropper & Oates [1992]), nor can it charge individual taxes. The informational structure is such that the government knows what technologies are out there but does not necessarily need to know exactly which firm has which technology. In Section 4.4, I briefly consider the case where the regulator has two instruments at his disposal, a uniform emission tax and a subsidy on output.

4.1 The General Framework

I consider a quantity-setting Cournot game with n firms, where the number of firms is assumed to be exogenously given. The firms produce a homogeneous commodity. Its market price is determined by aggregate output according to $p = P(Q)$. The firms' technologies satisfy Assumption 4. Thus, if a firm is subject to an emission tax, its profit is given by

$$\Pi^i(q_i, e_i, q_{-i}) = P\left(Q\right) q_i - C^i(q_i, e_i) - \tau e_i \quad , \tag{27}$$

where $q_{-i} = (q_1, \ldots, q_{i-1}, q_{i+1}, \ldots, q_n)$ is the strategy profile of the remaining $n-1$ competitors. Firms are assumed to play Nash equilibrium, which due to our model assumptions is unique and stable. We also assume that the Nash equilibrium yields positive amounts of output and emissions, denoted by $(q_1^*(\tau), \ldots, q_n^*(\tau), e_1^*(\tau), \ldots, e_n^*(\tau))$. Thus the equilibrium strategies are interior solutions to the firms' non-cooperative profit maximization problems and thus satisfy the following first-order conditions for all $i = 1, \ldots, n$:

$$P'\left(Q^*(\tau)\right) q_i^*(\tau) + P\left(Q^*(\tau)\right) - C_q^i(q_i^*(\tau), e_i^*(\tau)) = 0 \tag{28}$$

$$-C_e^i(q_i^*(\tau), e_i^*(\tau)) = \tau \tag{29}$$

In the following we omit the asterisks and for simply write for short $q_i(\tau)$, $e_i(\tau)$ and so on.

4.2 Comparative Statics

In order to study the impact of a tax raise on output and emissions, we can differentiate the $2n$ equations (28) and (29) with respect to τ to obtain

$$\begin{aligned} [P''q_i + P']Q' + [P' - C_{qq}^i]q_i' - C_{qe}^i e_i' &= 0 \quad , &(30)\\ -C_{qe}^i q_i' - C_{ee}^i e_i' &= 1 \quad . &(31)\end{aligned}$$

where for convenience I have again written $q_i' = dq_i/d\tau$ and so on. Solving the $2n$ equations for q_i' and e_i' yields

$$\begin{aligned} q_i' &= -\frac{C_{ee}^i[P''q_i + P']Q' + C_{qe}^i}{C_{ee}P' - A_i} \quad . &(32)\\ e_i' &= -\frac{C_{qe}^i[P''q_i + P']Q' + C_{qq}^i - P'}{C_{ee}^i P' - A_i} \quad . &(33)\end{aligned}$$

where $A_i = C_{qq}^i C_{ee}^i - [C_{qe}^i]^2$ is the Hessian of the cost function. In contrast to the monopoly case we cannot unambiguously sign q_i', since the sign of the first term of the numerator of (32) is ambiguous. However, by summing over (32) and rearranging we obtain

$$Q' = -\left[\sum_{i=1}^{n} \frac{C_{qe}^i}{C_{ee}^i P' - A_i}\right] \cdot \left[1 + \sum_{i=1}^{n} \frac{C_{ee}^i[P''q_i + P']}{C_{ee}^i P' - A_i}\right]^{-1} < 0 \tag{34}$$

Studying these terms, we see that by virtue of Assumptions 1 and 4 Q' is negative. This gives rise to the following result:

Proposition 3 *Under Assumptions 1 and 4, aggregate output is decreasing in* τ*.*

This result also is obtained by Levin [1985] and Ebert [1992] proceeding from more restrictive assumptions. By contrast, signing E' is not possible in general, as summing over (33) yields

$$E' = \sum_{i=1}^{n} \frac{C^i_{qq} - P'}{C^i_{ee}P' - A_i} + Q' \cdot \sum_{i=1}^{n} \frac{C^i_{ee}[P''q_i + P']}{C^i_{ee}P' - A_i} \tag{35}$$

Here the first term is negative, but under Assumption 1 the second term is positive, such that the sign of the whole expression cannot be determined unambiguously. Below, I consider some special cases where we can sign the change of aggregate emissions as a function of the emission tax. It will transpire, however, that in general the sign of $dE/d\tau$ is indeed ambiguous.

What about the firm's profits? One can show that where firms are sufficiently symmetric profits go down if the tax rate increases. Simpson [1995] shows that if firms are sufficiently different, one firm may benefit from taxation. Carraro and Soubeyran [1996] indicate detailed conditions under which both uniform and firm-specific taxes lead to an increase or decrease in profits and market shares. This effect can be illustrated by a simple duopoly example with constant marginal costs $c_1 \leq c_2$, pollution proportional to output, i.e. $e_i = \delta_i q_i$, and linear demand: $P(Q) = 1 - Q$. In this case, profits are given by $\Pi^i = (1 - 2(c_i + \delta_i\tau) + c_j + \delta_j\tau)^2/9$. Thus $d\Pi^i/d\tau > 0$ if and only if $\delta_j > 2\delta_i$. Thus firm i benefits from a higher tax rate if and only if the other firm pollutes double as much per unit of output as firm i.

4.3 Second-Best Taxation

Let us now consider the regulator's problem. He maximizes

$$W(\tau) = \int_0^{Q(\tau)} P(z)dz - \sum_{i=1}^{n} C^i(q_i(\tau), e_i(\tau)) - D(E(\tau)) \tag{36}$$

Differentiating (36) with respect to τ and employing (28) and (29) (assuming an equilibrium with all firms producing positive quantities), we obtain

$$\begin{aligned} W'(\tau) &= \sum_{i=1}^{n} \left[P(Q) - C^i_q(q_i, e_i)\right] q_i' - \sum_{i=1}^{n} C^i_e(q_i, e_i)e_i' - S'(E)\sum_{i=1}^{n} e_i' \\ &= -\sum_{i=1}^{n} P(Q)q_i q_i' + \sum_{i=1}^{n}[\tau - S'(E)]e_i' \end{aligned} \tag{37}$$

where we have again written q_i' for $dq_i/d\tau$ and so on.

Setting $W'(\tau) = 0$ and "solving" for τ (note again that the right hand side also depends on τ), we obtain for $i = 1, \ldots, n$:

$$-C_e^i(q_i, e_i) = \tau^* = D'(E) + \frac{P'(Q)\sum_{i=1}^n q_i q_i'}{E'} \quad . \tag{38}$$

where $E' = \sum_{i=1}^n e_i'$. As we have seen above, E' can be positive if firms are extremely asymmetric. But this implies that the second-best optimal tax rate may also exceed marginal damage. The main findings can be summarized as follows:

Proposition 4 *Let Assumptions 1, 2, and 4 hold. Then the following is true:*

- *i) If firms are sufficiently similar, in the sense that the differences of their costs $|C^i(q,e) - C^j(q,e)|$ (including derivatives) are sufficiently small (leading to similar equilibrium output and emission levels), then*
  - *(a) aggregate emissions are decreasing in the emission tax rate;*
  - *(b) the second-best optimal tax rate falls short of marginal pollution damage;*
  - *(c) both firms' profits fall if the tax rate increases.*
- *ii) If firms are sufficiently asymmetric, in the sense that their cost functions are sufficiently different, then*
  - *(a) it is possible that for particular tax-rate intervals aggregate emissions are increasing;*
  - *(b) the second-best tax rate may exceed marginal damage;*
  - *(c) in a duopoly, one firm at most can benefit from a tax raise. In an oligopoly model with $n > 2$, at least one firm will incur decreasing profits, but several firms may enjoy increasing profits when the tax goes up.*

Thus, we see that if firms are symmetric or sufficiently similar, we obtain the same results in qualitative terms as in the case of monopoly. If firms are asymmetric, some perverse effects may arise. The intuition is that if the marginal cost differential between the firms is different from the difference in emission coefficients, taxation changes the cost structure between the firms. This can not only lead to a situation where one firm gains whereas the another firm suffers from a tax increase, but can also cause aggregate pollution to rise and the tax rate to exceed marginal damage. For the last two effects to arise, however, asymmetry of firms does not suffice. We also need an inverse demand function which has an extreme curvature, i.e. which is either sufficiently convex or sufficiently concave (see Levin [1985] and section 4.3.1.B below).

4.3.1 Some Special Cases

A: Symmetric Firms If firms are symmetric, i.e. $C^i(\cdot,\cdot) = C(\cdot,\cdot)$ for all i, uniqueness of equilibrium requires a symmetric equilibrium, i.e., $q_i = q = Q/n$. In this case (35) becomes

$$E' = -\frac{n}{C_{ee}} - \frac{C_{qe}}{C_{ee}}Q' = -\frac{n}{C_{ee}} + \frac{n[C_{qe}]^2}{C_{ee}[P''Q + (n+1)P'] - A} < 0 \quad ,$$

and hence $e' = E'/n < 0$.

The second-best optimal tax rate from (38) simplifies to

$$\tau^* = D'(E) + P'(Q)q\frac{dq}{de} \tag{39}$$

$$\text{or:} \qquad = D'(E) + \frac{P(Q)}{n\epsilon}\frac{dq}{de} \tag{40}$$

where dq/de is the reaction of output to the relaxation of an emission cap. In all these equations, the second term is clearly smaller than zero. Therefore, as in the monopoly case, the tax rate falls short of marginal social damage. Since the oligopolistic industry output $Q(\tau^*)$ is less than the competitive output, and since $\frac{\partial}{\partial q}e(q,\tau) > 0$, aggregate emissions $E(\tau^*)$ are smaller than they are in the case of perfect competition. Hence, the (second-best) optimal emission tax rate is lower for oligopoly compared to the Pigouvian tax rate under perfect competition.

Moreover, (40) suggests that the second-best optimal tax rate increases if the number of firms increases.[9] This is quite intuitive. The higher the number of firms, the closer the market outcome is to the competitive outcome and

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[9] Inspection of (40) shows that the direct effect of increasing n on the second best tax

the closer the tax rate is to the Pigouvian level. This is also emphasized by Katsoulacos and Xepapadeas [1996].

B: No Abatement Technology (The Models by Levin [1985] and Simpson [1995]) This case mainly serves to illustrate that *raising* an emission tax can indeed cause *more* pollution. Therefore I assume, as in the Levin model [1985], that $e_i = \delta_i q_i$ for each firm. Let $D := \sum_{i=1}^{n} \delta_i$. The firms' cost functions $C_i(q_i)$ depend on output only. Moreover, for simplicity I assume $C_i'' = C''$ for all i. If firms face a uniform tax on emissions, their first-order profit maximization conditions in Nash equilibrium are given by

$$P'(Q)q_i + P(Q) - C_i'(q_i) - \tau\delta_i = 0 \qquad i = 1, \ldots, n \tag{41}$$

Carrying out the comparative statics exercise yields

$$E' = \frac{1}{P' - C''}\left[\sum_{i=1}^{n} \delta_i^2 - \frac{D[P'D + P''E]}{P''Q + (n+1)P' - C''}\right] \tag{42}$$

where $E = \sum_{i=1}^{n} \delta_i q_i$. This shows that the sign of E' is negative (positive) as

$$P''[ED - Q\sum \delta_i^2] > \ (<) \ \frac{\sum \delta_i^2[(n+1)P' - C''] - D^2P'}{D \cdot E}$$

Thus aggregate emissions increase with a rise in tax if the inverse demand function is either sufficiently concave or sufficiently convex. Since aggregate output definitely drops as the tax rate goes up, we can conclude that in Levin's example a small emissions subsidy will increase welfare since output goes up while emissions go down. However, we cannot conclude from Levin's result that it is *optimal* to subsidize pollution whenever $E'(0) > 0$. The reason that emissions go up while industry output goes down must be that some firms with high pollution raise their output whereas those with low pollution cut down on production. However, if the tax rate is set sufficiently high, so that each firm's output goes down, then aggregate emissions also have to go down, compared to the *laissez-faire* level. It should not be difficult to find examples with sufficiently steep damage functions where a sufficiently high tax improves welfare in comparison with to the *laissez-faire* level.

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rate is positive. To show that the direct effect dominates the indirect effects, we need to differentiate (40) totally with respect to τ. In order to establish the result $d\tau^*/dn > 0$, we have to assume that the third derivatives of the firms' cost functions C^i have the "right" sign or are sufficiently bounded. Assumptions like these are always necessary when doing comparative statics of second-best instruments with respect to exogenous parameters.

C: Symmetric Firms with Pollution Proportional to Output [Ebert's Model] In the first part of his paper, Ebert [1992] assumes that emissions are completely determined by output, i.e. $e = \delta q$.[10] In this case, the emission tax leads to the socially optimal outcome:

$$\begin{aligned} \tau^* &= D'(E^*) + \frac{P'(Q^*)Q^*}{n\delta} && (43) \\ &= D'(E^*) + \frac{P(Q^*)}{n\delta\epsilon} && (44) \end{aligned}$$

Note that the term $-P'(Q)Q/n$ is equal to the optimal subsidy ζ on output, if we could subsidize output directly.[11] Hence we can rewrite (43) as $\tau^* = D'(E^*) - \zeta/\delta$, i.e. the tax equals marginal damage minus the optimal subsidy divided by the emission coefficient, which seems reasonable. The main insights gained in this subsection can therefore be summarized as follows:

Proposition 5 *a) If oligopoly is symmetric and firms do not have an abatement technology, i.e., pollution is determined completely by output, then there is always an emission tax rate that implements the social optimum.*

b) In a case like this, the tax can also be charged on output. The optimal output tax t^{out} *(or subsidy if it is negative) would then be given by*

$$t^{out} = \delta D'(\delta Q^*) + P'(Q^*)\frac{Q^*}{n} \quad . \qquad (45)$$

The last statement is easily verified.

4.4 Emission Taxes cum Subsidy System

4.4.1 The Basic System

We have seen that if emissions are completely determined by output, and firms are symmetric, the regulator can simultaneously stir emissions and output to the optimal level. If the firms can decide separately on output and emissions, the regulator will need at least two instruments to regulate output

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[10] In fact, Ebert's model is slightly more general by assuming that e is an increasing function of q.

[11] See Section 4.4 below, where we study a tax/subsidy system in more detail for the case where the firm can separately decide on output and emissions.

and emissions. However, if firms are asymmetric, even the two instruments lead to second-best allocations only.

In this section we will consider the case where the regulator has two instruments, an emission tax τ and a subsidy on output ζ. In this case the firms' first-order profit maximization conditions, which constitute the Nash equilibrium, are given by

$$\begin{aligned} P(Q)q_i + \zeta + P'(Q) - C^i_q(q_i, e_i) &= 0 \\ -C^i_e(q_i, e_i) &= \tau \end{aligned}$$

In the case of a uniform tax/subsidy system, we obtain the following formula for the second-best optimal tax/subsidy system:

$$\tau = D(E) + P'(Q)\frac{\left(\sum_{i=1}^n q_i \frac{\partial q_i}{\partial \tau}\right) \frac{\partial Q}{\partial \varsigma} - \left(\sum_{i=1}^n q_i \frac{\partial q_i}{\partial \varsigma}\right) \frac{\partial Q}{\partial \tau}}{\frac{\partial E}{\partial \tau}\frac{\partial Q}{\partial \varsigma} - \frac{dE}{d\varsigma}\frac{\partial Q}{\partial \tau}} \tag{46}$$

$$\varsigma = P'(Q)\frac{\left(\sum_{i=1}^n q_i \frac{\partial q_i}{\partial \tau}\right) \frac{\partial E}{\partial \varsigma} - \left(\sum_{i=1}^n q_i \frac{\partial q_i}{\partial \varsigma}\right) \frac{\partial E}{\partial \tau}}{\frac{\partial E}{\partial \tau}\frac{\partial Q}{\partial \varsigma} - \frac{\partial E}{d\varsigma}\frac{\partial Q}{\partial \tau}} \tag{47}$$

Furthermore, one can show that $\partial q_i/\partial\tau < 0$, $\partial e_i/\partial\tau < 0$, $\partial q_i/\partial\varsigma > 0$, and $\partial e_i/\partial\varsigma > 0$ if the firms are not too different. In this case too, $\partial Q/\partial\tau < 0$, $\partial E/\partial\tau < 0$, $\partial Q/\partial\varsigma > 0$, and $\partial E/\partial\varsigma > 0$ hold.

If firms are symmetric, the formulas (46) and (47) boil down to

$$\tau = D'(E^*) \tag{48}$$

$$\zeta = -P'(Q^*)\frac{Q^*}{n} \tag{49}$$

In this case the optimal tax/subsidy system (τ, ζ) in fact implements the social optimum. This is not surprising as we have two targets q and e, identical for all firms, and two instruments.

4.4.2 Extensions of Tax/Subsidy Schemes

Tax/Tax-refunding Schemes As set out in Section 3.4, subsidies on output are not a realistic policy option for coping with market power. Gersbach and Requate [2004], however, show that in a Cournot model a tax/tax-refunding scheme may mimic such a tax-subsidy scheme. They study emission taxes with a system of *refunding* tax revenues back to firms according to market shares, as is the case for the NO_X-emission tax system in Sweden. If firms compete à la Cournot, the firms' objective function is then determined by

$$\pi^i(q_i, e_i, q_{-i}, e_{-i}) = P(Q)q_i - C^i(q_i, e_i) - \tau e_i + \varphi \frac{q_i}{Q} \tau \sum_{i=1}^{n} e_i$$

where φ with $0 \leq \varphi \leq 1$ is the share of tax revenues to be refunded to firms. Gersbach and Requate show that if market failure through pollution exceeds the market externality through market power, an optimal tax/tax-refunding scheme mimics an optimal tax/tax-subsidy system. They also show that in symmetric oligopoly, except where the marginal distortion from oligopolistic behavior exceeds the marginal social damage, it is possible to find a tax rate τ and a refunding share φ that implement the social optimum. Since the optimal share φ is usually smaller than 1, complete refunding, as exercised in Sweden for NO_X emissions, is, however, generally not optimal.

Leontief Technologies Requate [1993a] considers an asymmetric duopoly with linear technologies, i.e. firms have constant marginal costs $c_1 < c_2$, and emissions are proportional to output $e_i = \delta_i q_i$. The interesting case is where the firm with the lower private cost has the higher emission coefficient, i.e. $\delta_1 > \delta_2$. Since emissions are determined by output, Requate finds that in this case also, there exists a tax/subsidy system that implements the social optimum.

Optimal Non-linear Tax/Subsidy Schemes We have seen in Section 4.4 that a regulator can decentralize the first-best allocation by a uniform tax/subsidy system only if firms are symmetric. Kim and Chang [1993] propose an ingenious non-linear tax/subsidy scheme that works for asymmetric firms engaging in imperfect competition. Though their scheme is non-discriminatory, it nevertheless leads to the first-best allocation. This system, which is a modified version of the one proposed by Loeb and Magat [1993] to regulate utilities, can even be employed if the regulator is imperfectly informed about the firms' technologies. The system works as follows:[12] The regulator proposes a non-linear tax/subsidy function $T(q_i, e_i, \tilde{q}_{-i}, \tilde{e}_{-i})$,

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[12] Kim and Chang model the firms' cost functions in a slightly different way. I have adapted their model and notation to the model used throughout this survey.

where $\tilde{q}_{-i} = \sum_{j \neq i} q_j$ and $\tilde{e}_{-i} = \sum_{j \neq i} e_j$ represents the aggregate output and emissions of the other firms with the exception of firm i. The profit of a typical firm is then given by

$$\Pi^i(q_i, e_i, q_{-i}, e_{-i}) = P(Q)q_i - C^i(q_i, e_i) - T(q_i, e_i, \tilde{q}_{-i}, \tilde{e}_{-i})$$

which leads to the following first-order conditions in Cournot-Nash equilibrium:

$$\begin{aligned} P(Q) + P'(Q)q_i - C^i_q(q_i, e_i) &= T_{q_i}(q_i, e_i, \tilde{q}_{-i}, \tilde{e}_{-i}) && (50) \\ -C^i_e(q_i, e_i) &= T_{e_i}(q_i, e_i, \tilde{q}_{-i}, \tilde{e}_{-i}) && (51) \end{aligned}$$

From this we see that if we choose the function $T(\cdot)$ as follows:

$$T(q_i, e_i, \tilde{q}_{-i}, \tilde{e}_{-i}) = D(e_i + \tilde{e}_{-i}) - D(\tilde{e}_{-i}) + q_i P(Q) - \int_0^{q_i} P(x + \tilde{q}_{-i})dx$$

then the Nash-equilibrium conditions induce the first-best outcome.[13]

What makes this mechanism so attractive is that it is not only non-discriminatory but also reduces the regulator's informational burden. The regulator only needs to know the damage and the demand functions; he requires no knowledge of private firm data. Of course, each advantage is offset by some disadvantage. The firms do not know exactly how large their final costs will be since their tax bill (or subsidy) depends not only on their own decision but also on the choices about output and emissions made by the other firms. Note, however, that this is also the case under a system of tradable permits.

4.5 Standards

As I shall be dealing with regulation by permits in a separate section (7), I here briefly discuss the two kinds of standards that have already been introduced in Section 3. Actually, for symmetric oligopoly, the results are not very different from the monopoly case. For simplicity, I will only treat the symmetric case here, restricting my attention to instances where the firms' technologies satisfy Assumption 4.

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[13] Note that the term $D(\tilde{e}_{-i})$ is not necessary for efficiency. It does however guarantee that each firm only pays for the additional damage it generates over and above the other firms' emissions. It prevents the firms' tax burden from becoming too high.

As under an *absolute emission standard* no firm is allowed to emit more than $\bar{e}$ units of emissions, the Cournot-Nash equilibrium of a symmetric industry is determined by just one equation:

$$P(nq) + P'(nq)q - C_q(q, \bar{e}) = 0 \tag{52}$$

This yields symmetric individual output $q(\bar{e})$. It is easy to show that if the standard is binding, output goes up when the standard is relaxed, i.e. $q'(\bar{e}) > 0$. The regulator again maximizes welfare with respect to $\bar{e}$, yielding

$$-C_e(q, \bar{e}) = D'(n\bar{e}) + P'(Q)qq'(\bar{e})$$

Accordingly, the marginal abatement costs are once again lower than marginal damage. If the right-hand side of the last equation is positive, taxes and standards are equivalent, which is not surprising in the light of the monopoly model.

A *relative standard* restricts emissions per units of output: $e \leq \alpha q$. If the standard is binding, the firms' profits can be written as: $P(Q)q - C(q, \alpha q)$, as in the monopoly case, and the Nash equilibrium condition in symmetric oligopoly is given by

$$P'(Q)q + P(Q) - C_q(q, \alpha q) - \alpha C_e(q, \alpha q) = 0 \tag{53}$$

Again, the comparative statics effect $dq/d\alpha$ is ambiguous, although we intuitively would expect $dq/d\alpha > 0$, i.e. a stricter standard would lead to lower output per firm. The second-best optimal standard satisfies the following condition:

$$-C_e(q, \alpha q) = D'(E)\left[1 + \frac{\alpha}{q}\frac{dq}{d\alpha}\right] + P'(Q)\frac{dq}{d\alpha}$$

We see that there is no general way of determining whether or not the marginal abatement costs exceed or fall short of marginal damage. In the "normal" case, i.e. $dq/d\alpha > 0$, the strategic term $P'(Q)\frac{dq}{d\alpha}$ is negative but the multiplier $1 + \alpha\frac{dq}{d\alpha}$ is greater than 1. The *marginal abatement cost* may now *exceed marginal damage.* The intuition is the same as in the case of pure monopoly: the relative standard can be met by reducing emissions or extending output. The latter strategy is not conductive to the protection of the environment. In order to work against such a strategy, the regulator using an inefficient instrument has to devise a the stricter standard than in the case of an absolute emission standard.

If we have the "perverse" effect of $dq/d\alpha < 0$, the strategic term is positive but the multiplier $1 + \alpha\frac{dq}{d\alpha}$ is smaller than 1. Thus the two effects $\alpha\frac{dq}{d\alpha}$ and $P'(Q)\frac{dq}{d\alpha}$ always work in opposite directions.

4.6 Further Extensions of Emission Taxation in Cournot Oligopolies

4.6.1 Emission Taxes and Endogenous Market Structure

In the model with constant marginal costs $c_1 < c_2$ and emission coefficients $\delta_1 > \delta_2$, referred to above, Requate (1993a) also discusses endogenous market structure. I.e., depending on the size of the tax rate, the outcome can be either monopoly or duopoly. For this purpose, Requate writes the damage function as $D(E, s)$, with $D_s > 0$ and $D_{Es} > 0$. The parameter s determines the slope of the damage function and can be interpreted as a damage parameter where higher s leads to both higher damage and higher marginal damage.[14] As is intuitively obvious I show that it is socially optimal for firm 1 only to produce if the damage function is sufficiently flat, for firm 2 only to produce if the damage function is sufficiently steep, and for both firms to produce in the case of moderately steep damage functions. I use $[\underline{s}, \bar{s}]$ to denote the interval of damage parameters at which it is optimal for both firms to produce. I show that the first-best allocation can only be induced by an emission tax if the damage parameter is sufficiently low, i.e. for $s <\underline{\underline{s}}$ (where $\underline{\underline{s}}$ is some parameter smaller than $\underline{s}$), in which case only firm 1 will produce, or if the damage parameter is sufficiently high, i.e. for $s > \overline{\overline{s}}$ (where $\overline{\overline{s}}$ is some parameter greater than $\bar{s}$), in which case only the cleaner firm will produce. As mentioned above, the first-best allocation can be restored for each s by a suitable tax/subsidy system.

4.6.2 Inter-Firm Externalities

Yin [2003] presents an important extension of the oligopoly model by considering externalities between the producers. This model is based on the assumption that the firms' costs are raised by total pollution. For both

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[14] The steepness of the damage function (the slope of the marginal rates of substitution of the preferences) is also of significance in related models, for example in Weitzman's [1974] paper on regulation under imperfect information. See also Baumol and Oates [1988].

Cournot and price competition with differentiated commodities, Yin finds that the second-best optimal tax rate exceeds marginal damage (which here is determined by the firms' productivity and profit loss caused by the externality) if the externality is considerable and the number of competing firms is large. More specifically, this is the case if and only if the tax effects on total pollution and on total output go in opposite directions. Interestingly, when output increases by raising the tax rate, there is no trade-off between environmental quality and consumer surplus.

4.6.3 Pre-investment

Carlsson [2000] extends the duopoly model proposed by Simpson [1995] to allow for pre-investment in abatement capital with a view to reducing future emissions from production. The firms' profit functions are given by

$$\Pi^i(q_1, q_2) = P(q_1 + q_2)q_i - C^i(q_i, x_i) - rx_i - te^i(q_i, x_i)$$

where q_i denotes output, x_i the amount of abatement capital to be invested in the first period, r the price of capital, and $e(q_i, x_i)$ the emission function. Firms play one-, two- or three-stage games, respectively. In the first game, firms play open-loop strategies by committing simultaneously and irreversibly to the levels of both investment and production. The second game is the usual two-stage game where firms invest in the first stage and compete à la Cournot in the second stage. In the third game, one firm is a Stackelberg leader, with the first-mover advantage of choosing the level of capital. The authors find that if abatement capital enhances the marginal costs of production, then in the open loop game the second-best optimal tax rate falls short of marginal damage for "normal" parameters. The same holds true for the closed loop game, except in the case where firms are extremely different. By contrast, little can be said about the Stackelberg case.

4.6.4 Dynamic Model with Accumulating Pollutants

Benchekroun and Van Long [1997] extend the duopoly models proposed by Simpson [1995] and Katsoulacos and Xepapadeas [1997] to the case of an accumulating stock pollutant leading to a dynamic model with an infinite time horizon. Two firms compete à la Cournot in the final output market, and their emissions are subject to taxation. Firms are symmetric and emissions are proportional to output. The firms may employ either open-loop or

Markov perfect (feedback) strategies. Benchekroun and Van Long find that in both cases a time-independent tax rule exists, i.e. a tax rule depending on the current stock of pollution only, which leads to a socially optimal outcome. This is not surprising in the light of Proposition 5 from the static model. The tax rate may be negative, i.e. it turns into a subsidy in the initial time interval when the pollution stock is still low. Surprisingly however, this subsidy induces the firms to produce less than they would in the case of *laissez-faire*. The reason is that they know that if they produce more, then the subsidy will be reduced in future and/or will (sooner) be converted into a tax.

4.6.5 Durable Goods

Runkel [2002] and [2004] investigates the taxation of oligopolists producing a durable good that creates waste after it has expired. He finds that if the durability of the good is exogenous, the second-best tax rate in the second period falls short of marginal damage (as usual), whereas in the first period the emission tax rate may be higher or lower than marginal damage. If durability is endogenous, over-internalization may also occur.

4.6.6 Ecological Tax Reforms under Imperfect Competition

Imperfect competition in the output market has also been considered in the recent literature on ecological tax reforms. After the enthusiasm about the existence of a double dividend was dampened by Bovenberg & De Mooji [1994] and several other papers by Bovenberg and co-authors[15], some researchers have tried to rescue the idea of a double dividend by introducing imperfect competition into the models. In a model with monopolistic competition on the output market, Marsiliani and Renström [1997] show that besides the environmental dividend a second dividend on the labor market caused by boosting employment may or may not arise as a result of a revenue-neutral ecological tax reform. Holmlund and Kolm [2000] come to a similar conclusion.

Bayindir-Upmann [2000] investigates a general equilibrium model with Cournot competition on the output market for a dirty consumption good. Assuming sticky nominal wages and consumers displaying Cobb-Douglas pref-

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[15] I have not listed all these papers here because this is not the central concern of this article. For an excellent survey see Bovenberg [1999].

erences with respect to clean and dirty goods, Bayindir-Upmann shows that a double dividend resulting in both a reduction in consumption of the dirty good and more employment can be achieved if both the initial labor tax rate and the share of income spent on the dirty good are sufficiently low. However, for the more interesting and more relevant case involving a high initial labor tax rate and a high consumption level for the dirty good, a double dividend does not exist. This is not because raising the tax rate on the dirty good further increases unemployment, but rather because consumption of the dirty good rises so that the environmental dividend is lost. This conversely implies that lowering the tax rate on the dirty good will improve environmental quality but at the same time raise unemployment. The range of parameters for which a double dividend exists shrinks with the degree of competition. Hence the results are less optimistic than in the case of pure monopoly, which is discussed in Bayindir-Upmann [1997]. This result is also consistent with the findings of Fullerton and Metcalf [2002].

It is worth mentioning that many authors of ecological tax-reform literature only consider the comparative statics effects of a revenue-neutral ecological tax reform and do not investigate the second-best optimal tax structure.[16]

4.6.7 Financial Structure of Firms and Emission Taxes

Damania [2000] presents an oligopoly model in which he explicitly takes account of the firms' financial structure. He considers a regime in which the regulator first makes a commitment to his tax rate, and then the firms play a three-stage game. In the first stage they choose the financial structure (level of leverage), in the second they choose their level of abatement (or their abatement technology), and finally they decide on the level of output. Damania shows that higher tax rates can lead to higher output and emission levels. In that model the reason is that an increase of emission taxes increases the probability that firms go bankrupt, so firms will focus only on the solvent states of the world. This in turn encourages firms to increase output and emission levels. One result of this may be that increasing emission tax leads to the adverse effect of raising emissions.

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[16] This does not hold for the most influential paper on the double dividend by Bovenberg and de Mooji [1994] or for other papers by Bovenberg and co-authors.

4.6.8 Dynamic Approach with Capital Accumulation in Clean and Dirty Technology

Stimming [1999] studies the dynamic implications of emission taxes by setting up a Cournot duopoly model where firms can accumulate capital for dirty and clean technologies, respectively. She finds that, for both a tax and a permit regime, a stricter policy induces firms to reduce investment in the dirty technology, whereas the effect on the clean technology is ambiguous. As expected, output and emissions go down. A perverse effect - stricter environmental policy increasing aggregate emissions - can result, if the firms are regulated differently, one by a tax, the other by a standard.

4.6.9 Dominant Firm with a Competitive Fringe

Besides perfect competition and symmetric Cournot oligopoly, Conrad and Wang [1993] also consider the case where the market is governed by both a dominant firm and a competitive fringe. The model is thus similar to Innes et al. [1991], to be discussed in Section 9. The authors only consider the comparative statics effects, they do not investigate the second-best optimal tax rule. The results are as expected. If both the dominant and the competitive firms are subject to the same tax rate, a tax increase induces a decrease of both output and emissions from both types of firm. If the fringe firms are foreign firms not subject to taxation, the effect of an increase in domestic tax may be offset by an increase of foreign emissions (the leakage effect). The authors also investigate abatement subsidies in models of symmetric oligopoly and monopoly, alongside their dominant firm model. They find that, contrary to the case of perfect competition with a fixed number of firms, increasing the subsidy leads to an increase in output. Hence emissions may rise or fall.

4.6.10 Differentiated Emission Taxes

Van Long and Soubeyran [2005] study asymmetric Cournot oligopoly with differentiated taxes. They also take account of the marginal costs of public funds such that the regulator also has a motive for collecting taxes. They find that high-cost firms should be taxed at a higher rate. Moreover, the optimal tax structure leads to an increase in market concentration as measured by the Herfindahl index.

5 Emission Taxes in Price-Setting Duopoly

In this section I treat oligopoly models where firms use prices as strategic variables. I start by outlining the case of genuine Bertrand Competition, i.e. price competition where commodities are homogeneous and firms incur constant marginal costs without being capacity-constrained. Then in Section 5.2, I discuss the case of price competition with differentiated commodities. I have elected to restrict analysis to the duopoly case for several reasons. In the genuine Bertrand case, more than two firms do not lead to any further insights. In the case of differentiated commodities, there are no general symmetric models of price-setting oligopoly with differentiated commodities. Moreover, asymmetric models with more than two firms would require a large amount of notational clutter without yielding any essential additional insights.

5.1 Bertrand Duopoly with Homogeneous Commodities

Requate [1993c] studies price competition among firms that supply a homogeneous good and have constant marginal costs without being capacity-constrained. This kind of competition is usually referred to as real *Bertrand competition.* For this purpose I use the same model as in Section 4.6.1, i.e. two firms producing with constant (asymmetric) marginal costs $c_1 < c_2$ and emitting a pollutant proportional to output, i.e. $e_i = \delta_i q_i$. I consider both cases, where the firm with lower production cost, i.e. firm 1, is also the cleaner firm, i.e. $\delta_1 < \delta_2$, and the case where it is the worse polluter, i.e. $\delta_1 > \delta_2$. The first case is not very interesting since firm 2 will be out of business for any level of tax rates. Therefore we focus on the second case, i.e. $\delta_1 > \delta_2$. Tough competition (of this kind) implies that the tax can always induce only one firm to produce whenever this is socially optimal. However, the regulator is not able to enforce optimal allocation between the two firms when it is socially optimal for both firms to produce. I shall briefly outline the argument. The firms have the same technologies as in Section 4.6.1 but now set prices denoted by p_1 and p_2 rather than quantities. To determine the firm's demand, I follow the standard Bertrand model: If firms charge prices

p_1 and p_2, firm i's demand is given by

$$G_i(p_i, p_j) := \begin{cases} G(p_i) & \text{if} \quad p_i < p_j \quad , \\ Gp_i)/2 & \text{if} \quad p_i = p_j \quad , \\ 0 & \text{if} \quad p_i > p_j \quad , \end{cases} \tag{54}$$

where $G(p)$ is the market demand function.[17] This definition is based on the assumption that consumers are perfectly informed about the prices, that they always buy from the cheaper firm if prices differ and split up equally if prices are equal, and that the firms are not capacity-constrained. The firms' demand functions will be different if we consider regulation by permits, which naturally imposes capacity-constraints on the firms. This will lead us to Bertrand–Edgeworth rather than Bertrand competition and will require a rationing rule. I will return to that case in Section 7.3. In a price-setting game like this, it is well-known that for symmetric firms there is a unique Bertrand–Nash equilibrium where firms charge a price equal to marginal cost. Where, say, $c_1 < c_2$ and $c_2 < p_1^m$, in which p_1^m is firm 1's monopoly price, I follow the industrial organization literature and take $p_1 = p_2 = c_2$ as the unique Bertrand–Nash equilibrium price. Hence I will call $p = \min\{p_i^m, c_j\}$ *the* Bertrand equilibrium price if $c_i < c_j$.

Suppose now that a uniform linear tax is imposed on emissions such that the firm's marginal cost amounts to $c_i + \delta_i \tau$. If $p_i^m(\tau) := \arg\max_p\{[p - (c_i + \tau\delta_i)]G(p)\}$ denotes the monopoly price under an emission tax, the market price under Bertrand competition is given by

$$p(\tau) = \min\{c_j + \tau\delta_j, p_i^m(\tau)\}. \tag{55}$$

From this it can readily be seen that the regulator can always induce only one firm to produce if it is optimal to do so. In this case, the regulator can even induce the first-best outcome by setting the tax equal to

$$\tau = \max\left\{c_i - c_j + \frac{\delta_i}{\delta_j}D'(\delta_i q_i^*), D'(\delta_i q_i^*) + \frac{P'(q_i^*(\tau))q_i^*(\tau)}{\delta_i}\right\}$$

when it is optimal for only firm i to produce. Note that the first term in the bracket refers to the case where the firm to be regulated engages in *limit-pricing*, while the second term refers to *monopoly pricing*. As mentioned above, the first-best allocation cannot be induced if it is optimal for

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[17] I use the letter G for demand instead of D as usually found in textbooks, since I reserve D for the damage function.

both firms to produce, because in this case the social optimum requires the following relationship to hold:

$$c_1 + \delta_1 D'(\delta_1 q_1^* + \delta_2 q_2^*) = c_2 + \delta_2 D'(\delta_1 q_1^* + \delta_2 q_2^*)$$

Setting the tax rate equal to marginal damage would induce identical marginal costs. The demand would then split up equally among the firms, and this does not necessarily correspond to the socially optimal allocation. Requate [1993c] characterizes the second-best optimal tax for such a case in more detail. The tax rate turns out to be discontinuous. Note also that, contrary to the Cournot case, the first-best allocation cannot be induced by a tax-subsidy system in the Bertrand case.

5.2 Price-Setting Duopoly with Differentiated Commodities

Lange and Requate [1999] study price setting duopoly with differentiated commodities. They find that the results obtained previously, i.e. that the second-best optimal tax rate should be set below marginal social damage, is not corrupted under imperfect price competition unless firms are extremely different. This holds true irrespective of whether the commodities are substitutes or complements. Only if the firms are extremely different with respect to both their technology and their market demand functions, is it possible for the second-best optimal tax rate to exceed marginal social damage.

5.2.1 Outline of the Model

There are two firms offering differentiated commodities. The utility of a representative consumer is given by a separable quasi-linear utility function

$$u = U(q_1, q_2) + q_0 - D(e_1, e_2) \tag{56}$$

where commodity 0 is a numeraire with the price normalized to one. The subutility function U is quasi–concave and monotonically increasing. Further assumptions are imposed on the Marshallian demand functions for the two commodities 1 and 2. We use e_1 and e_2 to denote the firms' emissions, as defined below. $D(e_1, e_2)$ denotes the disutility (or damage) caused by the pollution from the two firms. The utility-maximizing consumer clearly sets $U_i \equiv \partial U(q_1, q_2)/\partial q_i = p_i$ where p_i is the price of commodity i. Let $G^i(p_1, p_2)$

denote the solution of this problem, i.e. the demand for commodity i. The two commodities are substitutes (complements) if $G^i_j \equiv \partial G^i/\partial p_j > 0$ (< 0) holds. Further, the authors assume that $G^i_i \equiv \partial G^i/\partial p_i < 0$, and that firm i's revenue $p_i \cdot G^i$ is concave in p_i.

The firms produce with constant marginal costs $c_i \geq 0$, and generate pollution $e_i = \delta_i q_i$ proportional to output. If the firms have to pay an individual tax τ_i (which may be uniform as a special case), the firms' profit is given by

$$\pi^i(p_1, p_2) = (p_i - c_i - \delta_i \tau_i) G^i(p_1, p_2) \quad . \tag{57}$$

5.2.2 Differentiated Emission Taxes

The Nash equilibrium of the simultaneous price-setting game is then determined by the following set of equations:

$$G^i(p_1, p_2) + (p_i - c_i - \delta_i \tau_i) G^i_i(p_1, p_2) = 0 \qquad \text{for } i = 1, 2 \quad . \tag{58}$$

The comparative static effects of *differentiated* taxes are quite intuitive.

Proposition 1 *i)* $\partial p_i/\partial \tau_i > 0$ *for* $i = 1, 2$. *ii)* $\partial p_i/\partial \tau_j > 0$ *if commodities are substitutes and* $\partial p_i/\partial \tau_j < 0$ *if commodity* i *is a complement to commodity* j.

The second-best optimal set of differentiated taxes can be characterized as follows:

$$\tau_i = \frac{\partial D}{\partial e_i} + \frac{G^i}{\delta_i G^i_i} = \frac{\partial D}{\partial e_i} - \frac{p_i}{\delta_i \eta_i} \tag{59}$$

where $\eta_i = -G^i_i p_i / G^i$ denotes the demand elasticity for commodity i.

Note that formula (59) provides the same structure for the second-best optimal tax rates as in the pure monopoly case (see Section 3). Of course, the two rules for τ_1 and τ_2 given by (59) are not independent of each other. But if both marginal damage and demand elasticity are known or can be determined empirically, rule (59) is easy to handle if taxes can be differentiated, especially if the two firms supplying different commodities emit different pollutants.

5.2.3 Uniform Emission Tax

If the regulator can set a uniform tax only, the comparative static effects are less clear-cut. Lange and Requate obtain the following result:

Proposition 2 *i) If the commodities are substitutes, both prices will increase if the tax rate goes up. ii) If the commodities are complements and the firms have asymmetric cost and demand structures, one of the prices may go down.*

The second-best optimal tax rate is now more complicated:

$$\tau = \frac{\delta_1 \frac{\partial D}{\partial e_1}\frac{dG^1}{d\tau} + \delta_2 \frac{\partial D}{\partial e_2}\frac{dG^2}{d\tau} + \frac{G^1}{G^1_1}\frac{dG^1}{d\tau} + \frac{G^2}{G^2_2}\frac{dG^2}{d\tau}}{\delta_1 \frac{dG^1}{d\tau} + \delta_2 \frac{dG^2}{d\tau}} \quad . \tag{60}$$

If the pollutant is uniform, i.e. if $D(e_1, e_2) = \widetilde{D}(e_1 + e_2)$ implying $\partial D/\partial e_1 = \partial D/\partial e_2 = \widetilde{D}'$, we obtain

$$\tau = \widetilde{D}' + \frac{\frac{G^1}{G^1_1}\frac{dG^1}{d\tau} + \frac{G^2}{G^2_2}\frac{dG^2}{d\tau}}{\delta_1 \frac{dG^1}{d\tau} + \delta_2 \frac{dG^2}{d\tau}} \quad . \tag{61}$$

If firms are sufficiently similar, i.e. $G^1 \approx G^2$ and $G^1_1 \approx G^2_2$ as well as $\delta_1 \approx \delta_2$, the formula for the optimal tax rate approximates

$$\tau \approx \widetilde{D}' + \frac{G^i}{\delta_i G^i_i} \quad . \tag{62}$$

Note that this is independent of whether the two commodities are complements or substitutes.

If firms are extremely different, however, the second term on the right hand side of (61) taking accounting of the strategic interaction between the firms may be positive, resulting in a second-best optimal tax rate that *exceeds* marginal damage. Lange and Requate [1999] present a numerical example where this is in fact the case. The reason for the high tax rate in that example is firm 1's extreme advantage with respect to private cost. In order to offset this advantage and to cut down emissions, the regulator has to choose a tax rate that is higher than marginal damage.

6 Monopolistic Competition and Free Entry

In this section I summarize models of imperfect competition where the number of firms is determined endogenously. The industrial organization literature offers three prototype models of this kind: Cournot competition with free entry, the Dixit-Stiglitz model of product differentiation, and Salop's model of the circular city. Katsoulacos and Xepapadeas [1995], Requate [1997], and S.-H. Lee [1999] all investigate the Cournot model with free entry by polluting firms. Lange and Requate [2000] discuss the two remaining models of monopolistic competition. In all these papers, the authors proceed on the assumption that an emission tax is the only policy instrument available to the regulator. Therefore it is important to emphasize that this instrument now has to deal with three market imperfections: firms pollute, their prices are higher than is socially optimal, and the number of firms is not optimal (in general). In particular, the Cournot model leads to excessive market entry by firms in the absence of regulation. Therefore it may be the case that the second-best optimal tax rate *exceeds* marginal social damage, which contrasts with the results obtained so far.

6.1 Emission Taxes in Cournot Oligopoly with Free Entry

The material of this subsection is based on Requate [1997]. Katsoulacos and Xepapadeas [1995] study a special case of this model, assuming linear demand and a cost function additively separable into output and emissions. S.-H. Lee [1999] replicates the results of Requate [1997] focusing on the case where pollution is proportional to output. Here, we will study both cases, i.e. where firms have abatement technologies and where emissions are completely determined by output. For the latter case we obtain the neat result that the second-best optimal tax rate equals marginal damage if demand is linear.

6.1.1 Basic Assumptions and the Firms' Behavior

Throughout this section I assume that firms are symmetric.[18] Since the number of firms is determined endogenously by a zero-profit condition, we need to explicitly take account of fixed costs. Hence I write the costs as $C(q) = v(q) + F$ if emissions are proportional to output, i.e. $e = \delta \cdot q$, and $C(q, e) = v(q, e) + F$ if the cost function satisfies Assumption 4.

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[18] In models of free entry this is a standard assumption. It can be justified by arguing, first that only firms using technologies inducing the lowest average costs will prevail, and second, that if several technologies are randomly drawn from a continuous distribution of parameters, it is extremely unlikely that two different technologies will induce the same average cost.

Further, I only consider the case where the regulator moves first by making a commitment to his tax rate. In the second stage, firms decide whether or not to enter the market, and in the third stage they engage in Cournot competition. For the case where emissions are proportional to output, the Nash equilibrium condition in the last stage (assuming the existence of an interior Cournot Nash solution with output $q^* > 0$) is given by[19]

$$P'(Q^*)q^* + P(Q^*) - v'(q^*) - \tau\delta = 0 \quad . \tag{63}$$

In the second stage of the regulation game, a number $n^*$of firms enters the market until all firms earn zero profits:

$$P(n^*q^*)q^* - v(q^*) - F - \tau\delta q^* = 0 \quad . \tag{64}$$

If abatement is possible, i.e. if the firms' cost functions satisfy Assumption 4, a Nash equilibrium in the last stage (again assuming an interior equilibrium $q^* > 0$, $e^* > 0$) is characterized by

$$\begin{aligned} P'(Q^*)q^* + P(Q^*) - v_q(q^*, e^*) &= 0 \quad , & (65) \\ -v_e(q^*, e^*) &= \tau \quad . & (66) \end{aligned}$$

Free entry in the second stage yields

$$P(n^*q^*)q^* - v(q^*, e^*) - F - \tau e^* = 0 \quad . \tag{67}$$

6.1.2 The Government's Problem

Employing the usual procedure of welfare maximization leads to the following second-best optimal tax formula:

$$\tau = D'(E) + P'(Q)\frac{Q \cdot (dq/d\tau)}{dE/d\tau} \quad . \tag{68}$$

The sign of $dE/d\tau$ is ambiguous in general. However, one can derive the following result:

Proposition 6 *Under symmetric oligopoly with free entry where the firms' technologies satisfy Assumption 4, the second-best optimal emission tax rate exceeds marginal social damage if*

i) $v_{qe} = 0$ *and* P *is (weakly) convex,*

or if

ii) $v_{qe}q + v_{ee}e \geq 0$ *and* P *is linear.*

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[19] Our assumptions guarantee that an equilibrium exists and that it is unique and stable.

In the case of emissions proportional to output, one can even show that the following holds:

Proposition 7 *In a symmetric oligopoly with free entry and emissions proportional to output, the second-best optimal emission tax rate is given by*

$$\tau = D'(E) + \frac{P'QP''q}{\delta[v'' - 2P']} \quad . \tag{69}$$

The second-best optimal tax rate

a) exceeds marginal damage if demand is strictly concave,

b) falls short of marginal damage if demand is strictly convex,

c) is equal to marginal damage if demand is linear.

We see that if no abatement technology exists, the second-best optimal emission tax rate equals marginal damage for linear demand despite imperfect competition. Thus we obtain the same result as under perfect competition, which again is interesting in the light of Buchanan's [1969] early attack on the Pigouvian tax rule. This result also contrasts with Katsoulacos and Xepapadeas [1995], who find that for linear demand the second-best optimal tax rate exceeds marginal damage if the marginal abatement costs are independent of the level of output.

Note that in the case where no abatement technology exists we consider a situation where the regulator has only one instrument to regulate two market imperfections: the wrong quantity of output (and hence pollution), plus excessive entry by firms. Little can be said in general about whether output is too high or too low. On the one hand, individual firms hold down output due to imperfect competition; on the other, individual firms do not account for the social damage caused by pollution, which in this case is strictly proportional to output.

If the number of firms were fixed or regulated by another device, such as a license scheme (as is the case in many taxi markets), the regulator could implement the first-best outcome precisely by taxing either emissions or output.

In the case of free entry, however, the potential rents earned by virtue of imperfect competition attract more firms. Since there is excessive entry by firms, they produce and thus pollute to a higher degree than is optimal, and they dissipate fixed costs. To mitigate this excess entry effect, the regulator has to set the second-best optimal tax rate higher than in the case where the number of firms is exogenous. Whether this tax rate is higher or lower than marginal damage, depends, as we have seen, on the curvature of the inverse demand function.

Note that in the case where demand is linear and emissions are proportional to output (Proposition 7), we can neither conclude that the emission tax implements the first-best outcome nor that the second-best optimal emission tax rate regulating an oligopoly with an endogenous number of firms is the same as for regulating a competitive market. Since under imperfect competition the firms price higher than marginal cost, they produce less and accordingly also pollute less than under perfect competition. Hence, in oligopoly with an endogenous number of firms and linear demand, the second-best optimal tax rate has to be set lower than in the case of perfect competition.

The results summarized so far have been derived under the assumption that all the existing firms are identical. Requate [1997] also discusses the case of several possible technologies. Even though generically only one technology will survive, there may exist other potential, possibly cleaner technologies that may be used if a suitable environmental policy is implemented. Requate [1997] shows that for at most one particular tax rate two *different* firms can be active at the same time. However, although from a social point of view it may be optimal for different types of firms to share the market, a regulator will not in general be able to enforce the desired technology mix by setting an appropriate Pigouvian tax. The reason is that under free entry a multiplicity of equilibria exists. The various equilibria, however, lead to different levels of pollution, some with excessive, others with too little pollution.[20]

6.2 Standards

In this section we briefly investigate standards in oligopoly with free entry. We start with absolute emission standards and then look at relative standards. I only consider the case where the firms' technologies satisfy Assumption 4.

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[20] This phenomenon does not depend on the assumption of imperfect competition but also materializes under perfect competition. See Requate [1995], Requate and Unold [2001] and [2003].

6.2.1 Absolute Emission Standard

In addition to the first-order Nash equilibrium condition (52), the zero-profit condition must again hold. The comparative statics exercise now yields

$$\begin{aligned}\frac{dq}{d\bar{e}} &= \frac{P'C_{qe}q - C_e[P' + P''q]}{P'q[2P' + P''q - C_{qq}]} \\ \frac{dn}{d\bar{e}} &= \frac{(n-1)P'C_{qe}q + C_e[(n+1)P' + nP''q - C_{qq}]}{P'q[2P' + P''q - C_{qq}]} > 0\end{aligned}$$

The last effect implies that a stricter emission standard leads to market exit. By contrast, the effect on output is ambiguous.

The second-best optimal standard satisfies the following condition:

$$-C_e(q, \bar{e}) = D'(E)\left[1 + \frac{e}{n}\frac{dn}{d\bar{e}}\right] + P'(Q)q\frac{dq}{d\bar{e}}$$

This gives us the following result:

Proposition 3 *If a Cournot oligopoly with free entry is regulated by an absolute emission standard, then*

1. *the second-best optimal standard can be greater or smaller than marginal damage.*
2. *If* $\frac{dq}{d\bar{e}} < 0$*, then it will exceed marginal damage.*

6.2.2 Relative Standards

Next I consider the effect of a relative standard restricting units of emissions per output: $e \leq \alpha q$. If the standard is binding, the firms' profits can be written as $P(Q)q - C(q, \alpha q)$. The equilibrium is now given by the Nash condition (53) and the zero-profit condition. The comparative statics exercise yields:

$$\begin{aligned}\frac{dq}{d\alpha} &= \frac{-C_e[P' + P''q] + P'(C_e + q(C_{qe} + \alpha C_{ee})}{P'[P''q + 2P' - (C_{qq} + 2\alpha C_{qe} + C_{ee})]} \\ \frac{dn}{d\alpha} &= \frac{C_e[nP''q + (n+1)P' - (C_{qq} + 2\alpha C_{qe} + C_{ee})]}{P'q[P''q + 2P' - (C_{qq} + 2\alpha C_{qe} + C_{ee})]} \\ &\quad - \frac{-(n+1)P'[C_e + q(C_{qe} + \alpha C_{ee})]}{P'q[P''q + 2P' - (C_{qq} + 2\alpha C_{qe} + C_{ee})]}\end{aligned}$$

Now both $dq/d\alpha$ and $dn/d\alpha$ are completely ambiguous. However, the change of total output is given by

$$\frac{dQ}{d\alpha} = \frac{d[nq]}{d\alpha} = \frac{C_e[P' - (C_{qq} + 2\alpha C_{qe} + C_{ee})] + P'[C_e + q(C_{qe} + \alpha C_{ee})]}{P'q[P''q + 2P' - (C_{qq} + 2\alpha C_{qe} + C_{ee})]}$$

This term cannot be signed in general but is positive for quadratic cost functions.[21]

The second-best optimal relative standard now satisfies the following condition:

$$-C_e(q, \alpha q) = D'(E)\left[1 + \frac{\alpha}{Q}\frac{dQ}{d\alpha}\right] + P'(Q)\frac{dq}{d\alpha}$$

If we compare the term for $dq/d\alpha$ to $dQ/d\alpha$, we see that $dQ/d\alpha$ is larger than $dq/d\alpha$ if $P'' \leq 0$ or $|P''|$ is sufficiently small. Hence, if $dq/d\alpha$ is positive (which is the case for example for quadratic cost functions) the term $\frac{\alpha}{Q}\frac{dQ}{d\alpha}D'(E)$ dominates the term $P'(Q)\frac{dq}{d\alpha}$, which accounts for the distortion resulting from imperfect competition. The intuition here is that the oligopoly rent attracts more firms than is optimal, and due to the relative standard more firms induce more pollution. Therefore the standard has to be set more strictly than in the case where the number of firms is exogenous, meaning that the marginal abatement costs exceed marginal damage.

6.3 The Dixit–Stiglitz Model

In this subsection, I present the implications for environmental policy in *the* prototype model of imperfect *price* competition with free entry, i.e. the Dixit-Stiglitz-Spence model. I extend that model by assuming that the differentiated commodity is produced by emitting a pollutant that is proportional to output. The pollutant is subject to taxation. The social damage is measured in units of the numeraire commodity. We establish that the second-best optimal tax rate is always lower than marginal damage. Contrasting with the Cournot model this suggests that the Dixit-Stiglitz model does not lead to excess entry in a way requiring the regulator to set a tax rate above marginal damage. Moreover, we find that the more competition we have, the closer

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[21] If $C(q, e) = [\beta q - e]^2/2$, then the last term boils down to $C_{qe} + \alpha C_{ee} = \alpha - \beta$ which is smaller than zero if the relative standard bites, i.e. $\alpha < \beta$. All the other terms of the numerator are positive under the assumptions we make throughout this chapter.

we should set the second-best optimal tax rate to marginal social damage. These results hold true under rather general conditions. On the one hand, the result is quite intuitive and is in line with what we already know about the regulation of monopolistic firms. On the other, the result is not completely obvious in the light from the findings from the Cournot model with free entry.

6.3.1 Outline of the Model

In the Dixit-Stiglitz model, the representative consumer draws utility from $n+1$ commodities, a compound commodity I that is supplied in n different varieties, and a numeraire commodity 0. The consumer also suffers from the aggregate level of pollution $E=\sum_{i=1}^{n} e_i$, where e_i is the amount of pollution generated by firm i. The damage from pollution, measured in units of the numeraire commodity, is denoted by $D(E)$. Thus we can write the utility as

$$u = U\left(\left(\sum_i q_i^{\rho}\right)^{1/\rho}, q_0 - D(E)\right),$$

where $q_0 = M - \sum_{i=1}^{n} p_i q_i + \tau E$ is the consumption of the numeraire commodity, i.e. gross income M minus expenditures for the commodities $i=1,\ldots,n$, plus tax revenues that are redistributed to the consumer in a lump sum way. The price for commodity i is denoted by p_i, while the price for commodity 0 is normalized to 1.

Moreover, it is usually assumed that the numeraire commodity 0 and the compound commodity I are normal goods. Then utility maximization leads to the following relationship:

$$p_i U_0 = \left(\sum_i q_i^{\rho}\right)^{1/\rho - 1} q_i^{\rho-1} U_I \qquad \text{for } i = 1,\ldots,n \quad .$$

where U_0 and U_I are the partial derivatives of utility with respect to the numeraire and the compound commodity, respectively. If n is large, a change of price p_i and thus a change in demand for commodity i has little effect on $\sum_{j=1}^{n} q_j^{\rho}$ and hence little effect on U_0 and U_I.[22] Accordingly, the demand for commodity i can be approximated by

$$q_i(p_i) \approx k \cdot p_i^{\frac{1}{\rho-1}} \tag{70}$$

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[22] See Tirole [1988], pp. 298-299.

where k is a constant.

The firms produce at constant marginal cost $c > 0$ and incur fixed costs $F > 0$. To keep the model simple, pollution is assumed to be proportional to output. Therefore without loss of generality we can identify pollution with output. If the government charges a tax τ on pollution, a typical firm's profit – if it decides to enter the market – is given by

$$\Pi_i = (p_i - c - \tau)q_i(p_i) - F \approx (p_i - c - \tau)k \cdot p_i^{\frac{1}{\rho-1}} - F.$$

Profit maximization leads to the monopoly price

$$p_i = \frac{(c+\tau)}{\rho}.$$

Zero profit through free entry implies

$$q_i = \frac{F}{s(c+\tau)} \quad , \tag{71}$$

where $s = 1/\rho - 1$. Thus a symmetric equilibrium consisting of a price p, a firm's output q, and the number of firms n as endogenous variables is represented by the following equations:

$$\begin{aligned} p &= \frac{(c+\tau)}{\rho} \quad , && (72)\\ q &= \frac{F}{s(c+\tau)} \quad , && (73)\\ \frac{U_I(A,B)}{U_0(A,B)} &= n^{-s}\frac{(c+\tau)}{\rho} \quad , && (74) \end{aligned}$$

where, using (71) and employing symmetry in the consumption of the differentiated goods, the expressions A and B are defined as:

$$\begin{aligned} A &= I - npq + n\tau q - D(nq) = I - n\left(F + c\frac{F}{s(c+\tau)}\right) - D\left(n\frac{F}{s(c+\tau)}\right)\\ B &= n^{1/\rho}q \end{aligned}$$

We are now ready to investigate the comparative statics effects of raising the tax rate and look for the structure of the second-best optimal tax rate.

6.3.2 The Effect of Increasing the Tax Rate

One interesting aspect is the question of how an introduction or increase of an emission (or output) tax affects the endogenous variables of the model. Unfortunately, these effects are quite ambiguous. It may even be the case that both the number of firms and total emissions will rise as a result of increasing the emission tax.[23] If we assume a fully quasi-linear utility function by specifying

$$U(q_0 - D(E), q_I) = q_0 - D(E) + V(q_I),$$

where $q_I = n^{1/\rho} q$, we can say rather more about the relationship between the size of the tax rate and the number of firms.

Proposition 4 *Denoting the elasticity of marginal utility by* $\eta = -\frac{V''(q_I)q_I}{V'(q_I)}$, *we obtain*

$$dn/d\tau < 0 \quad \textit{if and only if} \quad 0 < 1 - \eta < \rho$$

Note, however, that if we assume that demand for each particular product decreases as the number of firms goes up, i.e. product diversity increases (the price being held fixed), it follows that[24]

$$1 - \eta - \rho < 0 \tag{75}$$

If we further assume that $\eta < 1$,[25] we obtain $n' < 0$. Both assumptions together also guarantee the existence of a finite number of products (=firms) in the first-best allocation, given an arbitrary social damage function. Hence $dn/d\tau < 0$ is more likely to hold, although $dn/d\tau > 0$ cannot be excluded.

6.3.3 The Second-Best Optimal Tax Rate

We are now able to make a general statement about the second-best optimal tax rate:

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[23] Lange and Requate (2000) provide a numerical example for such a case.

[24] Dixit and Stiglitz [1976], p.298, refer to this assumption in their original model as the "natural" case.

[25] This assumption corresponds to price elasticity of demand for the compound commodity that is greater than 1. Assume for a moment that n firms collude and jointly maximize their profits. Then $\eta < 1$ is a necessary condition for guaranteeing the existence of a joint profit maximum.

Proposition 8 *If in the Dixit–Stiglitz model pollution is proportional to output and the emission tax is the government's only regulatory device, the second-best optimal emission tax rate is smaller than marginal social damage.*

Interestingly, it is not possible to obtain a rule similar to the case of monopoly or oligopoly stating that the *"tax rate is equal to marginal social damage plus a (negative) term taking account of imperfectly competitive behavior"*. Rather, one can show that $\frac{c+\tau}{c+D'}$ is smaller than one, implying $\tau < D'$. In contrast to the Cournot model this suggests that the Dixit-Stiglitz model does not lead to excess entry in a way requiring the regulator to set a tax above marginal social damage. Note that a complete analysis of excess entry at this stage is not possible. In general there are several conflicting forces that lead to a deviation from the social optimal level in the number of firms. Spence [1976] analyzes the problem of excess entry in a standard model of monopolistic competition, i.e. without social damage caused by production. Even in this context, the question of excess entry cannot be answered generally but only for some special cases. In addition, in our model the impact of an increase in the tax rate on the number of firms is ambiguous. Hence we are not able to compare the number of firms to the socially optimal level.

For the case of quasi-linear utility functions, Lange and Requate [1999] show the following neat convergence result:

Proposition 9 *Assume that $1 - \eta - \rho < 0$ for ρ close to one. Then, the higher the degree of competition, i.e. the better substitutes the goods are (the closer ρ is to one), the closer the second-best optimal tax rate is to marginal social damage. In the limit, i.e. $\rho = 1$, when the commodities become perfect substitutes, the second-best optimal tax rate coincides with marginal social damage.*

The results obtained in this section confirm generally accepted wisdom on second-best taxation for imperfect competition, i.e. the second-best optimal tax rate falls short of marginal social damage but converges to it as competition gets tougher. On the one hand, this result is satisfactory since it does not contradict our knowledge about second-best taxation of a monopolist; after all, pure monopolies rarely exist since every monopolist competes with other firms in some way. On the other hand, the result is not trivial, since from Cournot competition with free entry we know that the second-best optimal emission tax rate may exceed marginal damage with a view to mitigating excess entry.

6.4 Salop's Model of the Circular City

However, if the goods under consideration are physically identical but only differ with respect to their location, the conclusion in Proposition 8 does not necessarily hold in general. To show this, Lange and Requate [1999] discuss an extended version of Salop's model of the circular city. For this purpose the authors slightly modify Salop's original model by relaxing the usual assumption of unit demand, but rather assuming downward sloping demand in order to obtain variable aggregate output and thus variable pollution (otherwise environmental policy such as taxation would not be very interesting).

6.4.1 Outline of the Model

Each consumer has elastic demand for the consumption good supplied by n firms located on a circle with perimeter 1. Consumers are also located uniformly on the circle with density one. The utility of a consumer with distance x to the closest firm is given by

$$u_x = U(q) - pq - tx \quad ,$$

where q is the quantity of the commodity consumed, p is its price, and t is the consumer's marginal transportation costs. Let $q(p)$ denote the consumer's Marshallian demand and $V(p) := U(q(p)) - pq(p)$ the consumer's gross indirect utility function, i.e. the utility disregarding the transportation costs. To obtain a concave revenue function the authors assume that $2(q')^2 - qq'' > 0$ holds.

As in the last section, the firms are identical, they produce with constant marginal costs $c \geq 0$ and pollute proportional to output. For simplicity we again identify pollution with output. Given that the firms are located at equal distances around the circle and all potential competitors offer the good at price p, the demand for firm i's good is given by

$$G^i(p_i, p) = q(p_i)\left[\frac{V(p_i) - V(p)}{t} + \frac{1}{n}\right]$$

where the second term is the share of consumers buying at firm i. If the firms are subject to an emission tax which in this case can also be charged on output, a firm's profit is determined by

$$\begin{aligned}\pi^i(p_i,p) &= [p_i-c-\tau]\,G^i(p_i,p)\\ &= [p_i-c-\tau]\,q(p_i)\left[\frac{V(p_i)-V(p)}{t}+\frac{1}{n}\right] \quad .\end{aligned}$$

Profit maximization leads to the following first-order condition which is also the Nash-equilibrium condition in the second stage of the game, once the firms have entered the market.

$$\begin{aligned}\frac{\partial\pi^i}{\partial p_i} &= G^i(p_i,p)+[p_i-c-\tau]\,q'(p_i)\left[\frac{V(p_i)-V(p)}{t}+\frac{1}{n}\right]\\ &\quad +[p_i-c-\tau]\,q(p_i)\frac{V'(p_i)}{t}=0 \quad . \end{aligned} \tag{76}$$

Using Roy's identity, i.e. $V'(p_i)=-q(p_i)$, and the symmetry of equilibrium we can write: $p=p_i$ and $q=q(p)$. Further we write $q':=q'(p)$. Thus, the first order Nash-equilibrium condition (76) becomes

$$q+(p-c-\tau)\left[q'-q^2\frac{n}{t}\right]=0 \quad . \tag{77}$$

Zero profits yield

$$(p-c-\tau)\frac{q}{n}=F \quad . \tag{78}$$

6.4.2 The Effect of Increasing the Tax Rate

Now we investigate the impact of raising the emission rate. Differentiating the system (77) and (78) with respect to the tax rate τ, and solving for both $p'=dp/d\tau$ and $n'=dn/d\tau$ yields (for details of the algebra see Lange and Requate [1999]):

$$p' = \frac{q'-2q^2\frac{n}{t}}{2q'-2q^2\frac{n}{t}+(p-c-\tau)(q''-3qq'\frac{n}{t})} \quad . \tag{79}$$

$$n' = \frac{(p-c-\tau)(2(q')^2-qq'')}{F\left[2q'-2q^2\frac{n}{t}+(p-c-\tau)(q''-3qq'\frac{n}{t})\right]} \quad . \tag{80}$$

The denominators are clearly negative by the firms' second-order conditions of profit maximization. Thus $p'>0$. Since we have further assumed that the firms' revenue is concave, i.e. $2(q')^2-qq''>0$, we obtain $n'<0$. Thus the price rises and the number of firms fall if the emission tax is raised, as we would have expected.

6.4.3 The Second-Best Optimal Tax Rate

We now turn to the regulator's problem. If we again assume that the tax is the only instrument available to the regulator, she or he maximizes welfare defined as follows

$$W(\tau) := U(q(p)) - 2nt \int_0^{\frac{1}{2n}} s ds - cq(p) - nF - D(q(p)) \quad , \tag{81}$$

where p and n, determined by (77) and (78), are functions of the tax rate. Note that the second term on the right hand side of (81) takes account of the consumers' transportation costs. It is easy to calculate that this term is equal to $\frac{t}{4n}$.

Differentiating (81) with respect to the tax rate and solving for τ yields

$$\tau = D'(E) + \frac{q}{q' - q^2 \frac{n}{t}} - \frac{n'}{p'q'} \left(\frac{t}{4n^2} - F \right) \quad . \tag{82}$$

Since up to now we have not made use of the zero-profit condition in this subsection, we immediately obtain the following result:

Proposition 10 *If the number of firms is fixed or if a regulator has direct control over it, for example by a licence scheme, the second-best optimal tax rate is given by*

$$\tau = D' + \frac{q}{q' - q^2 \frac{n}{t}} \tag{83}$$

and thus falls short of marginal damage.

Let us now get back to the case where the regulator has no direct control over n. Since the second term of (82) is clearly negative and both $n' < 0$ and $p' > 0$ hold, the second best tax rate falls short of marginal damage if $F < \frac{t}{4n^2}$. However, Lange and Requate [1999] show by example that in equilibrium the last inequality may also be reversed. Thus the second-best optimal tax rate may exceed of fall short of marginal damage. Thus paralleling the Cournot model, there is excessive entry in the extended version of the Salop model. Since the second-best optimal emission tax has to correct for three market imperfections, i.e. pollution, too little output per firm, and too many firms entering the market, the latter may be suff

7 Permit Trading in Oligopoly

In standard oligopoly theory, the firms' technologies are represented by their cost functions. In doing so, one implicitly assumes that the firms behave as price-takers in all factor markets. If an industry is regulated by issuing tradable permits, those permits can be considered an additional input. If the firms behave competitively on the market for permits, the price for permits has the same impact as an emission tax on the firms. In the fully competitive model, the regulator could issue a suitable number of permits instead of charging an emission tax. Firms, however, will only behave as price-takers if the number of firms is large. Since in oligopoly the number of firms is small by definition, competitive behavior on the permit market can only be justified if there are other firms outside the oligopolistic industry that operate on the same permit market. For pollutants arising in many different production processes, such as CO, CO_2, NO_x and others, this will certainly be a realistic assumption. However, in some industries, for example the chemical industry, pollutants are emitted that are specific to that industry, i.e. the few competitors on the output market are the only emitters of a certain pollutant. In this section, I discuss this kind of industry structure. In the next subsection I start with a duopoly model, then going on to discuss why it is difficult to extend the approach to more than two firms.

7.1 Cournot Duopoly

I begin my discussion with Cournot competition, presenting an adapted version of von der Fehr's [1993] model.[26] Requate [1993a] independently develops a similar model, assuming, however, that the firms' technologies are linear.[27] We proceed on the assumption that the government issues (grandfathers) a number of permits denoted by L. The process in the economy can be divided into two stages. Initially, the firms hold an endowment (l_1, l_2) of permits with $l_1 + l_2 = L$. In the first stage, they are allowed to trade, i.e. one firm sells some or all permits to the other firm. Firms thus end up with a new allocation of permits $e = (e_1, e_2)$ where $e_1 + e_2 = L$. In the second stage, firms engage in Cournot competition and choose quantities $q_1(e)$, $q_2(e)$ given

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[26] In fact, von der Fehr's model is slightly more general since he allows for quantity competition with differentiated products.

[27] This means that firms have constant marginal costs and emissions are proportional to output.

the allocation of permits $e = (e_1, e_2)$.

Writing $Q(e) = q_1(e) + q_2(e)$, a Cournot–Nash equilibrium $(q_1(e), q_2(e))$ then satisfies the following conditions for $i = 1, 2$:

$$\begin{array}{lrcl}
 & P'(Q(e))q_i(e) + P(Q(e)) - C_q^i(q_i(e), e_i) & \leq & 0 \quad [= 0 \text{ if } q_i(e) > 0] \quad , \\
 & \text{if} \quad C_e^i(q_i(e), e_i) & < & 0 \quad , \\
\text{and} & P'(Q(e))q_i(e) + P(Q(e)) - C_q^i(q_i(e), \hat{e}_i) & \leq & 0 \quad [= 0 \text{ if } q_i(e) > 0] \\
 & \text{if } \exists\ \hat{e}_i < e_i \text{ such that} \quad C_e^i(q_i(e), \hat{e}_i) & = & 0 \quad , \ i = 1, 2.
\end{array}$$

Note that we have to allow for corner solutions here because one firm might buy all the permits from the other firm. If firm i produces, i.e., $q_i(e) > 0$, and the permit constraint is binding, the first-order (Nash equilibrium) conditions reduce to

$$P'(Q(e)) \cdot q_i(e) + P(Q(e)) - C_q^i(q_i(e), e_i) = 0 \quad \text{for } i = 1, 2. \tag{84}$$

To figure out how the firms will trade the permits in the first stage, we have to study the gains from trade. For this purpose we use $\Pi_i^N(e_1, e_2)$ to denote the profit of firm i if the final allocation of permits in the first stage is (e_1, e_2) and both firms choose Nash quantities in the second stage. Observe that starting from any allocation $(l_{1,} l_2)$ a gain from trade will be fully conditional on the existence of an allocation (e_1, e_2) such that

$$\Pi_1^N(l_1, l_2) + \Pi_2^N(l_1, l_2) < \Pi_1^N(e_1, e_2) + \Pi_2^N(e_1, e_2) \quad .$$

In this case there exists a real number T that is interpreted as a *transfer payment* from firm 1 to firm 2 (which may of course be negative), such that

$$\begin{array}{rcl}
\Pi_1^N(e_1, e_2) + T & > & \Pi_1^N(l_1, l_2) \quad , \\
\Pi_2^N(e_1, e_2) - T & > & \Pi_2^N(l_1, l_2) \quad .
\end{array}$$

This is the same procedure as in the model for several local monopolists (see subsection 3.5.3). We do not need to bother about how the firms figure out T. For example, they could agree on the Nash–bargaining solution. The maximum gain from trading permits is then determined by

$$\max_{e_1, e_2} \left[\Pi_1^N(e_1, e_2) + \Pi_2^N(e_1, e_2)\right] \qquad \text{s.t. } e_1 + e_2 \leq L,\ e_1 \geq 0,\ e_2 \geq 0. \tag{85}$$

On the assumption that firms behave as profit-maximizers, it is natural to make the following assumption:

Assumption 5 *Firms trade permits in the first stage such that the final allocation* (e_1^*, e_2^*) *solves (85).*

Note that this assumption also allows for the case of one firm buying all the other firm's permits and thus resulting in a monopoly on the market. Observe further that the solution of (85) does not depend on the initial allocation (l_1, l_2), in contrast, of course, to the final profits (net transfer payments). But we need not be concerned about this as the distribution of profits among the firms does not affect welfare.

Thus, by virtue of the institutional permit-market framework, cooperation becomes feasible to a limited degree. Since by anti–trust laws it is usually forbidden for firms to sign binding contracts to maximize joint industry profits, firms can do no better than choosing Nash quantities. However, if firms buy or sell pollution permits, they implicitly commit either to a direct capacity constraint - in case that pollution is strictly proportional to output and no additional abatement technologies exist - or to extremely high production costs which amounts to an indirect capacity constraint. Hence, by trading permits, the firms can achieve joint maximization of Cournot–Nash profits.

I shall not work out the maximization problem of (85) here. It is important to note, however, that for no solution of (85) can it be the case that both firms hold permits and at the same time the permit constraint is not binding on one of the firms. Otherwise a firm i would have idle pollution capacity and would engage at the same time in Cournot competition with the other firm. In this case, firm i could increase its profits by buying all the permits from firm j, thus establishing a monopoly position. On the other hand, monopoly does not necessarily maximize total industry profits as if both firms incur sharply increasing marginal production costs, it might be more profitable for both of them to share both the permits and production with one another, despite Cournot competition in the second stage.

Solving the regulator's problem is quite a complicated matter due to the sequential nature of the firms' game. One can show, however, that if the firms trade the permits so that they both hold permits in equilibrium, the regulator's optimal permit supply satisfies the following conditions:

$$
\begin{aligned}
&D'(L) + P'(Q(e(L))[Q(L)Q'(L) - \\
&\qquad \left\{ q_1((e(L))\frac{\partial q_2(e(L))}{\partial e_i} + q_2(e(L))\frac{\partial q_1(e(L))}{\partial e_i} \right\}] \\
&= \lambda = -C_e^i(q_2(e(L)), e_2(L))
\end{aligned}
$$

where λ is the Lagrange multiplier with respect to constraint $e_1 + e_2 = L$ and $\partial q_i / \partial e_j$ is the reaction of firm i with respect to output if firm j obtains more permits. Note that if the term in curled brackets is positive for one firm, it must be negative for the other firm, since $\partial q_i/\partial e_j = -\partial q_i/\partial e_i$. This implies that in general we will have

$$
-C_e^1(q_1(L), e_1(L)) \neq -C_e^2(q_2(L), e_2(L))
$$

i.e. the firms do not level out their marginal abatement costs. In the first stage of the game, for strategic reasons the firms commit to an inefficient distribution of permits and thus to an inefficient cost structure in order to commit to lower output, thus extracting a higher rent in the second stage of the game when they engage in Cournot competition. The Lagrange multiplier λ can be interpreted as the opportunity cost of shifting a permit from one firm to the other. Accordingly, it is the oligopolistic industry's shadow price for pollution.

Von der Fehr [1993] emphasizes that allowing for trade may in fact be welfare-decreasing since it leads to monopolization in the permit market. Sartzetakis and McFetridge [1999] offer a graphical analysis illustrating how permit trading in duopoly affects and shifts the firms' reaction curves in the output market.

7.2 Welfare Comparison between Permits and Taxes

The fact that in general, marginal abatement costs are not equalized across firms if they trade permits strategically, does not however necessarily imply that regulating duopoly by permits is, in general, more inefficient than regulation by emission taxes. To see this, consider the simple linear model developed in Requate [1993a] where firm 1 has lower marginal costs $c_1 < c_2$ but emits more pollutants per unit of output, i.e. $\delta_1 > \delta_2$. Assume that the social damage function is relatively steep so that it is socially optimal for the "cleaner" firm 2 to serve almost the whole market, whereas firm 1 should produce only very little. Under a permit regime it may be optimal to issue a small number of permits so that firm 2 does indeed buy almost all the permits, while under taxes the worse polluting firm 1 produces too much. For the case of linear technologies assumed in Section 4.6.1, Requate [1993a] fully characterizes the regions where taxes and permits lead to higher welfare, depending on a damage parameter that determines the slope of the damage function. The bottom line of that analysis is that, in general, neither policy is superior to the other, i.e. for some parameters the second-best optimal permit policy yields higher welfare than the second-best optimal tax policy, whereas for other damage parameters the opposite is true.

7.3 Price Competition

If firms engage in price competition we end up with Bertrand-Edgeworth rather than Bertrand competition, since firms face either increasing marginal costs or they are capacity-constrained if they have linear technologies and emissions are proportional to output. It is well known that under Bertrand-Edgeworth competition, pure strategy equilibria do not exist in general. For the case of linear technologies, however, Requate [1993a] shows that the firms trade the permits in such a way that the Cournot outcome is a pure strategy equilibrium (see Kreps and Scheinkman [1983]). Again, the welfare comparison with the tax regime is ambiguous.

7.4 Permit Trading and Subsidies on Output

Requate [1993a,c] shows that, in the case of linear technologies, subsidies on output and permits to regulate emissions always lead to the first-best allocation, irrespective of whether firms engage in quantity (Cournot) or in price (Bertrand) competition. The intuition is the same as in the case of taxes. The regulator has two instruments for dealing with two distorted decisions. The result does not hold, of course, if firms are asymmetric and their technologies satisfy Assumption 4.

7.5 More than Two Firms

In the last few subsections we have considered a model where the firms trade the permits in the first stage and engage in Cournot competition in the second. In the first stage, the permits are traded in such away that the joint Nash profits to be earned in the second stage are maximized. The question is whether this procedure can be generalized in a natural way to apply to more than two firms.

Let there be n firms, and let $(l_1, \dots, l_n)$ be an initial allocation of permits with $\sum_{i=1}^n l_i = L$. Let $e = (e_1, \dots, e_n)$ be a feasible allocation, i.e., $\sum_{i=1}^n e_i = L$. Finally, let $\Pi_i^N(e)$ denote the profit for firm i if each firm holds e_i (many) permits and all the firms have chosen Cournot-Nash quantities. Let us further assume that the firms achieve the cooperative outcome in the first stage by solving

$$\max_e \sum_{i=1}^n \Pi_i^N(e) \quad \text{s.t. } \sum_{i=1}^n e_i = L \quad ,$$

and let $e^* = (e_1^*, \dots, e_n^*)$ be the corresponding maximizer.

Such a procedure, however, presumes that the firms can commit to their share e_i^* of permits and do not engage in further trade with other firms once that allocation of emissions has been set. The government could set an aggregate pollution quota for certain pollutants, and the firms may cooperatively agree on the degree to which each firm is allowed to pollute within a certain period of time. The agreement allows for transfer payments between the firms. Once the agreement has been signed, no further trade is allowed. Thus the firms commit themselves to an allocation of permits that remains unaltered for a certain period of time.

However, for most actually existing permit trading regimes the institutional framework is different. An agreement about the allocation of permits cannot be enforced, and it may be profitable for any two given firms to engage in a further trade of permits and improve upon an allocation e^* that maximizes $\sum_{i=1}^n \Pi_i^N(e)$. In other words, the *core* of permit allocations may be empty. Weigel [1992] provides numerical examples of a Cournot market with three firms facing linear demand and quadratic cost functions, where the core is indeed empty. The point is that, by trading permits, two firms impose a negative monetary (as opposed to a real) externality on the third firm. The negative monetary externality materializes because, by trading the permits, two firms can make the cost structure more efficient for each other, thus gaining a greater market share and inducing the market price to fall, which hurts the third firm. Proposing a solution concept for a final allocation of permits if there are more than two firms is an unresolved problem requiring further research.

7.6 Extensions

Sartzetakis [1997b] also investigates the interaction between permit markets and oligopolistic output markets. In contrast to the model presented above, the author assumes that the permit market is competitive, while on the output market the firms engage in imperfect competition. Trading permits has offsetting effects by equalizing marginal abatement costs, but it can make inefficient firms more profitable. Sartzetakis shows, however, that the net welfare effect of permit trading is positive compared to the non-trade situation.

In an extension of our basic model with completely inelastic permit supply, von der Fehr [1993] also considers the case where the regulator uses an increasing supply function of permits. The duopolists can now act strategically on both the input and the output market. In a two-stage game the firms first buy the permits, then going on to engage in quantity competition in the second stage. The main result is that if the firms' quantities are strategic substitutes, the firms over-invest in emission permits in comparison to the first-best outcome. The reason is that the firms commit themselves to a low-cost structure by shifting their reaction curves outwards. This is the usual effect when firms can invest in the first period to achieve lower production costs in the second. For price competition the result is ambiguous. But even in that case, over-investment in emission permits may occur.

iciently strong such that the emission tax has to be set higher and above marginal damage.

8 Market Power in Input Markets

In this section I study situations where polluting firms have market power in some input market. For this purpose I study models where pollution is proportional to one input. I begin with monopsony and then discuss briefly the case of a quantity-demanding (Cournot) oligopsony. The firms may exercise market power either in the market for the dirty input or in a market for a clean input.

8.1 Monopsony Power over a Polluting Input

I consider a firm that is now a price-taker in an output market where p is the price of the output good. The output is produced by (at least) two inputs

$q = f(x_1, x_2)$, one of which, say input 1, causes pollution proportional to its quantity $e = \delta x_1$. The firm has market power in the factor market of input 1. To model this, I use $w_1(x_1)$ to denote the supply function in the upstream sector producing input 1. That sector is assumed to be competitive, i.e. the suppliers of input 1 act as price-takers. Let $C_i(x_i)$ denote the cost function of the representative firm in sector $i = 1, 2$, where we assume $C_i' > 0$ and $C_i'' > 0$. The market for input 2 is assumed to be competitive, with the factor price denoted by w_2. Assuming that input 1 is subject to an environmental tax τ, this firm's profit can be written as

$$\Pi(x_1, x_2) = pf(x_1, x_2) - [w_1(x_1) + \tau\delta]x_1 - w_2 x_2$$

The first-order conditions for the monopsonist's profit maximum are given by

$$p\frac{\partial f}{\partial x_1} = w_1(x_1) + \tau\delta + w_1'(x_1)x_1 \tag{86}$$

$$p\frac{\partial f}{\partial x_2} = w_2 \tag{87}$$

The upstream input suppliers' first-order conditions correspond quite simply to $C_i'(x_i) = w_i$. From this we can even derive the supply function for good 1 as $w_1(x_1) = C_1'(x_1)$. Obviously, $w_1(x_1)$ is upward-sloping due to increasing marginal costs of the input suppliers. To ensure that the second-order condition of the monopsonist is satisfied, we assume $2w_1'(x_1) + w_1''(x_1) > 0$. This is a similar condition to (1) for the monopolist's inverse demand function.

To characterize the social welfare function, we assume a small open economy with respect to the output market. This allows us to neglect consumer surplus. This procedure does not restrict the validity of the results in any way. Thus we have

$$W = pf(x_1, x_2) - C_1(x_1) - C_2(x_2) - D(\delta x_1)$$

Taking into account the monopsonist's choice of inputs, determined by (86) and (87) and denoted by $x_1(\tau)$ and $x_2(\tau)$, the regulator maximizes W with respect to the tax rate. Solving for the optimal tax rate we obtain

$$\tau = D'(\delta x_1) - \frac{w_1'(x_1)x_1}{\delta}$$

This gives us the following result:

Proposition 5 *If a polluting firm has monopsony power on a market for a polluting input, the first-best allocation can be achieved by levying an input tax. The optimal tax is lower than marginal damage.*

Note that for the size of the tax rate the result does not change if the regulator *taxes* the *output* of the input supplier. Thus, although the input supplier is a price-taker, the distortion of the monopsonist requires setting the tax rate below marginal damage. This result is important, as it suggests that it is not sufficient to look at the market structure of the polluting firm alone.

8.2 Second-Best Analysis: When Monopsony Power is Exercised over a Clean Input

Things are slightly different if the firm exercises monopsony power over a non-polluting input but uses another dirty input supplied on a competitive market. For this purpose we can simply rewrite the above model by assuming that pollution is equal to the second input: $e = \delta x_2$.

Dealing with the welfare maximizing exercise as above, one can determine the second-best tax rate as

$$\tau = D'(\delta x_2) - \frac{w_1'(x_1)x_1}{\delta}\frac{dx_1/d\tau}{dx_2/d\tau}$$

Differentiating (86) and (87) with respect to the tax rate, we obtain $dx_2/d\tau < 0$, i.e. the output of the polluting input goes down, and thus pollution goes down as the emission tax rises. The effect on the clean input is, however, ambiguous. We obtain $dx_1/d\tau < 0$ if and only if $f_{12} = \partial^2 f(x_1, x_2)/(\partial x_1 \partial x_2) > 0$, which is the case for most production functions used in applied work (in particular in CGE models), such as CES or nested Leontief/CES functions. This gives rise to the following result for the second-best tax rate.

Proposition 6 *Consider a monopsonist exercising monopsony power in a market for a clean input and using a polluting input that it buys in a competitive factor market. If the regulator can only target the emissions of the polluting input, the second-best optimal tax rate falls short of (exceeds) marginal damage if and only if* $f_{12} > 0$ *(*$f_{12} < 0$*).*

This result can be interpreted as follows: If $f_{12} > 0$, the level effect due to a rise in the emission tax dominates the substitution effect, such that the firm reduces dirty and clean inputs as the tax rate rises. Hence the welfare-maximizing regulator does not want to set the tax too high because the monopsonist produces too little anyway. If $f_{12} < 0$ holds, the substitution effect dominates the level effect. In that case, the welfare-maximizing regulator will want to set a tax rate that exceeds marginal damage in order to encourage the monopsonist to substitute the input clean for the dirty one.

8.3 Oligopsonies

The results do not change dramatically when we move from monopsony to oligopsony. Hence, we will only outline the results here. The model can be generalized à la Cournot by assuming that the factor price on an input market depends on the total input demand of several firms: $w_1 = w_1(x_1^1 + ... + x_1^n)$, where x_1^j is the input demand of firm j. We can summarize the results as follows:

Proposition 7 *Assume n firms have market power in a factor market. Assume the factor is homogenous so that there is only one price.*

i) If firms are symmetric and exercise market power in a market for a polluting input and if no further abatement technologies exist, the first-best allocation can be achieved by implementing either an input or an emission tax. The optimal tax rate is lower than marginal damage. Raising the tax rate lowers pollution.

ii) If either the situation is the same as in i) except that firms are symmetric, or if firms exercise market power in a market for a clean input, the first-best allocation can neither be achieved by a uniform input nor by a uniform emission tax. If firms are not too different, the second-best optimal tax rate is lower than marginal damage, and raising the tax rates lowers pollution.

iii) If firms are sufficiently different with respect to their cost structure, perverse effects may arise, i.e. pollution may increased be raising the tax rate, and the second-best tax rate may exceed marginal damage.

8.4 Mixed Structures

We have seen that in situations with market power in an input market, the second-best optimal tax rate usually falls short of marginal damage. Hence it is clear that if a firm exercises market power in both the output and the input market, the effects will "add up".[28] The more market power there is, the lower the second-best tax rate will be. This also holds if we have either a vertical monopoly or a vertical monopsony chain. Since in this case the distortions work into the same direction and the total distortion increases, the second-best optimal emission tax rate designed to regulate a vertical monopoly or monopsony chain is lower than in the case where there is market power in one market only.

As set out above, the Pigouvian tax rule also fails to hold for a competitive firm if this firm sells to a monopsonistic downstream firm or if it buys some input from a monopolistic upstream firm. Thus the regulator needs to be conversant with the complete vertical industry structure when determining the second-best optimal level of his tax rate. According to my knowledge, the literature has been silent on market structures as outlined in this section.

8.5 Market Power in Markets for Clean Inputs and Clean Technology

David & Sinclair [2005] and Requate [2005] study market power in an upstream market for abating inputs or for cleaner technology, respectively. David and Sinclair consider a competitive polluting industry where emissions $e(x, w)$ are a function of output x and abatement input w. The latter is supplied by an upstream industry, the firms of which engage in Cournot competition. If the polluting downstream firms are taxed and the tax is the only instrument at the regulator's disposal, the second-best optimal tax rate will *exceed* marginal damage. David and Sinclair [2005] further show that a voluntary approach to pollution abatement may be doomed to failure unless some limitations are imposed on the eco-industry's market behavior.

Requate [2005] discusses a model with a monopolistic R&D firm developing new technology for a polluting downstream sector. He also finds that the second-best optimal tax rate exceeds marginal social damage if the regulator can make an ex ante commitment to the level of his tax rate. In both models,

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[28] The effects, of course, do not necessarily add up in a linear way.

the intuition for the high tax rate is that the upstream sector sets its prices too high, which leads to an inefficiently low purchase of the abating input in the model by David and Sinclair and to an inefficiently low purchase of the advanced abatement technology in Requate's model. By raising the tax rate the regulator enhances demand for the clean input or the new technology, respectively.

9 Market Power in the Permit Market

So far we have mainly studied imperfect competition in the output market. Permit markets have either been assumed to be competitive, or non-competitive permit markets have been modelled by bargaining between two or several firms (see Section 7). If the permit market is small, i.e. if there are only a small number of traders, there is no competitive demand side. Hence it is not possible to model a non-competitive permit market with a small number of firms, as in a Cournot model and to apply the standard models on market power in factor markets. However, there are markets with many small firms and a few big firms, e.g. in the US market for SO_2 permits (see Howe 1994). In his influential paper, Hahn (1984) sets up a stylized model with many small firms and a single firm exercising market power in the market for tradable permits. In this section I present a generalized version of the Hahn model allowing for the presence of several large firms.

9.1 A Model of Permit Trading with Large and Small Firms

To model oligopoly power on the permit market, I divide the set of firms participating in the permit market into a set of large firms $i = 1, ..., n$ and a set of small firms $i = n+1, ..., m$. This divide is exogenous, which is certainly a weakness of this approach. But to date the literature has not provided a viable alternative. Moreover, I intend to neglect the output market in this section. Hence we can represent the firms, whether small or large, by their abatement cost functions $C_i(e_i)$. Each firm owns an initial endowment of permits, denoted by $\hat{e}_i$. Accordingly, we are studying a system of grandfathered permits. A typical firm's total costs can then be written as

$$C_i(e_i) + \sigma \cdot [e_i - \hat{e}_i]$$

where σ is the market price for permits.

The small firms act as price-takers and thus set their marginal abatement costs equal to the market price of permits:

$$-C_i'(e_i) = \sigma$$

Accordingly, emissions e_i of the small firms can be written as $e_i(\sigma)$ and can be interpreted as the factor demand for permits. Summing up these demands for all the small firms we obtain the demand in the competitive sector:

$$E^c(\sigma) = \sum_{i=n+1}^{n+m} e_i(\sigma)$$

If we invert this curve, we obtain the competitive sector's inverse demand function for permits:

$$\sigma(\cdot) = (E^c)^{-1}(\cdot)$$

The number of permits employed by the competitive sector is the amount left by the large firms. Hence,

$$E^c = L - \sum_{i=1}^{n} e_i$$

and the market price for permits will be

$$\sigma = \sigma\left(L - \sum_{i=1}^{n} e_i\right)$$

Now we can write the total costs of the large firms as

$$C_i(e_i) + \sigma\left(L - \sum_{i=1}^{n} e_i\right) \cdot [e_i - \hat{e}_i]$$

The permits market with large and small firms is now modelled in a Cournot-like way. The first-order condition for the cost minimization of a typical large firm can now be written as

$$-C_i'(e_i) = -\sigma'\left(L - \sum_{i=1}^{n} e_i\right) \cdot [e_i - \hat{e}_i] + \sigma$$

Thus, if in equilibrium $e_i > \hat{e}_i$, then $-C_i'(e_i) > \sigma$, and if $e_i < \hat{e}_i$ then $-C_i'(e_i) < \sigma$. This observation leads us immediately to the following result:

Proposition 8 *Consider a permit market with grandfathering.*

- *i) If in equilibrium a large firm is a net buyer (seller), the large firm sets its marginal abatement cost higher (lower) than the permit price.*
- *ii) Only if the large firms obtain an initial endowment corresponding to the efficient final allocation will permit trading lead to an efficient outcome.*

The intuition for i) is the following: A large firm that wants to *buy* additional permits buys fewer than optimal in order to keep the permit price low. Thus the net buyer behaves as an *oligopsonist* (or as a monopsonist if $n = 1$). A large firm that wants to *sell* spare permits, sells less than the efficient amount in order to keep the permit price high. Thus the net seller behaves as an *oligopolist* (or a monopolist for $n = 1$). Trade will only lead to an efficient outcome if the large firms' initial endowments correspond to their efficient emission levels. In this case, the large firms do not participate in trade and cannot distort the market price for permits. This does not generally imply, however, that large firms should not participate in trade. Since trade always goes in the right direction, it will improve efficiency, i.e. the final allocation is less inefficient than the initial allocation. Where legally and informationally feasible, the regulator should, however, allocate approximately as many permits to the large firms as they will ultimately need, even after trade. Maeda [2003] obtains the same results for the case of $n = 2$ and illustrates the model by simulating the international trade in carbon dioxide allowances, investigating which country is likely to have market power.

9.2 Extensions of the Hahn Model

There are several extensions to this kind of model. They take into account output markets (Malueg [1990], Innes et al., [1991], and Misiolek and Elder [1989]) and intertemporal permit trading (Hagem and Westskog, [1998] and Sartzetakis [1997a] and [1997b]), or they study the possibility of noncompliance (van Egteren and Weber [1996], Malik [2002], and Chavez and Stranlund [2003]).

9.2.1 Including the Output Market

Innes et al. [1991] extend the Hahn model by assuming that a large firm has market power in both the output and the permit market. They argue that, in contrast to Hahn's result, the big firm should participate in trade, and they show that a regime of tradable emission permits is welfare-superior compared to a regime where both the monopolist and the competitive firms are regulated by a *uniform tax*. Moreover, they show that there exists an initial allocation of permits that leads to the same final allocation of permits as a discriminating tax system. Under a discriminating tax, the monopolist needs to be regulated by a lower tax rate than the competitive firms in order to mitigate his market power. Allowing the output monopolist to exercise monopoly power in the permit market as well means that he virtually faces a lower price for permits than the competitive firms, which mimics the discriminating tax system. This leaves us with the question of what is more difficult: finding exactly the right initial allocation of permits or finding exactly the right discriminating tax rates? Both may be equally difficult. However, it may be easier to adjust the tax rates than to reallocate the permits after firms have engaged in trade.

Misiolek and Elder [1989] extend the Hahn model in a different way by assuming that the (only) large firm acts as a price-taker in the output market. Nevertheless, the large firm takes into consideration how buying permits from the (small) rival firms raises those rivals' costs, affects the output price, and increases the large firm's market share.

Sartzetakis [1997a] takes a similar approach to Misiolek and Elder, assuming, however, that (two) firms engage in imperfect (Cournot) competition in the output market. However, there is still one firm assumed to have market power in the permit market, whereas the second firm is a price-taker in the permit market. In the output market, by contrast, the firms are symmetric with respect to their behavior, as both of them play the simultaneous quantity-setting game à la Cournot-Nash. Sartzetakis then discusses a two-stage game where the large firm sets the price for permits in the first stage. In the second stage, firms simultaneously decide on both abatement - including how many permits to buy or sell - and on the quantities of output. Sartzetakis shows that market power in the permit market can reduce competition in the output market, a feature also observed in cases where firms have other strategic options for raising their rivals' costs (see Salop and Sheffman [1983] and [1987]). The regulator can mitigate this anti-competitive tendency by issuing fewer permits to the powerful firm and more to the weak firm. The question remains why the two firms display different behavior in the permit market but symmetric behavior in the output market.

In a companion paper Sartzetakis [1997b] shows that allowing Cournot oligopolists to engage in trade is welfare-improving compared to command control, where each firm faces the same absolute emission standard. Sartzetakis assumes interior solutions such that marginal abatement costs equalize. Malueg [1990], by contrast, allows for corner solutions and finds that permit trading in oligopoly may be welfare-decreasing.

9.2.2 Intertemporal Permit Trading

Hagem and Westskog [1998] draw on Hahn's [1984] model by including the *intertemporal aspect*. In their model there is only one large firm and it is always a seller of permits. The authors study a two-period model and compare two different permit schemes. In the first scheme, all firms can *bank and borrow permits* in an unlimited way. In the second, one permit allows its holder to emit a constant stream of emissions in each period, a system the authors refer to as a *durable quota system*. Under the first system, all firms efficiently allocate emissions over time. The monopolist, however, as in the model described above, sells too few permits, so that his marginal abatement costs are smaller than those of the competitive firms. Depending on the initial allocation of permits, one or the other system may lead to lower total abatement costs in industry.

9.2.3 Market Power and Non-Compliance

Van Egteren and Weber [1996] extend the Hahn model by considering the possibility of non-compliance, i.e. firms emitting pollution in excess of the number of permits they hold. Firms are audited with a certain probability and are fined if any cheating is discovered. For the competitive firms, the incentive to cheat is higher, the higher the market price is for permits. Hence the authors find that if the (only) large firm is compliant, a redistribution of the initial allocation of permits from the competitive firms to the big firm increases the total of violations. If the large firm is non-compliant, then clearly the firm is less likely to cheat if it receives a higher initial allocation of permits.

Malik [2002] extends the model proposed by van Egteren and Weber [1996] by investigating the efficiency consequences of non-compliance combined with the market power of one firm. He shows that in the presence of market power non-compliance by the small price-taking firms is potentially desirable. Conversely, in the presence of non-compliance, some market power by the (only) big firm is desirable. The reason is that the monopolistic firm retires some permits and thus reduces some of the excess pollution emitted in the case of non-compliance. In my view, the recommendation to maintain monopoly power in order to mitigate non-compliance by competitive firms seems rather strange, as the regulator could in principle mimic the monopolist's behavior by issuing a smaller number of permits.

Chavez and Stranlund [2003] complement the work of van Egteren and Weber by endogenizing the enforcement of compliance. Whereas Hahn [1984] finds that the (only) large firm should obtain an allocation of permits such that it does not want to trade, Chavez and Stranlund suggest that the large firm should be a buyer (seller) of permits when monitoring costs are increasing (decreasing) in the firm's initial endowment of permits.

9.3 Market Power through Innovation

Fisher et al. [2003] consider a model where a single firm, called the innovator, is able to invent a new technology that leads to lower (marginal) abatement costs. Since the innovator needs fewer permits after innovation, the equilibrium price for permits decreases. This gives the innovator a degree of market power. Fisher et al. [2003] do not study the consequences of the allocation of permits. They find, however, that free permits provide fewer incentives for innovation than auctioned permits. The reason is the endowment effect. The value of the innovator's permit endowment depreciates through the invention of new technology.

Montero [2002a] also studies investment incentives in different kinds of policy instruments, notably tradable permits and two kinds of standards, emission and performance standards. Besides allowing for perfect and imperfect competition in the output market, he - like Innes et al. [1991] - models imperfect competition in both the output and the permit market. In the latter case, firms negotiate on the permit price, as proposed in Section 7. The firms employ the Nash bargaining solution, taking the level of R&D as given and anticipating the expected output decisions in the last stage of the game. Since firms have market power in both markets, trading permits has a strategic effect with respect to the output market. This causes the firms to invest more under an emission standard and a regime of auctioned permits than in a regime of free permits.

Montero [2002b] studies both Cournot and price competition with differentiated products, allowing for R&D spill-overs and again assuming imperfect competition both in the output and the permit market. Besides emission standards and permits he also analyzes emission taxes. Montero finds that no strategic effect results from levying an emission tax, as the marginal costs of both firms are constant. Taxes can provide more, less, or the same incentive to invest in innovation than/as both emission standards and auctioned permits, whereas free permits provide fewer incentives to innovate than taxes. With Bertrand competition in the output market, taxes provide a higher incentive than an emission standard, which in turn provides a higher incentive than free permits. Auctioned permits again can offer more, less or the same incentive than/as taxes. Montero concludes that in the Cournot case, either emission standards, taxes, or auctioned permits can provide the highest incentive, whereas in the Bertrand case this holds either for taxes or for auctioned permits.

9.4 Results from Experimental Studies

Given the lack of empirical data for analyzing the efficiency of permit markets, laboratory experiments on permit trading have become an attractive substitute for empirical field investigations on markets for emission allowances. In particular the Hahn model on monopoly power in permit markets has attracted considerable attention from experimental economists. To my knowledge, Brown-Kruse and Elliott [1990] and Brown-Kruse et al. [1995] were the first to test for market power in emission-trading experiments. In their experimental treatments a single seller or a single buyer is confronted with ten buyers and ten sellers, respectively. Godby [2000] extends this approach including the product market. By setting the product market price either exogenously or endogenously, he is able to mimic the models developed by Hahn [1984], Misiolek and Elder [1989], and Innes et al. [1995].[29]

The experimental design of Godby's [2000] first series of treatments follows that of Brown-Kruse and Elliott [1990] and Brown-Kruse et al. [1995]. Whereas the large firm has a production capacity of ten units, each of the ten fringe firms can produce only one unit. Pollution is proportional to output. Thus under a *laisser-faire* policy, the market would produce and pollute 20 units. The number of emission permits allocated to industry, however, is

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[29] Apparently Godby was not aware of the work done by Innes et al. [1995] since he does not cite that paper. It is not quite clear from the description of the experimental set-up whether his treatments are closer to the model of Innes et al. or to that of Misiolek and Elder [1989].

10. Godby carries out four different treatments. In the first two treatments the product market price is given exogenously, and all the permits are either allocated to the large firm (treatment 1) or equally distributed to the fringe firms (treatment 2). Thus the big firm is a net seller in the first case and a net buyer in the second. Since the product market price is exogenous, Godby calls the big firm's manipulation of the permit market *simple manipulation.* In the other two treatments the output price is determined endogenously. Following Misiolek and Elder [1989], Godby calls this kind of market power *exclusionary manipulation*, because if the large firm is a net seller, it has an incentive to sell fewer permits than is socially optimal for two reasons: it does not only want to keep the price for permits high and thus earn high revenues from selling permits, it also wants to increase the product market price by increasing the production costs of the fringe firms and thus reducing supply in the product market. If the big firm is a net buyer of permits, there are two offsetting effects. On the one hand, the large firm has an incentive to buy fewer permits than is socially efficient in order to hold down the market price for permits. On the other hand, it wants to raise the competitors' costs by buying more permits than would be efficient. For the case of *exclusionary manipulation,* Godby again conducts two experiments. In one case, all the permits are allocated to the large firm (treatment 3) while in the second the fringe firms initially receive all the permits (treatment 4).

Godby extends this design by reducing the number of fringe firms from 10 to 5 and enhancing their capacity from 1 to 2 units. Thus he also gives limited market power to the small firms. The reason for this modification is the empirical observation that the market for NO_X permits in Ontario was governed by an electricity utility that demanded about 50% of the permits, whereas 5 other firms, such as producers of iron and steel, cement, etc., demanded about 10% each.

Godby [2000] replicates several of the results produced by Brown-Kruse and Elliott [1990] and Brown-Kruse et al. [1995]. In particular, he finds that the prediction of the Hahn model is well confirmed by the experimental outcomes in treatments 1 and 2, where the price on the output market is taken as exogenously given. When the large firm is a seller, the efficiency gain through trade over the initial allocation is approximately 60% - 70% of the gains that are theoretically achievable through perfect competition. If the large firm is a buyer, the efficiency loss through market power turns out to be much smaller (approximately 80% - 95% of the maximal possible gains). In both treatments the efficiency loss is greater when there are only

5 fringe firms with high capacity.

Under *exclusionary manipulation*, by contrast, permit trading results in negative efficiency. Godby establishes an efficiency of approximately - 40% in treatment 3, and of -120 to -140% in treatment 4 (in the latter case, the efficiency loss is even larger for the case of 10 small fringe firms). In other words, permit trading turns out to be inferior to command-and-control.

Godby [2002] replicates the analysis of Godby [2000] with one large firm holding a capacity of ten units and five fringe firms with a capacity of 2 units each. Compared to his earlier paper he adds two more treatments where the permits are allocated proportionally to the firms' capacities, i.e. the dominant firm gets 5, whereas the fringe firms receive 1 permit each. Using statistical techniques, Godby [2002] arrives at basically the same results as in Godby [2000]: In all treatments the hypothesis that the dominant firm exercises market power cannot be rejected when looking at the end points of the permit double-auction price series. Product market prices also indicate convergence toward the market power benchmarks. Observed quantities deviate from competitive levels in the theoretically predicted direction. Moreover, when exclusionary manipulation is possible, permit trade leads to efficiency losses relative to the command and control benchmark. Finally, Godby finds evidence that players engage in speculative behavior.

Muller et al. [2002] carry out similar experiments. They generate market power on the seller or buyer side by aggregating 5 sellers and 5 buyers, respectively. They also observe market power in double auctions. Their main conclusion is that, contrary to the proposals by Smith [1981], the double-auction design is not as robust with regard to market power.

In contrast to Godby [2000,2002], who avoids any framing, Carlén [2003] conducts a framed experiment, mimicking the international carbon trade where the big trader - a buyer - is interpreted as the US. Moreover, in contrast to most other laboratory studies, the participants have no chance of gaining experience. The authors argue that this setting comes closer to international permit trading in the field. In contrast to the other experiments referred to here, Carlén does not find evidence for distortions through potential market power. Bohm and Carlén [1999] additionally introduce an information structure to mimic more realistic field conditions for the carbon dioxide emission-permit trading program. However, they do not find that changes in the information structure significantly affect market efficiency.

Finally, Cason et al. [2003] also conduct a framed field experiment in order to mimic permit trading of nitrogen allowances among sewage treatment plants. The novelty of their study is the introduction of asymmetric information by letting one or two large emitters know the abatement costs of the small emitters, whereas the small emitters do not know the costs of the big ones. The authors also test for the impact of different initial allocations. They find that in a monopoly situation with one large seller the market price for permits is larger than in the duopoly treatment, although the difference is not significant. However, in sharp contrast to the findings of Brown-Kruse et al. [1995] and Godby [2000, 2002], they find that the prices, profits, and transaction volumes are much closer to the competitive equilibrium prediction than to the monopoly or duopoly prediction.

In conclusion, it is worth pointing out that the subject pools participating in these experiments were mainly students and not real decision-makers.

10 Environmental Policy, Imperfect Competition, and International Trade

A survey on environmental policy under imperfect competition would certainly not be complete without addressing the issue of imperfect competition on international markets. Environmental policy in open economies has become a topic of major interest in environmental economics since Markusen's [1975] seminal paper. Assuming that all markets are competitive, Markusen makes the point that, in the absence of tariffs, for example due to a free trade agreement, emission taxes can be used to influence the *terms of trade* and can thus serve as a substitute for trade policy. As a consequence an exporting country would like to over-internalize environmental damage in order to *improve its terms of trade*. But this implies that with the competitive trade model it is not possible to explain what both environmentalists and economists refer to as *environmental dumping* [cf. Rauscher, 1994].

Brander and Spencer [1985] set off a new direction of research on trade theory by showing that, under imperfect quantity competition, the optimal policy consists in making exports cheaper (through subsidies) rather than improving the terms of trade by making them more expensive (through export taxes or import tariffs). Thus trade policy does not aim at improving the terms of trade by making export goods more expensive, but rather tries to increase market shares at the expense of *worsening* the terms of trade. This is the celebrated *rent-shifting effect.*

Conrad [1993], Barrett [1994], and Kennedy [1994] were the first to discover that, in the presence of imperfect (Cournot) competition, emission taxes can be used to indirectly subsidize exports by under-internalizing even the domestic environmental damage. Whereas Conrad looks at a model where two governments support their domestic industries to increase their market share in a third country's market, Kennedy [1994] studies a similar model of a closed two-country economy. Barrett [1994], studying both quantity and price competition, finds that under imperfect price competition, the optimal unilateral policy should over-internalize marginal damage.[30] [31] In a series of follow-up papers, several authors (among others Ulph [1994a], [1994b], [1996a], [1996b], Nannerup [1998], Markusen et al. [1993, 1995], Simpson and Bradford [1996], Hamilton and Requate [2004], and others) extend the Conrad-Kennedy-Barrett type of model by including imperfect information, pre-investment in cost reduction, R&D, choice of location, and other decisions to be made before firms engage in imperfect quantity or price competition.[32] Since environmental policy in the presence of international trade has been surveyed extensively elsewhere (see Althammer & Buchholz [1995, 1999], Ulph [1997a, 1997b], Rauscher [1997], and Duval & Hamilton [2002]), it is not my concern here to fully summarize the results of this literature. That literature, however, contains rival and sometimes even contradictory interpretations of the decomposition of the unilaterally optimal tax rate. Accordingly, I wish to highlight the structure of the unilateral second-best optimal tax rate that has to target both *imperfect competition at home*, which harms domestic consumers, and the *market power of domestic firms on the international market*, which favors domestic welfare. For this purpose, I shall concentrate on Cournot competition and regulation by taxes.[33] It has become fashionable to talk about *ecological* (or *environmental*) *dumping* whenever a country sets its emission tax below marginal damage. Partially following Rauscher [1994] and Duval & Hamilton [2002], I argue that this

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[30] In contrast to Conrad and Kennedy, Barrett uses standards.

[31] Conrad [1996a] extends Conrad [1993] by assuming that the good supplied on the world market by oligopolistic firms is also consumed at home. Conrad [1996b] extends Barrett's model by also studying taxation in a price-setting duopoly model with differentiated commodities.

[32] Simpson and Bradford [1996] use a model of imperfect competition and R&D prior to market competition to challenge the Porter-hypothesis proposed in Porter [1990], [1992].

[33] Ebert [1999] studies the strategic use of *relative standards* in open economies where the regulated domestic firms exercise market power in an international market.

view is not entirely appropriate.[34]

10.1 Extension of the Basic Model to International Trade

As is usual, I assume that there are only two countries (governments), one domestic and one foreign. Furthermore, I assume that there is a free trade agreement such that the governments are not allowed to impose tariffs or to subsidize their firms directly. I extend my basic model by denoting the *world inverse demand function* by $P_w(Q_w)$, where Q_w is world total output. Furthermore, I write the *domestic inverse demand function* as $P_d(Y_d)$, where Y_d is the domestic level of consumption. Moreover, there are n_d domestic and n_f foreign firms. $C^i(q_i, e_i)$ represents the cost function of a typical firm from country i. Within one country, all firms have identical technologies (inducing identical cost functions). Moreover, I denote the domestic damage by $D_d(E_d)$, where $E_d = s_d^d n_d e_d + s_f^d n_f e_f$ is effective (or ambient) pollution arriving in the domestic country caused by emissions from both domestic and foreign firms. Domestic emissions are multiplied by the emission coefficient s_d^d that indicates how much domestic pollution affects the home country, whereas s_f^d indicates how much of the foreign firms' emissions arrive in the domestic country. Analogously, I denote foreign damage by $D_f(E_f)$, where effective foreign pollution is given by $E_f = s_f^f n_f e_f + s_d^f n_d e_d$.

10.1.1 Cooperative Environmental Policy

In this subsection I briefly study the benchmark case where governments agree on their environmental policies in a cooperative way. In order to avoid problems of imperfect competition in the permit market, I assume that the governments use taxes as policy instruments. To achieve a fully cooperative solution it is sometimes necessary for one country to compensate another country for potential welfare losses caused by cooperative environmental policy.[35] Hence I assume that transfer payments between governments are possible to achieve the cooperative outcome. This assumption allows us to ignore

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[34] Rauscher [1994] provides a detailed discussion on the meaning of ecological dumping in the framework of a competitive model.

[35] One country might be much more seriously affected by pollution than an other country.

participation constraints, thus simplifying matters considerably.[36] [37] In this case, the objective of the two governments is represented by

$$\max_{t_d,t_f} \int_0^{Q_w} P_w(Q)dQ - n_d C^d(q_d, e_d) - n_f C^f(q_f, e_f) - D_d(E_d) - D_f(E_f).$$

Omitting the algebra, the cooperative tax rates are given by:

$$t_d = D_d'(E_d)s_d^d + D_f'(E_f)s_d^f + P_w^{'}(Q_w)q_d\frac{\partial q_d}{\partial e_d} \quad (88)$$

$$t_f = D_f'(E_f)s_f^f + D_d'(E_d)s_f^d + P_w^{'}(Q_w)q_f\frac{\partial q_f}{\partial e_f} \quad (89)$$

This implies that, when regulating its own domestic industry, each country takes into account the marginal damage inflicted by its own industry on both the domestic and the foreign country. Each country also takes into account the *oligopolistic distortion* caused by its own industry on the world market. These formulas are essentially equivalent to formula (39) in Section 4 and can also be found in Duval and Hamilton [2002].

10.1.2 Non-Cooperative Environmental Policy

Let us now turn to the more interesting case of non-cooperative policy setting. In this case we have to add the market value of exports and imports, to domestic welfare. The institutional set-up in this scenario is that domestic and foreign firms compete imperfectly à la Cournot in an international market that may also consist of third-country markets. The governments are not allowed to subsidize their firms directly. Hence they will conceivably attempt to use *environmental policy as trade policy.* The objective function of the domestic government is now given by

$$W = \int_0^{Y_d} P_d(Y)dY - n_d C^d(q_d, e_d) + P_w(Q_w)[n_d q_d - Y_d] - D_d(E_d), \quad (90)$$

taking into account that domestic firms compete imperfectly in the international market. The firms' first-order conditions are familiar from Section 4

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[36] This problem has often been ignored in the literature.

[37] In reality, direct transfer payments are not so common, but examples do exist. For instance, Germany and the Netherlands made direct payments to France for abating effluents from salt mining. In other cases, indirect payments are made by negotiating multiple issues simultaneously.

and need not be repeated here. Differentiating (90) with respect to the tax rate, setting the derivative equal to zero, and solving for the tax rate yields the following formula for the unilaterally optimal (non-cooperative) domestic tax rate:

$$\begin{aligned}\tau_d^{nc} &= s_d^d D'(E_d) + s_f^d D'(E_d) \frac{n_f \frac{\partial e_f}{\partial \tau}}{n_d \frac{\partial e_d}{\partial \tau}} \\ &\quad - P'_w(Q_w)[n_d q_d - Y_d] \frac{n_d \frac{\partial q_d}{\partial \tau} + n_f \frac{\partial q_f}{\partial \tau}}{n_d \frac{\partial e_d}{\partial \tau}} + P'_w(Q_w) q_d \frac{\frac{\partial q_d}{\partial \tau}}{\frac{\partial e_d}{\partial \tau}}\end{aligned} \tag{91}$$

This decomposition, suggested by Duval and Hamilton [2002], consists of four parts: the first term represents the domestic marginal damage caused by the domestic firms. The second term represents the *leakage effect,* i.e. the domestic marginal damage caused by the foreign firms multiplied by the total indirect reaction of foreign firms' emissions to a domestic tax rise and divided by the total indirect reaction of domestic firms with respect to emissions. In the normal case, i.e. if domestic and foreign firms are not too different, we obtain both $\frac{\partial e_d}{\partial \tau} < 0$ and $\frac{\partial q_d}{\partial \tau} < 0$. The latter effect causes the world market price to rise (the terms-of-trade effect), and therefore induces the foreign firms to increase output and thus also to increase emissions, i.e. $\frac{\partial e_f}{\partial \tau} > 0$. Hence the second term of (91) is negative. Thus, even without the strategic aspects represented by the third and the fourth term, the domestic government should under-internalize the world's social damage for two different reasons: First, it does not take into account the damage to the foreign countries, i.e. it neglects the term $D'_f(E_f)s_d^f$ in (88). Second, in the absence of international coordination, the government should even under-internalize the domestic marginal damage, since by raising the domestic emission tax production and thus pollution shifts from home to abroad and then comes back across the border through wind or water. Thus the second term represents protection against transboundary pollution. Note that this *leakage effect* is always present, even if markets are competitive. Even though, the reaction of the firms, and thus the weight factor $n_f \frac{\partial e_f}{\partial \tau} / n_d \frac{\partial e_d}{\partial \tau}$, depends on the market structure. Note that taking the leakage effect into account is sometimes also called the *not-in-my-backyard incentive* (see Markusen et al. [1995]).

Strategic Aspects: Taking into Account Imperfect Competition and "Terms of Trade versus Rent-Shifting" Let me now turn to the third and fourth terms. These can be interpreted in different ways: Duval and Hamilton [2002] interpret the third term as the *terms-of-trade-effect* and the fourth term as the *imperfect competition effect.* The latter is clearly negative for the same *formal* reasons as in Section 4. However, the interpretation is different, as I will argue below.

Let us first study the *terms-of-trade effect.* The numerator of $\left[n_d \frac{\partial q_d}{\partial \tau} + n_f \frac{\partial q_f}{\partial \tau}\right] / n_d \frac{\partial e_d}{\partial \tau}$ is negative since $\frac{\partial q_d}{\partial \tau}$ is negative. The latter causes world output to fall and thus the market price for the polluting good to rise. Although the foreign firms react to this by increasing output[38], one can show that the total effect is negative under normal conditions (i.e. if the inverse demand function is not too convex and the firms' cost functions are not too different).[39] The denominator is clearly negative, as argued above. Since $P_w'(Q_w) < 0$, the whole third term is positive if and only if the *domestic country* is an *exporter of the polluting good.*

Finally let us study the fourth term. According to Duval and Hamilton [2002] this term corresponds to the usual *imperfect competition effect* that is always present, even in the absence of trade. Duval and Hamilton further claim that the regulator has to take account of too little production and hence this effect has nothing to do with eco-dumping. The question is what is meant by "too little production"? In a closed economy, the regulator takes into account too little production in order to mitigate the dead weight loss resulting from market power. But even if the traded good is a pure export good, i.e. if $Y_d = 0$, as for example is the case in Conrad's model and also in one version of Brander and Spencer's original model, the fourth term will not simply vanish.

Accordingly, in my view, the interpretation of the fourth term must be different: the regulator wants to help the export industry to improve the terms of trade. But due to market power, the firms can partially achieve this on their own. This help-yourself effect is represented by the fourth term, which then has to be substracted from the terms of trade effect. (By inspection is easy to verify that the fourth term is negative.)

Let us now present an alternative decomposition of the second-best opti-

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[38] Our assumptions guarantee downward-sloping reaction functions.

[39] Under perfect competition we need no further conditions to show this effect. The "normal" conditions refer to Cournot competition, where perverse effects can arise under extreme asymmetries of the firms or extreme curvatures of the inverse demand function.

mal tax rate. For this purpose we rewrite (91) as follows:

$$\begin{aligned}\tau_d^{nc} &= s_d^d D'(E_d) + s_f^d D'(E_d)\frac{n_f\frac{\partial e_f}{\partial \tau}}{n_d\frac{\partial e_d}{\partial \tau}} \\ &\quad -P_w'(Q_w)q_d\frac{(n_d-1)\frac{\partial q_d}{\partial \tau}+n_f\frac{\partial q_f}{\partial \tau}}{n_d\frac{\partial e_d}{\partial \tau}} \\ &\quad +P_w'(Q_w)Y_d\frac{n_d\frac{\partial q_d}{\partial \tau}+n_f\frac{\partial q_f}{\partial \tau}}{n_d\frac{\partial e_d}{\partial \tau}}\end{aligned} \tag{92}$$

A similar decomposition has been suggested by Althammer and Buchholz [1999]. Recall that q_d denotes total domestic output, while Y_d denotes domestic consumption. Now we can interpret the third term as the *strategic market effect*, which can be positive or negative since $\frac{\partial q_d}{\partial \tau}$ is negative and $\frac{\partial q_f}{\partial \tau}$ is positive, but the numerator of the multiplier $[(n_d-1)\frac{\partial q_d}{\partial \tau}+n_f\frac{\partial q_f}{\partial \tau}]/\ n_d\frac{\partial e_d}{\partial \tau}$, is less than the total change of output (which would be negative). Thus the numerator can be positive or negative. This means that the *strategic market effect* can be either a *terms-of-trade effect* or (!) a *rent-shifting effect.*

If the number of domestic firms is relatively large, i.e. $n_d - 1 \approx n_d$, then $(n_d-1)\frac{\partial q_d}{\partial \tau}+n_f\frac{\partial q_f}{\partial \tau} \approx \partial Q/\partial \tau < 0$. If in addition $q_d - Y_d > 0$, i.e. the domestic country is an exporter of the polluting good, the third and the fourth term together correspond to the terms-of-trade effect, and it will be optimal for the domestic government to make the output good more expensive to improve the terms-of-trade.

If, by contrast, the number of domestic firms n_d is small, especially if $n_d = 1$, the third term of (92) boils down to $-P_w'(Q_w)q_d[n_f\frac{\partial q_f}{\partial \tau}/\frac{\partial e_d}{\partial \tau}]$ which is exactly the familiar *rent-shifting-effect.* This term is clearly negative. If in addition, the good is a pure export good, i.e. $Y_d = 0$, then the third and the fourth term boil down to the implicit Brander-Spencer-Conrad subsidy represented by $-P_w'(Q_w)q_d[n_f\frac{\partial q_f}{\partial \tau}/\frac{\partial e_d}{\partial \tau}]$. If at all, it is this term which may be interpreted as the *environmental dumping effect.* In this case, the government wants to make the exported good cheaper in order to gain a higher market share in the international market and thus shifting rents from the foreign to the domestic firms.[40]

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[40] Interestingly, Duval and Hamilton [2002] do not mention the rent-shifting effect, while van Long and Soubeyran [1999] - using almost the same model and a decomposition similar to (92) - only mention the rent-shifting effect but do not refer to a terms-of-trade effect.

Let us finally interpret the *fourth term* in (92). This term takes into account the welfare loss of domestic consumers due to imperfect competition. Its sign is clearly negative, since total output decreases if the domestic tax rate goes up. However, this effect is bound to be smaller in an open economy than in the closed economy. The reason is another leakage effect: if the domestic government lowers the emission tax to increase output for the sake of increasing the domestic consumer surplus, the foreign firms will react by reducing their output, which harms the domestic consumers. Therefore, the regulator makes less of an effort to increase domestic consumption in an open economy than in a closed economy.

The bottom line from this analysis is that it depends crucially on the number of domestic firms whether the (domestic) government sets out to use the emission tax to improve the terms-of-trade or elects the opposite by increasing international market shares in order to shift rents from the foreign to the domestic firms. So allowing for more than just one firm in each country, as done by both Althammer & Buchholz [1995,1999] and Duval & Hamilton [2002], gives useful insights which are not possible in the one-firm-per-country models proposed by Conrad [1993], Barrett [1994], and follow-up papers such as Ulph [1994, 1996a, 1996b].

Note finally that, in this section, we have been investigating only quantity competition. It not possible to extend this analysis in a simple way to the model of price competition à la Barrett to the case of more than one firm in each country. The reason is that imperfect price competition requires differentiated products. However, apart from the Dixit-Stiglitz model, which does not really model the strategic interaction between firms, and Salop's model of the circular city, there exist no symmetric models of imperfect price competition with more than two competing firms.

10.1.3 Extensions to Models with Endogenous Numbers of Firms

There are a small number of recent papers that endogenize the number of firms in each country. Gürtzgen and Rauscher [2000] consider a model with the Dixit-Stiglitz type of monopolistic competition. They find that a stricter environmental domestic standard need not lead to an increase in domestic pollution. In our parlance, this means that the second term in (91) or in (92) need not necessarily be negative. Moreover, the standard improves the terms of trade in the domestic country. Finally, there is a negative term accounting for imperfect competition (similar to the closed economy model suggested by Lange and Requate [1999]). Thus in total, the marginal abatement costs may exceed or fall short of marginal damage.

Bayindir-Upmann [2004] studies a Cournot model where the domestic number of firms is fixed while the foreign number of firms is determined endogenously by a zero-profit condition. He shows that an increase in the domestic emission tax leads to an increase in the number of foreign firms but leaves total output and total pollution unaffected (domestic pollution goes down if the pollutant is not fully transboundary). Thus by raising the domestic tax rate, domestic production is crowded out at a one-to-one rate by foreign producers. An increase of the foreign emission tax, by contrast, leads to a decrease in the number of foreign firms and a reduction in total pollution. Hence the second-best optimal tax structure for the foreign government corresponds to (91) whereas for the domestic government the terms-of-trade effect vanishes. This is the case because the domestic government is not able to influence the foreign firms' costs. Consequently, the domestic government is not able to influence the terms of trade. Raising the tax rate would only result in losing market shares to the foreign country.

11 Conclusions and Proposals for Further Research

In this chapter I have summarized the main issues and results relating to environmental policy when firms subject to environmental regulation exercise market power on at least one market. The bulk of the literature refers to situations where the firms have market power on the output market, the most prominent of these models being monopoly, different kinds of oligopoly, and monopolistic competition.

The majority of models summarized in this chapter work on the assumption that a regulator has only one instrument for the regulation of various market imperfections, excessive pollution, insufficient output, and - sometimes - excessive market entry. One typical result is that the second-best optimal price for pollution is below the marginal social damage caused by the pollution. Roughly speaking, the reason is that, in comparison to a market structure with perfect competition, firms exercising market power hold down output and thus pollute less. How relevant is this insight? We have seen that the second-best optimal tax rate depends crucially on the size of the demand elasticity of the relevant market in which market power is exercised. Is it feasible to set particular tax rates for each market in which polluting firms exercise market power? In many cases, firms with market power in a particular market emit the same pollutant as other firms engaging in perfect competition in some other market. Is it feasible to set discriminatory taxes in this case? If it is, a whole array of different tax rates may be subject to lobbying effort by the industry thus regulated. Note that Innes et al. [1991] is one of the few papers that studies simultaneous regulation of both a large monopolistic firm and many competitive small polluting firms.

Moreover, we have seen two interesting theoretical findings. First, in Cournot models with free entry, the Pigouvian tax equal to marginal damage seems to be a good rule of thumb. Second, as Misiolek [1988] has pointed out, even in the monopoly case, rent-seeking efforts lead to (second-best optimal) tax rates higher than the monopoly tax rule, as was originally suggested by Barnett [1980]. So even under imperfect competition, the Pigouvian rule is not such a bad option. Accordingly, from a normative point of view, it seems to be a good strategy to stick to the Pigouvian rule and to encourage more competition through tough anti-trust laws or - if monopoly power cannot be excluded - by direct control of market power.

From my survey it has become evident that not every pollution-control instrument has been investigated for each kind of market structure. For example, in models of monopolistic competition it is largely the impact of taxes and second-best tax rules that has been investigated. It is certainly not necessary to fill up all the gaps by investigating each instrument for each kind of market structure. However, the observations I have outlined above indicate several directions for further research: The first one is empirical. It would be important to measure the market power (performance) of polluting firms in the output market in order to assess how serious the distortion from applying the Pigouvian rule to imperfectly competitive markets will be, and also for determining the second-best optimal tax levels in practice, if this is necessary. Determining the size of the second-best optimal tax rates would also require to the empirical estimation of demand elasticities for the output commodities.

A second avenue of research would be to investigate the relationship between anti-trust and environmental policy. As a matter of fact, in most countries competition law prevents a monopolist from simply charging the monopoly price (e.g. according to Art. 82 of the European Treatise abuse of market power is not allowed). Some industries with potential monopoly power, notably utilities, are subject to even stricter regulations. Given these institutional settings, the simple second-best optimal tax formulas, as developed by Barnett [1980] and many others including myself, do not apply.

Third, it would be interesting to investigate whether there are incentives for firms to (ab)use voluntary environmental agreements and commitments in order to bypass anti-trust laws. (Note that caps on emissions imply caps on output and thus raise prices). One paper aiming in this direction is Conrad [2001], who addresses a similar questions in a strategic international trade framework.

Moreover, there are very few papers studying the simultaneous regulation of both market power and pollution. In this case, the most simple rule is to tax emissions and subsidize output. Subsidies, however, are prohibited by several international agreements (EU Treatise, WTO rules etc.). Therefore more sophisticated mechanisms have to be developed for regulating a number of market imperfections. Besides Laffont (1994), Kim and Chang (1993) present one of the few papers proposing mechanisms for regulating both imperfections on the output market and externalities caused by pollution. Certainly more needs to be done on this issue.

Besides market power on the output market we have also summarized models with market power on factor markets. One important factor market is the market for emission-permits, which has attracted much attention from researchers since Hahn's influential paper [1984]. One unsatisfactory feature in this and several follow-up models is the exogenous and rather arbitrary division of firms into powerful and competitive firms. Here an issue for further research would be the question of how to endogenize the degree of market power depending on firm size. This question is certainly not specific to permit markets, though it is of special interest there since big and small firms interact in the same market. Possible tools for solving this problem could include techniques from the theory of multi-unit auctions.

Moreover, it has become clear from the analysis of factor markets that knowledge about market power in a particular market to be regulated is not enough. Strictly speaking, the regulator has to know the whole vertical structure, including the degree of market power at each step of the production chain, in order to determine the optimal tax rate, or the level of some other policy instrument. On this point, too, we still know relatively little about the relationship between optimal tax rules and market power at different stages of the production process.

A further point which has only been treated in the literature with reference to tradable permits is compliance. As summarized above, several authors, such as van Egteren and Weber [1996], Malik [2002], and Chavez and Stranlund [2003], have investigated the consequences of optimal permit policies when some firms exercise market power in the market for tradable permits and some firms do not fully comply to the regulations (i.e. if they emit in excess of the number of allowances they hold). This problem, however, is not specific to the permit instrument. Thus there is need for more general consideration of the relationship between the optimal level of pricing instruments and the optimal level of monitoring. There is also need to investigate the relationship between the pricing instrument and penalty fees in case of non-compliance.

In all the models studied here, pollution and the damage resulting from it is assumed to be deterministic. However, in many cases random elements may determine either emissions or damage. For example, accidental hazardous emissions may result from insufficient care on the firms' part. For those cases we have a different tool-box of environmental policy rules, i.e. liability rules such as strict liability or negligence. To my knowledge, the market structure of output markets has never been an issue in the literature discussing these rules. But even if emissions are determined completely by both output and the firms' abatement effort, the resulting damage may be influenced by natural shocks to resilience and nature's capacity for reducing pollution. Sometimes even the weather conditions are crucial in determining the size of the damage. In connection with stochastic damages, too, different forms of market structures have yet to be taken into account. In particular, we do not know how optimal emission taxes look like if firms have market power and damages are stochastic.

Besides the need for further theoretical and much more empirical work, experimental work may be useful to pre-test different forms of regulation in the laboratory. Surprisingly, there is a considerable amount of experimental research on the Hahn model, i.e. a permit market with one big and many small firms. There are, however, almost no experimental contributions on alternative forms of regulation. In particular it might be interesting to test mechanisms designed to regulate several distortions, such as the elegant mechanism suggested by Kim and Chang [1993]. The interesting issue here is that the price of pollution and the implicit subsidy on output does not only depend on the setting of the regulator, but also on the (strategic) behavior of the other firms. Since those mechanisms are relatively complex, it is far from clear whether the firms will fully understand the regulation scheme and whether they will act in a way that accords with what the theory predicts. If it turns out that firms behave differently from theoretical predictions, this has further consequences for the proper design of regulatory multi-issue schemes.

Although this chapter has become rather long and I have tried to cover the static models of complete information as fully as possible, I have only been able to touch on the literature on environmental policy under imperfect competition including (a) asymmetric information (see e.g. Kim and Chang [1993], Laffont [1994]), (b) dynamic modelling of accumulating pollutants (e.g. Benchekroun and Van Long [1997]), (c) R&D decisions prior to production (see e.g. Montero [2002a, 2002b], Fisher et al. [2003], and Requate [2005]), and several other issues. In particular the last-named issue is a promising field of research, since environmental regulation has a crucial impact on the direction taken by technological progress, and R&D typically creates market structures where only a small number of firms conduct R&D projects and thus engage in imperfect competition.

Finally, maybe a caveat is in place. Despite the need for further research in the various directions outlined above, distinguishing too many structural forms of competition and offering too many second-best rules for different instruments could do more harm than good to the authority of economics as a discipline. Politicians need simple and clear-cut rules. Complicated rules depending on too many parameters, such as marginal damage, demand elasticities in the output market, market conduct, and many more, may be either not be applied at all, or they run the risk of being manipulated by lobbyists. This gives rise to a final avenue of research, i.e. the dimension of political economy, and the question of which instruments and which institutional frameworks deciding on the level of those instruments are most effective in resisting the influence of political interest groups.

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