Technology Diffusion with Market Power in the Upstream Industry

Grischa Perino*

School of Economics, University of East Anglia, Norwich NR4 7TJ, United Kingdom

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Abstract

This paper compares taxes and tradable permits when used to regulate a competitive and polluting downstream industry that can purchase an abatement technology from a monopolistic upstream industry. Second-best policies are derived for the full range of the abatement technology's emission intensities and marginal abatement costs. The second-best permit quantity can be both above or below the socially optimal emission level. Explicit consideration of the output market provides further insights on how market power distorts the allocation in the downstream industry. The ranking between permits and taxes is ambiguous in general, but taxes weakly dominate permits if full diffusion is socially optimal. In addition, it is analysed how a cap on the permit price affects the diffusion of an abatement technology.

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1 Introduction

Environmental regulation plays a crucial role in stimulating 'green' technological change. The scarcity signals induced by emission taxes and tradable permit schemes create markets for abatement technologies and services. In recent decades the spread and tightening of environmental regulation in industrialised countries has led to the establishment of a sizable eco-industry that specialises in providing these abatement technologies and services (Sinclair-Desgagné 2008).

An important characteristic of the eco-industry - like in most industries specialised in providing new technologies - is imperfect competition. Economies of scale due to high fixed costs in the form of R&D investments, protection of intellectual property rights by patents, learning-by-doing and economies of scope are the main drivers of this market structure. With market power in the upstream eco-industry, the price paid by the polluting downstream industry for abatement technology and services is likely to exceed the true social marginal costs of provision.

However, most early papers on the interaction between environmental regulation and technological change ignore market imperfections in the upstream industry and assume that the costs of a new abatement device reflect true economic costs (Milliman and Prince 1989, Jung et al. 1996, Requate and Unold 2003). Another stream of the literature considers market power in the downstream industry but again assumes a zero mark-up on abatement technologies (Montero 2002, de Vries 2007).

*g.perino@uea.ac.uk, tel.: +44 1603 59 1090, fax: +44 1603 45 6259

The explicit consideration of market power in the eco-industry which allowed a more substantial analysis of the interaction between environmental instruments and research incentives started with Parry (1995) and Laffont and Tirole (1996). Parry (1995) studies the optimal emission tax if the government is not able to adjust its policy after a new abatement technology becomes available. He finds that the second-best tax rate should be below marginal damages to correct among others for monopoly pricing. Laffont and Tirole (1996) focus on tradable permits and a situation where the new technology is both perfectly clean and costless. They show that in this special case the government faces a commitment problem since after innovation it prefers to issue a non-binding number of permits in order to drive the mark-up of the eco-firm and hence R&D incentives down to zero. A policy that is clearly not desirable at the stage when R&D efforts are determined. The present paper highlights the importance of this type of commitment problem in much more general settings.

Denicolò (1999) compares the performance of taxes and tradable permits for abatement technologies that involve zero real abatement costs but are not perfectly clean. He concludes that both instruments are equivalent and implement the socially optimal rate of diffusion if the type of innovation is exogenous and the government is able to adjust stringency of environmental regulation after the innovation has arrived. This result has been challenged by Perino (2008). Although he focuses on multi-pollutant economies he also shows that upstream market power creates inefficiencies with permits under Denicolo's specifications. This is confirmed in the present paper and shown to hold for a more general class of abatement technologies. While Fischer et al. (2003) consider an imperfectly competitive upstream industry, they assume away any distortions due to monopoly pricing via the threat of imitation. Requate (2005) compares taxes and permits under upstream market power in a scenario with heterogeneous firms and different levels of government commitment. For the case when the government adjusts environmental policy after innovation but before adoption he finds that the efficiency of both taxes and permits is affected by upstream market power.

A imperfectly competitive industry for abatement services is studied by David and Sinclair-Desgagné (2005). They find that the second-best environmental policy should be more stringent than in the absence of market power in the eco-industry. Moreover, in David and Sinclair-Desgagné (2010) they show that the social optimum can be implemented if an emission tax is combined with an abatement subsidy paid to upstream firms (but not if paid to downstream firms). Finally, Greaker (2006) and Greaker and Rosendahl (2008) endogenise the degree of competition in the upstream industry and analyse the effects on export performance.

The present paper makes the following contributions. For a perfectly competitive, homogeneous and polluting downstream industry and a monopolistic upstream firm that provides an abatement technology it derives second-best permit and tax policies for all combinations of emission intensity and (linear) marginal abatement costs. This extends the set of technologies considered by Laffont and Tirole (1996) and Denicolò (1999). By explicitly modeling output markets it is able to capture additional distortions not present in Requate (2005). In contrast to Perino (2008) the second-best policy is described in more detail and compares the second-best number of permits to first-best emission levels. Somewhat surprisingly second-best emissions can be both higher and lower than in the social optimum depending on real marginal abatement costs. Whether or not taxes can always implement the social optimum crucially depends on whether the government can select the efficient equilibrium in cases when there are multiple equilibria, only one of them is efficient and firms are indifferent between them. Second-best permit and tax schemes are welfare ranked. Taking the R&D stage into account, the government might face a commitment problem with respect to instrument choice. For some types of technologies permits might induce more R&D while taxes can be more efficient at the adoption stage.

A further contribution is to provide the first analysis of how caps on the permit price affect the diffusion of abatement technologies and R&D incentives. Price bounds usually discussed in the context of marginal abatement cost uncertainty can reinstate efficiency in the presence of upstream market power. Hence, the government has an incentive to use them once an abatement technology has arrived. However, this will reduce research incentives and at the stage when R&D efforts are determined the government would prefer to bind its hands on that front. Small changes in the design of a permit scheme, like the level of penalties for excessive emissions, can therefore have a significant impact on the static and dynamic efficiency of regulatory interventions.

The remainder of this paper is organised as follows. Section 2 presents the model. The social optimum is derived in Section 3. The case of a competitive upstream industry is briefly considered in Section 4. The second-best permit and tax policies are presented and ranked in Section 5 while Section 6 extends the analysis to include a cap on the price of permits. The last section concludes.

2 The Model

Consider a competitive downstream industry that produces a homogeneous good, the quantity of which is denoted by Y. Demand for the good is represented by the good's inverse demand function $P(Y)$, with $P'(Y) < 0$. The industry's aggregate cost function is denoted by $C(Y)$ and is assumed to be non-decreasing and convex ($C'(Y) \geq 0$ and $C''(Y) \geq 0$). Despite free entry marginal costs might be non-constant at the industry level due to scarcity of some of the inputs used in production. However, all results hold for constant marginal costs. Initially production of one unit of output is associated with one unit of emissions, i.e. $E = Y$. Emissions cause environmental damage of size $D(E)$ which is assumed to be strictly increasing and strictly convex ($D'(E) > 0$ and $D''(E) > 0$).

There is also an upstream industry offering a given abatement technology that reduces the emission intensity of production to $e \in [0, 1)$. A unit of output produced using the abatement device emits only $e < 1$ units of emission instead of one unit of emission per unit of output for the initial dirty production process. Hence, total industry emissions are $E = Y^{di} + eY^{cl}$, where Y^{cl} is output produced with and Y^{di} is output produced without the abatement device. Total output is the sum of 'dirty' and 'clean' output ($Y = Y^{di} + Y^{cl}$) and the rate of diffusion of the abatement technology is Y^{cl}/Y. This setup represents a typical end-of-pipe abatement device like flue-gas desulfurisation devices (scrubbers) that reduce the amount of sulfur oxide in the emission stream of coal fired power plants by a given percentage. They can be retro-fitted on existing installations and hence diffusion rates are not restricted by the long life-time of power plants. Other examples are catalytic converters in cars and carbon capture and storage (CCS).

There are costs of producing, installing and operating the abatement device (excluding any sunk R&D costs). Since the downstream industry is competitive and hence consists of a large number of small firms, clean output Y^{cl} is proportional to the number of abatement units sold. Hence, total abatement costs are rY^{cl} where $r \geq 0$ are the real per unit costs of abatement.

The policy instrument available to the benevolent government is the aggregate number of pollution permits, $\hat{E}$, issued or the tax rate, τ, charged on emissions. In Section 6 an additional policy parameter in the form of an upper bound on the permit price will be introduced.

The timing is as follows. First, the government sets the environmental policy knowing the characteristics of the abatement technology. Second, the upstream industry sets a price for the abatement technology and in the last stage the downstream market clears. This timing reflects short but not long term commitment on environmental policy by the government. While it is assumed that the policy maker can react to the discovery of new technologies and its features, she is not able to condition her decisions on the degree of adoption by the downstream industry.

3 The Social Optimum

A social planner who has total control over output and adoption decisions maximises social welfare given by

$$W(Y^{di}, Y^{cl}) = \int_{z=0}^{Y} P(z)dz - C(Y) - r \cdot Y^{cl} - D\left(Y^{di} + e \cdot Y^{cl}\right). \tag{1}$$

The corresponding Kuhn-Tucker first-order conditions are

$$\frac{\partial W}{\partial Y^{di}} = P(Y) - C'(Y) - D'\left(Y^{di} + e \cdot Y^{cl}\right) \leq 0, \qquad (= if \quad Y^{di} > 0), \tag{2}$$

$$\frac{\partial W}{\partial Y^{cl}} = P(Y) - C'(Y) - r - e \cdot D'\left(Y^{di} + e \cdot Y^{cl}\right) \leq 0, \qquad (= if \quad Y^{cl} > 0). \tag{3}$$

There are three different cases: no, partial and full adoption of the abatement technology. Mathematically this translate into the following conditions.

If it is best not to use the abatement technology at all, condition (2) exclusively determines the socially optimal output $Y^* = Y^{di^*}$. This is the case if and only if

$$r > r^{no} = (1 - e) \cdot D'(Y^{di^*}). \tag{4}$$

Full diffusion of the abatement device is optimal if

$$r < (1 - e) \cdot D'(eY^{cl^*}), \tag{5}$$

holds, where Y^{cl^*} is determined by condition (3) given that $Y^{di^*} = 0$. Note that Y^{cl^*} is itself a function of marginal abatement costs r. Since optimal output is decreasing in the costs of using the abatement technology ($\partial Y^{cl^*}/\partial r \leq 0$) and marginal damages are increasing in emissions, (5) defines a unique r^{full} which is an upper bound on marginal abatement costs compatible with complete diffusion.

For all cost parameters $r \in \left[r^{full}, r^{no}\right]$ partial adoption of the abatement technology is chosen by the social planner. In this case both (2) and (3) hold simultaneously. The optimal amount of pollution emitted E^* is implicitly given by

$$r = (1 - e)D'(E^*). \tag{6}$$

Substituting (6) into (2) yields optimal aggregate output Y^*. Using the definitions of both E and Y allow to calculate Y^{di^*} and Y^{cl^*}.

Proposition 1 *The social optimum is characterised as follows:*

(a) For all abatement cost levels $r < r^{full}$ there is full diffusion of the abatement technology. Aggregate output (which all is clean) and total emissions are decreasing in abatement costs.

(b) For all abatement cost levels $r^{full} < r < r^{no}$ there is partial diffusion of the abatement technology. Aggregate and clean output are decreasing while dirty output and total emissions are increasing in abatement costs.

(c) For all abatement cost levels $r^{no} < r$ the abatement technology is not used at all. Aggregate output (which all is dirty) and total emissions are independent of abatement costs.

Proof see appendix.

Panels (a) - (c) of Figure 1 illustrate the thresholds r^{no} and r^{full}, the socially optimal output quantities and the socially optimal emission level, respectively. They are derived using a simple linear version of the model.[1]

[1] The specification of the model used to compute all Figures can be found in the appendix.

In panel (a) area A indicates all combinations of abatement costs r and emission intensities e for which the abatement technology is not used. Area B comprises all combinations for which partial diffusion is optimal and area C is the set of parameters that result in full diffusion of the abatement device in the social optimum. The monotonic downward sloping line representing r^{no} illustrates that costs and abatement effectiveness are very close (here indeed perfect) substitutes in determining whether the first unit of the abatement device should be installed. However, whether the last unit of output is produced in a clean or dirty fashion depends non-monotonically on the removal efficiency. For any given removal efficiency an increase in abatement costs makes full diffusion less attractive. However, keeping r constant, an increase in the emission intensity first makes it more and then less desirable to clean up all output. The latter is due to two effects that work in opposite directions. On the one hand, an increase in the emission intensity reduces the amount of pollution avoided by installing one additional unit. This makes full diffusion less attractive. On the other hand, a lower removal efficiency (i.e. an increase in e) causes the industry to emit more pollution and hence the marginal damage caused by each additional emission is larger. Full diffusion becomes more desirable. The latter effect is driven by infra marginal units and is largest for the decision of whether to clean-up the last unit of output (since then effectively all output is clean). For low emission intensities the second effect dominates while for high ones the opposite is the case. The vertical line at $e = 0.55$ indicates the range of parameters displayed in panels (b) and (c).

Panel (b) presents how total output (the bold line) changes as a function of abatement costs. For abatement costs between r^{full} and r^{no} the optimal levels of clean and dirty output are given illustrating the optimal degree of diffusion for each level of abatement costs. For sufficiently low abatement costs all output is clean and hence decreasing in abatement costs. In this range higher abatement costs imply higher marginal costs of production and hence lower total output. For abatement cost levels that render partial diffusion socially optimal the above effect is strengthened by the reduced attractiveness and hence lower diffusion rate of the abatement technology if abatement costs increase. Finally, if costs of abatement are prohibitively high, output does no longer depend on them.

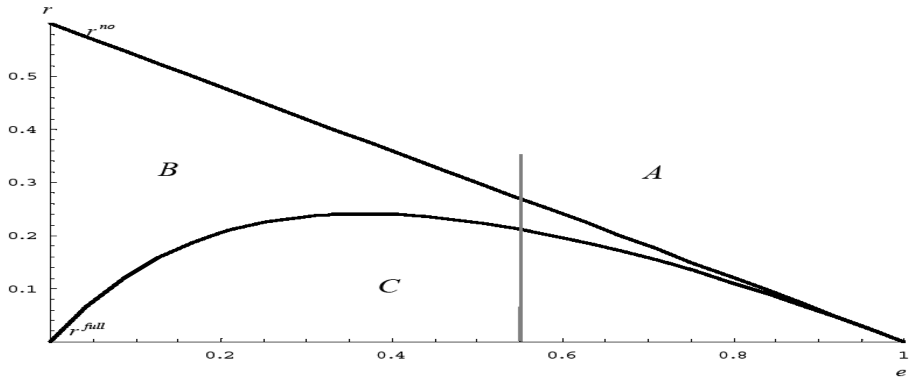
Panel (c) gives total emissions as a function of abatement costs in the social optimum. Note that emissions for very low abatement costs might (but do not have to) exceed emissions under very high abatement costs. This happens if emission reductions due to diffusion of the abatement technology are outweighed by higher emissions caused by the increase in output that follows from lower marginal costs of abatement.

4 Competitive Upstream Industry

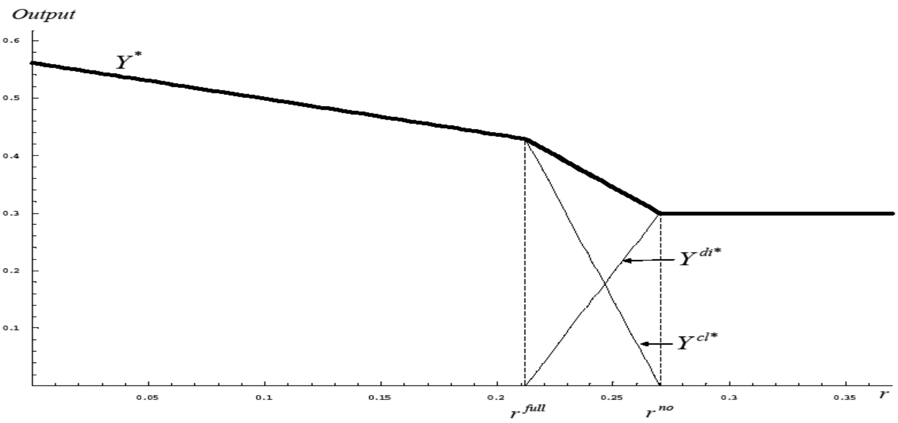
Let us now assume that the upstream industry supplying the abatement technology is competitive. Abatement devices are therefore available at marginal costs. This situation mimics the ex-ante optimal policy case in Requate and Unold (2003). The main difference is that they do not explicitly consider output markets. However, since both up- and downstream industries are competitive, this does not affect qualitative results. The following proposition therefore restates Proposition 6 of Requate and Unold (2003).

Proposition 2 *If the upstream industry is competitive, the government can implement the social optimum by issuing the socially optimal number of pollution permits. The social optimum can be implemented using taxes if full or no diffusion of the abatement technology is optimal. If partial diffusion is optimal taxes result in a continuum of equilibria of which only one is efficient.*

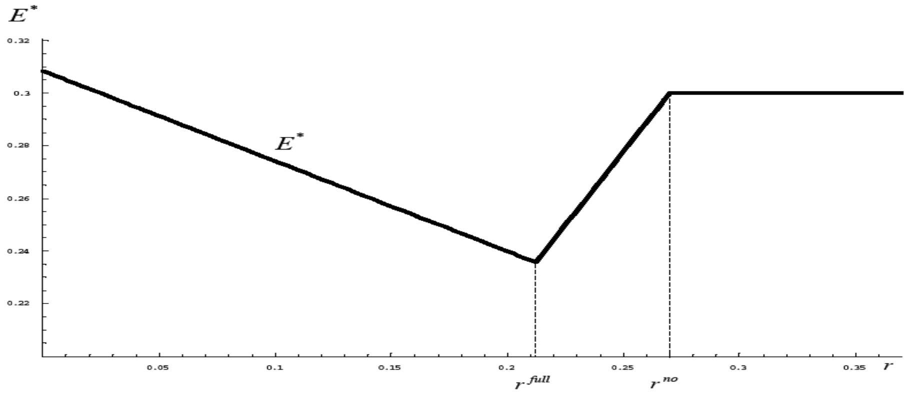
Proof see appendix.



(a) Abatement Cost Thresholds for Full and No Adoption in the Social Optimum



(b) Socially Optimal Levels of Total, Clean and Dirty Output



(c) Socially Optimal Permit Quantities

Figure 1: The Social Optimum

If there is only one market failure - a negative externality - one instrument (here: tradable permits) is sufficient to reinstate efficiency. If the government has access to a mechanism to select the equilibrium in the market clearing stage (e.g. by paying a penny to downstream firms in case they follow the government's wish), then taxes are able to implement the social optimum in all cases, too.[2] In the next section there will be a second market failure: market power in the abatement technology industry.

5 Upstream Monopoly

The market for the provision of advanced abatement technologies is often characterised by imperfect competition (Sinclair-Desgagné 2008). Economies of scale in research, development and production of new technologies and protection of intellectual property rights by patents are two of the main reasons for market power in this industry. Upstream firms will therefore charge a mark-up on the abatement equipment they sell to the downstream industry. Since this allows to recover sunk costs incurred e.g. in R&D, the anticipation of supra-normal profits earned in the marketing stage are a necessary condition for the investments to be made in the first place - given no direct innovation policies like research subsidies are in place. For simplicity it is assumed that there is only a single firm active in the production of abatement technology and hence that the upstream industry is monopolistic. The monopolist charges a mark-up of M on each unit of the abatement device sold. This mark-up could take the form of a license fee. The mark-up drives a wedge between the real economic costs of abatement, r, and the price downstream firms have to pay to clean up one unit of output.

The remainder of this section analyses how the presence of market power in the upstream industry affects the equilibrium outcome and the optimal pollution policy. Tradable permits are considered first. The simpler case of emission taxes and a welfare ranking are provided in Section 5.5.

5.1 Third stage: market clearing

Under tradable permits a representative, price-taking firm in the downstream industry maximises profits

$$\pi^{down}\left(Y^{di}, Y^{cl}\right) \quad = \quad P \cdot Y - C(Y) - \lambda \cdot Y^{di} - (\lambda e + r + M) \cdot Y^{cl}, \tag{7}$$

where λ is the equilibrium permit price and $\hat{E}$ the emission cap, subject to the permit constraint $\hat{E} \geq Y^{di} + e \cdot Y^{cl}$.

The corresponding first-order conditions yield the following set of equations.

$$\begin{aligned}
P(Y) &\leq C'(Y) + \lambda, & (= if \quad Y^{di} > 0), \quad (8)\\
P(Y) &\leq C'(Y) + r + M + e \cdot \lambda, & (= if \quad Y^{cl} > 0), \quad (9)\\
\hat{E} &= Y^{di} + e \cdot Y^{cl}. & (10)
\end{aligned}$$

Conditions (8) and (9) require that price equals marginal costs for each output type. The permit constraint is represented by (10). Jointly they determine the equilibrium quantities $Y^{di}(\hat{E}, M)$ and $Y^{cl}(\hat{E}, M)$ and the permit price $\lambda(\hat{E}, M)$.

Depending on the mark-up and permit quantity set in stages one and two, there are three cases to be distinguished: no, full and partial diffusion of the abatement technology.

None of the abatement devices is used if the marginal costs of clean output exceed those of dirty output. Using (8) and (9) this is the case if the mark-up on the abatement device is sufficiently high, i.e. $M > \overline{M} = (1-e)\lambda - r$. Note that in this situation (10) simplifies to $\hat{E} = Y^{di}$ (since $Y^{cl} = 0$) and the price of permits is determined by condition (8). The threshold

[2] Downstream firms are indifferent between all equilibria including the social optimum. So an aribtraily small incentive could induce them to choose the social optimum. However, such a mechanism is not part of the model presented in this paper.

for the mark-up that triggers zero diffusion of the abatement technology can, hence, be rewritten as $\overline{M}(\hat{E}) = (1-e)[P(\hat{E}) - C'(\hat{E})] - r$.

Full diffusion occurs if the marginal costs of clean output are lower than those of dirty output, i.e. if the costs of abatement plus the mark-up are less than the savings arising from reduced expenditures on permits ($M + r < (1-e)\lambda$). However, the price of pollution permits - now determined by (9) - is itself a function of the mark-up. Using $\hat{E} = eY^{cl}$ and (9) the threshold for the mark-up is $M < \underline{M}(\hat{E}) = (1-e)[P(\hat{E}/e) - C'(\hat{E}/e)] - r$.

Partial diffusion is an equilibrium if clean and dirty output are equally attractive to downstream firms ($M + r = (1-e)\lambda$). Given the cap on aggregate pollution $\hat{E}$, this is the case for all levels of mark-ups in the range $M \in [\underline{M}(\hat{E}), \overline{M}(\hat{E})]$. This is a non-degenerated interval since $e < 1$, $P'(Y) < 0$ and $C''(Y) \geq 0$. Using the first-order conditions (8) and (9) aggregate output under partial diffusion Y_{pa} is implicitly defined by

$$M + r = (1-e)[P(Y_{pa}) - C'(Y_{pa})]. \tag{11}$$

Note that under partial diffusion aggregate output does not depend on the permit quantity but on the mark-up alone. Clean and dirty output, however, are functions of both $\hat{E}$ and M. Using $Y_{pa} = Y_{pa}^{di} + Y_{pa}^{cl}$ and the permit constraint (10) it follows that

$$Y_{pa}^{di}(\hat{E}, M) = \frac{\hat{E} - e \cdot Y_{pa}(M)}{1-e}, \tag{12}$$

$$Y_{pa}^{cl}(\hat{E}, M) = \frac{Y_{pa}(M) - \hat{E}}{1-e}. \tag{13}$$

This completes the description of equilibrium quantities and the permit price as functions of the permit quantity and the mark-up on abatement devices.

5.2 Second stage: mark-up

Anticipating the outcome of the market-clearing stage the upstream monopolist charges a mark-up M that maximises profits

$$\pi^{up}(M) = M \cdot Y^{cl}(M). \tag{14}$$

The range of profit-maximising mark-ups has natural bounds. On the one hand, the supplier of the abatement technology will not set a mark-up in excess of $\overline{M}(\hat{E})$ since this would result in zero sales.[3] On the other hand, undercutting $\underline{M}(\hat{E})$ would also result in an unambiguous reduction in profits. It would not increase demand for the abatement device since the permit constraint prohibits further extension of clean output.

First, consider strict interior solutions characterised by partial diffusion of the abatement technology. In this case the first-order condition for the monopolist's profit maximisation problem is

$$\frac{\partial \pi^{up}}{\partial M} = Y_{pa}^{cl}(\hat{E}, M) + M \cdot \frac{\partial Y_{pa}^{cl}}{\partial M}\left(\hat{E}, M\right) = 0. \tag{15}$$

This is the standard condition for profit maximisation by a monopolist. Using (11) and (13) this condition can be expressed in terms of the demand and cost functions, exogenous parameters, aggregate output and the permit quantity set by the government (proof see appendix).

$$-\frac{(1-e)\,[P(Y_{pa}) - C'(Y_{pa})] - r}{(1-e)\,[P' - C'']\left(Y_{pa} - \hat{E}\right)} = 1, \tag{16}$$

[3] If $\overline{M}(\hat{E})$ is negative, the monopolist is indifferent between all $M \geq \overline{M}(\hat{E})$ including zero.

where the left-hand side represents the price elasticity of demand for the abatement technology. The numerator is the mark-up M charged on abatement devices (see (11)).

In the marked-clearing stage aggregate output is a function of the mark-up but not of the permit quantity given there is partial diffusion of the abatement technology. Condition (16) establishes a link between the permit quantity and the mark-up and hence equilibrium output can be expressed as a function of the policy variable. This function is labeled $Y_{pe}(\hat{E})$. Note that the permit constraint restricts $Y_{pe}(\hat{E})$ to the interval $\left[\hat{E}, \hat{E}/e\right]$ and hence $M(\hat{E})$ does indeed not exceed the thresholds $\underline{M}(\hat{E})$ and $\overline{M}(\hat{E})$. However, corner solutions are possible which is to what we turn next.

In principle there are two possible corner solutions. However, the upper bound on the mark-up $\overline{M}(\hat{E})$ is never binding. Recall that with mark-ups at the upper bound profits are zero since no one buys the abatement technology. Hence, if $\overline{M}(\hat{E})$ is strictly positive, it is not binding. A marginal reduction in the mark-up results in some abatement devices being sold and hence in strictly positive profits. However, the lower bound on the mark-up can impose a binding constraint. This corner solution is characterised by all firms using the abatement device ($Y_{pe}(\hat{E}) = Y_{pa}^{cl}(\hat{E}, M(\hat{E})) = \hat{E}/e$). Hence, a reduction in the mark-up does not increase the demand for the abatement technology since all firms already use the abatement device and expansion of output (e.g. by entry of new firms) is prohibited by a binding permit constraint. Condition (16) no longer holds. Instead

$$-\frac{(1-e)\left[P(Y_{pa}) - C'(Y_{pa})\right] - r}{(1-e)\left[P' - C''\right]\left(Y_{pa} - \hat{E}\right)} \geq 1 \tag{17}$$

holds, indicating that the monopolist would be willing to reduce the mark-up if demand for the abatement device were not limited by the permit constraint.

Whether the solution is interior or not depends on the number of permits issued by the government, $\hat{E}$, and the level of real abatement costs, r. For each $\hat{E}$ there is an abatement cost $r^{corn}\left(\hat{E}\right)$ for which (16) holds and all downstream firms use the abatement device (i.e. $Y_{pa}^{cl}(\hat{E}, M(\hat{E})) = \hat{E}/e$). Vice versa there is an $\hat{E}^{corn}(r)$ for each r. When deciding on the stringency of the emission cap the government will take the effect on this threshold into account.

The above solution is only a profit maximum if the following restriction on the convexity of demand and the concavity of the marginal cost function holds (the proof is in the appendix)

$$P''(Y) - C'''(Y) < -\frac{2 \cdot (1-e) \cdot \left[P'(Y) - C''(Y)\right]}{Y - \hat{E}}. \tag{18}$$

Note that the right-hand side of (18) is non-negative since $P'(Y) - C''(Y) \leq 0$. In what follows it is assumed that (18) is satisfied[4] so we focus on cases where the above solutions are indeed profit-maximising equilibria.

Regardless of whether the equilibrium is a corner solution or not the outcome now only depends on the government's choice of permit quantity.

5.3 First stage: policy choice

The benevolent government anticipates the mark-up setting and market-clearing stages and chooses a permit quantity $\hat{E}$ that maximises welfare. However, since the government has only one policy variable - the permit quantity - but faces two market failures - a pollution externality and market power in the upstream industry - this will result in a second-best welfare optimum. For a treatment of situations where the government has two instruments available to address

[4]This is the case e.g. for all linear demand and marginal cost curves.

the two market failures see Section 6 (permits with a price cap), Perino (2008) (tax and permits on different pollutants) and David and Sinclair-Desgagné (2010) (emission tax and abatement subsidy). With only permits at hand, the government maximises social welfare which is now given by

$$W^{permit}(\hat{E}) = \int_{z=0}^{Y_{pe}(\hat{E})} P(z)dz - C\left(Y_{pe}(\hat{E})\right) - r \cdot Y_{pa}^{cl}\left(\hat{E}, M(\hat{E})\right) - D\left(\hat{E}\right). \tag{19}$$

The corresponding first-order condition yields

$$\frac{\partial Y_{pe}}{\partial \hat{E}} \cdot \left[P\left(Y_{pe}(\hat{E})\right) - C'\left(Y_{pe}(\hat{E})\right)\right] - \left[\frac{\partial Y_{pa}^{cl}}{\partial \hat{E}} + \frac{\partial Y_{pa}^{cl}}{\partial M} \cdot \frac{\partial M}{\partial \hat{E}}\right] \cdot r = D'\left(\hat{E}\right), \tag{20}$$

where the first term on the left-hand side represents the gains from the expansion of output resulting from a marginal increase in the permit quantity. The second term are the abatement costs saved by a laxer emission target. The right-hand side are the marginal damages of pollution. This defines the second-best permit quantity $\hat{E}^{sb}$.

How the mark-up, total and clean output respond to a change in the permit quantity depends on the degree of diffusion of the abatement technology. Together with the criterion of whether the social optimum is feasible or not this divides the set of abatement costs into four regions (not all might exist for some given set of parameters) where the second-best allocation has different features.

For sufficiently high abatement costs the abatement technology will not be used at all. It turns out that this threshold coincides which the abatement cost level r^{no} that makes abatement unattractive for a social planner (see proof for Proposition 3(d)). In this range clean output is zero and does not vary with changes in the permit quantity. Since the emission intensity of dirty output is one, a unit change in the permit quantity translates into a unit change in dirty output. Condition (20) simplifies and matches the condition for a social optimum when all output is dirty (2). The government can implement the social optimum for all abatement cost levels $r > r^{no}$.

For all abatement cost levels below r^{no} at least some output will be produced using the abatement device. There is a range of partial diffusion for all abatement costs $r^{full\_sb} < r < r^{no}$. The lower bound r^{full_sb} is defined as the level of abatement costs for which the second-best optimal permit quantity derived for partial diffusion induces full diffusion. This implies that conditions (16), (20) and $Y_{pe} = Y_{pa}^{cl}$ hold at the same time (i.e. $r^{full\_sb} = r^{corn}\left(\hat{E}^{sb}(r^{full\_sb})\right)$). In this range of abatement costs a change in the permit quantity will affect the degree of diffusion of the abatement technology as well as aggregate output.

For abatement cost levels smaller than r^{full_sb} the second-best optimum is characterised by all output being clean. Note that the threshold r^{full_sb} is always lower than r^{full} that renders full diffusion socially optimal. The strictly positive mark-up charged by the upstream monopolist makes adoption less attractive to firms than to society. Furthermore, it is important to notice that full diffusion does not necessarily imply that the social optimum can be implemented. While the government has effective control over output *given* that diffusion is complete, the rate of diffusion might still depend on the permit quantity chosen. Recall that for any given r there is a corresponding permit quantity $\hat{E}^{corn}(r)$. Only permit quantities below this threshold will induce full diffusion (proof see appendix). Hence, if the socially optimal amount of emissions is above this threshold it cannot be implemented.

This leads to the fourth and last range of abatement costs. For all $r < r^{eff}$ the government is able to implement the social optimum by using tradable permits only. This threshold is defined by $\hat{E}^{corn}(r^{eff}) = E^*(r^{eff})$. Hence, for all abatement costs in this range condition (17) holds for the socially optimal output quantity.

For all abatement costs between r^{eff} and r^{full_sb} there is full diffusion of the abatement technology but the second-best permit quantity and hence output are below the social optimum.

Panel (a) of Figure 2 gives the threshold levels for all relevant emission intensities (again based on a linear version of the model). Compared to Figure 1(a) that presents the socially optimal thresholds for full and no diffusion, Figure 2(a) adds the two thresholds that characterise full diffusion in the second-best and the feasibility of the social optimum with full diffusion under permits. The area labeled C_1 indicates the set of parameters where full diffusion is socially optimal but where there is still some dirty output under permits. While the diffusion rate is socially optimal in area C_2 aggregate output is below the social optimum. The combination of emission rates and abatement costs that allow a government using permits to implement the social optimum with full diffusion of the abatement technology is given by area C_3. Again, the vertical line at $e = 0.55$ indicates the parameter space represented in panels (b) and (c). Note that the thresholds r^{full_sb} and r^{eff} exist only for some emission intensities but not for others. This indicates that for some abatement technologies a full-diffusion social optimum or full diffusion in general might not be feasible with permits regardless of the level of abatement costs.

The relationship between abatement costs and the second-best permit quantity and output levels is summarised in the following proposition (proofs see appendix).

Proposition 3 *The second-best optimal allocation with tradable permits is characterised as follows.*

(a) For all abatement costs $r \leq r^{eff}$ the social optimum can be implemented using tradable permits. Both aggregate output and emissions are decreasing in the level of abatement costs.

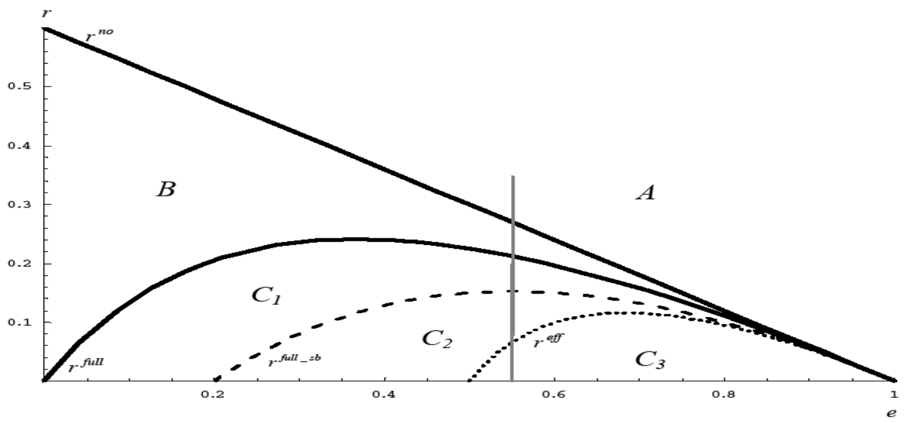
(b) For all abatement costs $r^{eff} < r \leq r^{full\_sb}$ the rate of diffusion is socially optimal but aggregate output and emissions are below the social optimum. Both aggregate output and emissions are decreasing in the level of abatement costs.

(c) For all abatement costs $r^{full\_sb} < r < r^{no}$ both diffusion and aggregate output are lower than in the social optimum. Emissions are smaller than socially optimal for abatement costs sufficiently close to the lower threshold r^{full_sb} but are higher for all abatement cost levels $r^{full} \leq r < r^{no}$ with $r^{full\_sb} < r^{full}$. Emissions are increasing in the level of abatement costs.

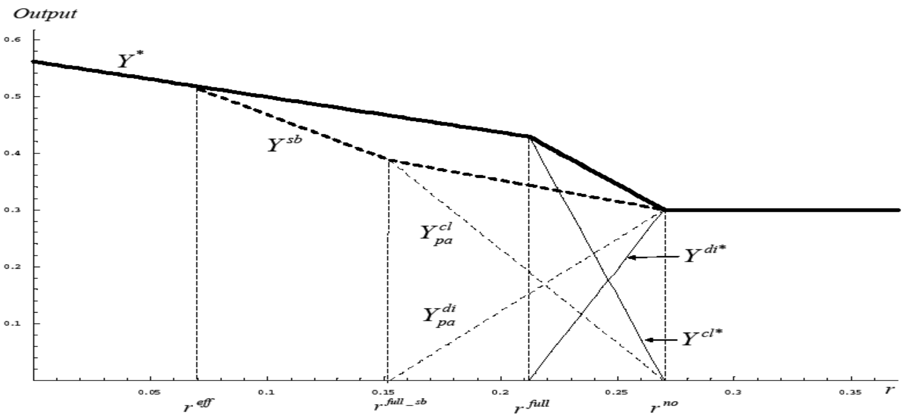
(d) For all abatement costs $r \geq r^{no}$ there is no diffusion of the abatement device which is socially optimal. Aggregate output and emissions are independent of abatement costs and socially optimal.

Panel (b) of Figure 2 presents both the socially optimal and the second-best (the dashed lines) output while panel (c) does the same for emissions. The emission intensity in this example is chosen such that an r^{eff} exists and hence for small abatement costs the social optimum can be implemented. In this range an increase in abatement costs increases the marginal costs of production for all output but does not affect the degree of diffusion. Output and hence emissions fall as a result.

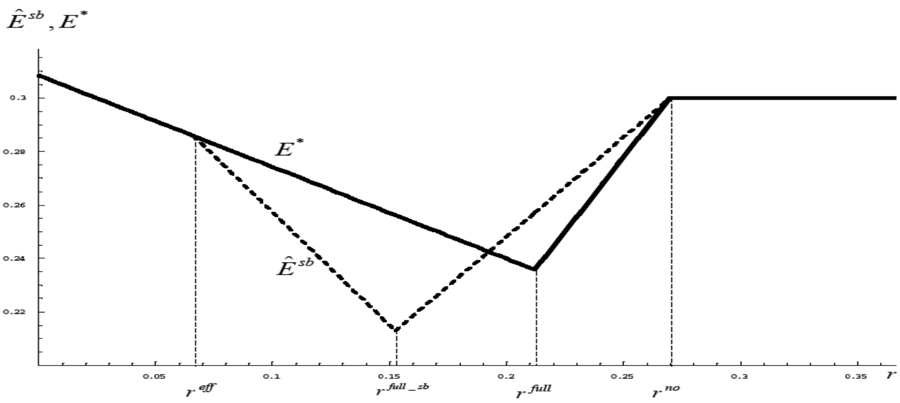
For the range of abatement costs where all output under a second-best permit scheme is clean but not socially optimal ($r \in \left[r^{eff}, r^{full\_sb}\right]$) the diffusion rate is still socially optimal. However, the government prefers to restrict emissions and hence output to a level below the social optimum. This increases the scarcity of permits and hence makes abatement sufficiently attractive that despite the mark-up charged on abatement devices full diffusion is still profit maximising for the downstream industry. This mimics a result by David and Sinclair-Desgagné



(a) Abatement Cost Thresholds



(b) Socially Optimal and Second-best Optimal Quantities



(c) Socially Optimal and Second-best Optimal Permit Quantities

Figure 2: Social Optimum and Second-Best Optimum

(2005) who assume that all firms use abatement goods and services but where the amount of abatement is endogenous. They find that the second-best emission tax exceeds social marginal damages in order to counterbalance the reduced attractiveness of abatement due to the mark-up of the eco-industry and thereby increase adoption. Within the range $r \in \left[r^{eff}, r^{full\_sb}\right]$ an increase in abatement costs now has two effects. Firstly, as before, it makes production (which is all clean) less attractive and thereby reduces the desirability of output. Secondly, since it decreases the attractiveness of abatement, the government has to make pollution rights scarcer in order to ensure that full diffusion is still an equilibrium. The second-best permit quantity therefore decreases faster than socially optimal emissions if abatement costs increase. The second effect (and hence the range $r \in \left[r^{eff}, r^{full\_sb}\right]$) exist only if revenue of the upstream monopolist is sensitive to a change in the mark-up even when all downstream firms use the technology. This requires either that the monopolist's revenue is a direct function of clean output (e.g. when downstream firms pay a license fee to the upstream monopolist that is proportional to clean output) or, in case the monopolist charges a lump-sum fee to buy an abatement device, that new firms can enter the market. Both interpretations are compatible with the model at hand. A necessary (but not sufficient) condition is that demand for the final good Y is downward-sloping in the relevant range. This condition also explains why Requate (2005) does not find a corresponding abatement cost range. He ignores output markets and assumes that firms pay a lump-sum fee to acquire the abatement device and that the number of active firms is fixed.

If abatement costs increase above the critical value r^{full_sb} but stay below r^{no}, the costs of ensuring full diffusion (i.e. output sacrifices) are higher than the benefits and hence the government relaxes the permit constraint and thereby allows for some output to be dirty. Everything else equal, a change in the permit quantity increases aggregate output and tends to reduce the attractiveness of abatement.[5] The second-best permit quantity is below the social optimum at the lower end of the range by continuity. However, for sufficiently large abatement costs the government issues more permits than in the social optimum. To see this, note that for all abatement costs $r \in \left[r^{full}, r^{no}\right]$ condition (20) simplifies to

$$\frac{\partial Y_{pe}}{\partial \hat{E}} \cdot M\left(\hat{E}\right) + r = (1-e) \cdot D'\left(\hat{E}\right), \tag{21}$$

since $\frac{dY_{pa}^{cl}}{d\hat{E}} = \frac{1}{1-e}\left[\frac{\partial Y_{pe}}{\partial \hat{E}} - 1\right]$ in this range. Aggregate output is increasing in the number of permits available (proof see appendix) and hence the left-hand side of (21) is larger than r. Recall that (6) implicitly defines the socially optimal amount of emissions by $r = (1-e) \cdot D'(E^*)$. Since marginal damages are increasing in emissions and the first term on the left-hand side is strictly positive, condition (21) implies that second-best emissions are above those in the social optimum for all abatement cost levels for which partial diffusion is socially optimal.

What is the rational behind granting additional pollution rights? At the first-best level of pollution, diffusion of the abatement device is less than socially optimal because the mark-up makes adoption less attractive to downstream firms. Hence, average pollution intensity of the downstream industry is higher than socially optimal and aggregate output is lower ($Y_{pe}(E^*) < Y^*$). Issuing additional permits increases aggregate output and makes pollution rights less scarce. As a result the permit price drops which reduces the attractiveness of abatement but also exerts a downward pressure on the mark-up. A lower mark-up increases diffusion of abatement devices which offsets at least some of the effect caused by the lower permit price. Increasing the number of permits above the socially optimal level reduces the distortion caused by market power in terms of the wedge between private and social marginal abatement costs and aggregate output. Aggregate output is below the social optimum for all abatement cost levels within the range $r \in \left[r^{full\_sb}, r^{no}\right]$. This is obvious for abatement costs close to the lower end of the range where the permit quantity is below the social optimum and some output is dirty and hence more pollution intensive. For abatement costs closer to the upper end of the range, the government

[5] The effect of an increase in the permit quantity on clean output is - in general - not unambiguous. While an increase in the number of permits reduces the permit price the monopolist responds by reducing the mark-up. The latter only dominates the former if the demand and the industry's marginal cost function are sufficiently inelastic.

allows emissions to exceed the social optimum. Hence, in principle, total output could exceed the first-best level. However, the mark-up makes abatement sufficiently unattractive such that the excessive share of dirty production more than compensates for the additional permits granted.

For abatement costs above the threshold r^{no} the abatement technology is not used at all in both the social optimum and the second-best optimum. The government can implement the socially optimal aggregate output and emission levels.

5.4 Discussion of the Second-Best Permit Policy

There are positive R&D incentives - in the form of profits to be appropriated by the upstream firm - for all types of technology that carry social value (areas B - C_3 in Figure 2(a)). R&D incentives are zero for those that do not carry a positive value (area A). Hence, if market power in the upstream industry is created by granting patents to a successful innovator, such a research policy would at least ensure that no resources are wasted developing technologies that are not socially desirable. However, the size of research incentives created does in general not match the social value of the abatement device. The reason is straightforward. A government restricted to one policy instrument - tradable permits in this case - is clearly unable to tackle two market failures (see Proposition 3). This assumes a commitment not to revise the scope and protection of intellectual property. Adding a third in the form of the private provision of a public good (knowledge) is unlikely to improve on this.

The horizontal axis in panel (a) of Figure 2 ($r = 0$) represents the case studied by Denicolò (1999). In contrast to one of his results, the social optimum cannot be implemented for all emission intensities but only for sufficiently dirty technologies (see also Perino, 2008). Another special case previously discussed in the literature is a perfectly clean ($e = 0$) technology with zero marginal abatement costs ($r = 0$) located in the origin in Figure 2(a). Laffont and Tirole (1996) show that the government is able to implement the first-best allocation, i.e. full diffusion of the abatement technology, by issuing an excessive number of permits (which is equivalent to abandoning environmental policy all together) and thereby push the mark-up down to zero. However, this result crucially depends on the assumption that all firms adopt the abatement device if marginal abatement costs are zero. While this might seem innocent it contrasts the tie-breaking rule used here and for example in Requate and Unold (2003) and Perino (2008). There it is assumed that for cases of equal marginal costs of two technologies the market share of each undetermined. However, commitment problems similar to the one described by Laffont and Tirole (1996) occur in Section 6 where a cap on the permit price is introduced.

5.5 The Second-Best Tax Policy

So far it has been assumed that the government uses pollution permits to regulate the downstream industry. In this subsection the (second-best) emission tax is briefly considered and compared to the second-best permit scheme. In deriving the equilibrium under taxes it is important to note that marginal costs of adopting the abatement device r are the same across firms and independent of the number of firms adopting. Furthermore, in contrast to the permit scheme, the upstream firm cannot influence the costs of emissions. Hence, the equilibrium in the production stage is determined by

$$P(Y) \leq C'(Y) + \tau, \qquad (= if \quad Y^{di} > 0), \tag{22}$$

$$P(Y) \leq C'(Y) + r + M + e \cdot \tau, \qquad (= if \quad Y^{cl} > 0), \tag{23}$$

where τ is the tax on emissions. All downstream firms will use the abatement device if $M < \tilde{M} = (1-e)\tau - r$. No firm will use it if $M > \tilde{M}$ and if the mark-up exactly equals the threshold $\tilde{M}$ the market share is not determined.

In the mark-up setting stage, the profit-maximising upstream monopolist will just undercut the threshold $\tilde{M}$ - given it is strictly positive - in order to ensure full adoption. If the threshold is strictly negative, the (non-negative) mark-up is irrelevant since no downstream firm will adopt the technology. In case $\tilde{M} = 0$, the monopolist is indifferent between all non-negative mark-ups but his choice will affect diffusion. If he sets $M = 0$, the rate of diffusion of the abatement technology is not determined, while it is zero for all strictly positive mark-ups.

The government faces the following choice situation when maximising welfare. It can either ensure full adoption by setting $\tau > \frac{r}{1-e}$, no adoption by setting $\tau < \frac{r}{1-e}$ or 'take a gamble' by setting $\tau = \frac{r}{1-e}$.

If either no or full adoption is socially optimal, the government is able to implement the welfare maximising allocation by setting $\tau = D'(Y^{di^*})$ or $\tau = r + eD'(eY^{cl^*})$, respectively. However, if partial adoption is socially optimal (i.e. $r \in \left[r^{full}, r^{no}\right]$), the choice is less straightforward. In this range of abatement costs and given full adoption, the government would like to set a tax rate lower than $\frac{r}{1-e}$. Given no adoption, the second-best welfare optimum requires a tax above $\frac{r}{1-e}$. Hence, the bounds on the tax rate are binding in both situations. By setting a tax of either $\frac{r}{1-e} - \epsilon$ or $\frac{r}{1-e} + \epsilon$, with $\epsilon > 0$ arbitrarily close to zero, the government is able to implement (approximately) the socially optimal aggregate output level (which requires $\tau = \frac{r}{1-e}$) but not the socially optimal rate of diffusion.[6]

The only way to achieve the first-best welfare maximum is to set $\tau = \frac{r}{1-e}$. However, in this case there is a continuum of equilibria in the mark-up stage and given the monopolist sets $M = 0$, there is another continuum of equilibria in the market clearing stage, only one of which is efficient. Note that both the monopolist and downstream firms are indifferent between all these equilibria. Only the government has preferences over the outcome in stages two and three of the game.

Whether the government sets $\tau = \frac{r}{1-e}$ or not crucially depends on whether it has a mechanism to induce the upstream monopolist and downstream firms to choose the equilibrium it prefers (i.e. by offering a penny in case they do). In the absence of such a mechanism, the government has to form beliefs over the probability that $M = 0$ and over diffusion rates.

The allocation under an emission tax is summarised in the following proposition (the proof is in the appendix).

Proposition 4 *If no or full diffusion of the abatement technology is socially optimal, an emission tax can implement the social optimum. If partial adoption is socially optimal*

(a) and the government has a mechanism to select its preferred equilibria in the mark-up and market clearing stages, then it sets $\tau = \frac{r}{1-e}$ *and always implements the first-best welfare maximum (*$M = 0$, $Y^{di}_{tax} = Y^{di^*}$ *and* $Y^{cl}_{tax} = Y^{cl^*}$*).*

(b) and in the absence of an effective equilibrium selection mechanism, the second-best tax policy is to

(i) set $\tau = \frac{r}{1-e} + \epsilon$ *for all* $r \in \left[r^{full}, \underline{r}^{tax}\left(\rho, \phi(Y^{cl}/Y^*)\right)\right]$ *(implement full diffusion),*

(ii) set $\tau = \frac{r}{1-e}$ *for all* $r \in \left[\underline{r}^{tax}\left(\rho, \phi(Y^{cl}/Y^*)\right), \overline{r}^{tax}\left(\rho, \phi(Y^{cl}/Y^*)\right)\right]$ *(the upstream monopolist and the downstream industry determine the rate of diffusion),*

(iii) set $\tau = \frac{r}{1-e} - \epsilon$ *for all* $r \in \left[\overline{r}^{tax}\left(\rho, \phi(Y^{cl}/Y^*)\right), r^{no}\right]$ *(implement no diffusion),*

where ρ *is the government's belief about the probability that* $M = 0$ *in the mark-up stage and* $\phi(Y^{cl}/Y^*)$ *is the distribution function representing the conditional belief over the diffusion rate in the market clearing stage, given that* $M = 0$.

[6] Strictly speaking there are no tax levels that meet this requirement since for any given ϵ_1 there is always a smaller ϵ_2 that yields higher welfare. However, $\epsilon = 0$ is ruled out. It is assumed that the government is able to solve that problem, which only arises in a continuous set-up. The same holds for the mark-up set by the monopolist.

In all cases aggregate output is (approximately) equal to the socially optimal aggregate output for all abatement cost levels. Only the expected rate of diffusion is suboptimal if partial diffusion is socially optimal and equilibrium selection by the government is not feasible. In the range where partial adoption is socially optimal, the monopolist's profits are (approximately) zero, regardless of the nature of the equilibrium.

The problem of equilibrium selection also occurs if the abatement technology is provided competitively (Requate and Unold 2003). The issue is somewhat more pronounced with an imperfectly competitive upstream industry since in this case there are two stages featuring a continuum of equilibria.

In welfare terms tradable permits and emission taxes rank as follows. If no or full diffusion of the abatement device is socially optimal, taxes perform at least as good as permits and are strictly better for marginal abatement costs in the range $r^{eff} < r < r^{full}$. If partial adoption is the preferred outcome, the ranking depends on the ability of the government to select the equilibrium that implements the socially optimal allocation. If equilibrium selection is possible, taxes always implement the first-best welfare optimum and hence dominate permits. If equilibrium selection is not possible, the ranking is ambiguous. For abatement costs above but close to r^{full}, taxes are preferred because they implement the first-best aggregate output and yield a diffusion rate closer to the socially optimal one than permits. For abatement costs smaller but close to r^{no}, permits yield higher welfare. While aggregate output is below the social optimum, this is due to the fact that the government is willing to trade off a reduction in aggregate output against an increase in the diffusion rate. With a tax scheme this trade-off is not possible and the outcome therefore less desirable.

However, for some types of technologies research incentives under permits are higher than those under taxes (certainly for all $r^{full} < r < r^{no}$ since $M = 0$ under taxes). Hence, depending on the characteristics of the research process, the government might have a preference to commit to tradable permits ex-ante even for technologies where ex-post taxes dominate permit schemes. This is especially pronounced if the government is actually able to always implement the social optimum under taxes: for all abatement cost levels where partial adoption is socially optimal, the government wants to commit to permits ex-ante but has incentives to use taxes ex-post.

6 Upstream Market Power and a Bounded Permit Price

The failure of the government to implement the socially optimal allocation using permit quantities alone established in the previous section is not surprising given that it faces two distinct market failures. However, environmental regulation is often not limited to a single control variable. Perino (2008) studies an industry that emits multiple pollutants and shows that an emission tax on one and tradable permit schemes for the remaining pollutants can implement the social optimum. Likewise, David and Sinclair-Desgagné (2010) explore the combination of an emission tax and an abatement subsidy and find that the social optimum can be implemented if the abatement subsidy is paid to the upstream industry but not if paid to downstream firms.

However, it is not necessary to introduce two separate policy instruments to increase the number of controls available to the government. Most real-world implementations of tradable permit schemes already comprise a multitude of mechanisms, rules and exemptions. One design parameter of particular interest in the context of diffusion of a new abatement technology is a cap on the permit price. A cap on the permit price requires that the government issues additional permits once that upper bound is reached. The supply of permits becomes perfectly elastic at that point. Such price caps have been widely discussed in the academic literature (Roberts and Spence 1976, Pizer 2002) and in the policy debate (Aldy and Pizer 2009). While the focus of such hybrid schemes has been on coping with uncertainties in marginal abatement costs this section is devoted to their effect on technological change in polluting industries. This aspect has

- to the best of my knowledge - so far been neglected in the economic literature.

Price caps are and have been part of numerous tradable permit schemes. In the form of fixed penalties on excessive emissions they were used in the former Danish carbon and the US ODS (ozone depleting substances) programs (OECD 2003). Numerous renewable energy obligations include buy-out options (DTI 2004, Aldy and Pizer 2009). Moreover, some of the proposed bills for a U.S. carbon trading scheme incorporate upper bounds on the price of carbon (Aldy and Pizer 2009).

The reason why caps on the permit price are relevant for technological change is that they - as will be shown below - also impose an upper bound on the mark-up charged on abatement devices. An upper bound on the permit price therefore allows the government to tackle the inefficiencies arising from market power directly and use the permit quantity to internalise externalities. However, there is a downside to this increased control of the government. Incentives to innovate will be weakly lower than in the case where a price bound is not available.

By introducing an upper bound on the permit price B as a new policy variable, the conditions for an equilibrium in the market clearing stage change as follows. While marginal costs of both 'clean' and 'dirty' output have to equal the price (conditions (8) and (9)), the permit constraint (10) is replaced by the conditional constraint

$$\hat{E} \;=\; Y^{di} + e \cdot Y^{cl}, \qquad if \quad \lambda < B. \tag{24}$$

This restricts the permit price $\lambda\left(\hat{E}, B\right)$ and hence the cost advantage of abatement. The upper bound on the mark-up $\overline{M}(\hat{E}, B) = (1-e) \cdot \min\left[P(\hat{E}) - C'(\hat{E}), B\right] - r$ is likewise affected. Whatever the permit quantity, the government now can restrict mark-ups to zero by setting the price cap at $B = r/(1-e)$. This ensures optimal diffusion and aggregate output for all marginal abatement costs that render partial diffusion of the abatement technology socially optimal. If full diffusion is socially optimal, the government can ease its grip on the upstream firm somewhat and is still able to implement the socially optimal allocation given that $r/(1-e) \leq B < P\left(Y^{cl*}\right) - C'\left(Y^{cl*}\right)$ which is a non-degenerate interval (due to conditions (3) and (5)).[7]

Proposition 5 *If the government can impose an upper bound on the permit price, implementation of the social optimum is feasible for all levels of marginal abatement costs.*

Note that the informational requirements for Proposition 5 to hold are the same as those of the previous propositions. The government is assumed to have perfect information.

While implementation of the social optimum in the diffusion stage of technological change seems beneficial, it does have negative repercussions on research and development. Imposing a binding upper bound on the mark-up of the upstream firm unambiguously reduces its profits. The only two ranges where profits are not affected are for technologies with marginal abatement costs that are either excessive ($r > r^{no}$ or area A in Figure 2(a)) or that are low enough ($r < r^{eff}$ or area C_3 in Figure 2(a)) to allow implementation of the social optimum even if no price cap is available. For all other cost levels, i.e. whenever a price cap improves ex-post efficiency, incentives to innovate decrease. They even drop to zero for all technologies that should be adopted only by some of the downstream firms ($r^{full} < r < r^{no}$ or area B in Figure 2(a)) because the mark-up is restricted to zero.

If the policy instrument of a cap on the permit price is available to the government, it has a clear incentive to make use of it once the abatement technology is developed. Ex-ante, i.e. before the upstream firm decides on R&D investment, the situation might be different. The government wants to stimulate R&D and therefore would like to commit not to use price caps

[7] In this case there is a continuum of equilibria, all implementing the static social optimum but differing in the upstream firm's profits - and hence research incentives. In what follows, the analysis is restricted to the equilibrium where profits are maximal.

in the future. It faces a problem of time-inconsistency in designing the environmental policy instrument. It is therefore not sufficient to credibly commit to granting and enforcing intellectual property rights (e.g. in the form of patents) but also to bind its hands with respect to design details of a permit scheme - which might be more difficult to achieve. This generalises a point first raised by Laffont and Tirole (1996).

Time-inconsistency will affect all policies that try to induce technological change with policies effective only after R&D has been undertaken. It is discussed in Perino (2008) and is also - potentially - a problem in David and Sinclair-Desgagné (2010) where subsidies are paid during the diffusion stage and hence after sunk costs have been incurred by the upstream eco-industry.

One further qualification on price caps is in order. Proposition 5 only holds if the costs of producing and installing the abatement device r are constant and the same across all downstream firms. The steeper the increase in r or the more heterogeneous firms are, the less effective are price caps in restricting monopoly pricing. However, bounds on the permit price will improve efficiency compared to permit schemes without a price cap because they make demand for the abatement technology more elastic and hence reduce marked power of the upstream eco-industry.

7 Conclusion

Stimulating the development of clean technologies is the main long-term goal of most environmental policies. This led to a growing eco-industry specialising on the provision of abatement services and technologies. However, the analysis of the effects of market power in the upstream industry on environmental regulation and in particular the choice and design of instruments is still in its early stages. The present paper contributes to this endeavour by extending the set of abatement technologies considered, by paying explicit attention to output markets and by providing a detailed analysis of second-best policies. Moreover, attention is drawn to design features of permit schemes that interact with upstream market power and the commitment problems arising thereof.

The following results are relevant for environmental policy making. First, clear results on when second-best permit quantities should be above or below first-best emissions are provided. Second, emission taxes and tradable permit schemes are ranked as follows: Taxes weakly dominate permits if full diffusion of the abatement technology is socially optimal. If partial diffusion is socially optimal, and the government lacks the ability to select the efficient equilibrium, permits dominate at least for some levels of marginal abatement costs. Third, tradable permit schemes with a price cap achieve static efficiency but reduce research incentives. Fourth, potential problems arising from time-inconsistency in instrument choice and design are highlighted.

While the theoretical analysis of the interaction between the emergence of a dedicated eco-industry with market power and environmental regulation is still in its infancy, the empirical literature on this aspect seems not to be born yet. Future work should try to fill this cap in order to inspire and guide the development and refinement of theoretical models as well as to provide a better foundation for policy recommendations.

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A Specification of the Model used in Simulations

All figures are computed using the following simplified version of the model.

$$P(Y) = 1 - Y \tag{A.1}$$
$$C(Y) = cY \tag{A.2}$$
$$D(E) = \frac{d}{2} \cdot E^2 \tag{A.3}$$

The parameter values used are

$$c = 0.1 \qquad e = 0.55 \qquad d = 2.$$

B Proofs

B.1 Proof of Proposition 1

Proofs for the thresholds r^{full} and r^{no} are given in the main text.

(a) For all abatement cost levels $r < r^{full}$: Totally differentiating condition (3) yields

$$\frac{\partial Y^{cl^*}}{\partial r} = \frac{1}{P' - C'' - e^2 D''} < 0.$$

Hence, aggregate output is decreasing in abatement costs. Since $E^* = eY^{cl^*}$ the same holds for total emissions.

(b) For all abatement cost levels $r^{full} < r < r^{no}$: Total emissions are determined by $(1-e) \cdot D'(E) = r$. Total differentiation yields

$$\frac{\partial E^*}{\partial r} = \frac{1}{(1-e)D''} > 0.$$

Total emissions are increasing in abatement costs. Total output is determined by $P(Y^*) = C'(Y^*) + D'(E^*)$. Total differentiation and using the above result yields

$$\frac{\partial Y^*}{\partial r} = \frac{\partial Y^*}{\partial E^*} \cdot \frac{\partial E^*}{\partial r} = \frac{1}{(1-e)(P' - C'')} < 0.$$

Aggregate output is decreasing in abatement costs. Combining $Y = Y^{di} + Y^{cl}$ and $E = Y^{di} + eY^{cl}$ and differentiating w.r.t. r yields

$$\frac{\partial Y^{di^*}}{\partial r} = \frac{1}{(1-e)^2} \cdot \left[\frac{1}{D''} - \frac{e}{P' - C''} \right] > 0,$$
$$\frac{\partial Y^{cl^*}}{\partial r} = \frac{1}{(1-e)^2} \cdot \left[\frac{1}{P' - C''} - \frac{1}{D''} \right] < 0.$$

Clean output is decreasing and dirty output increasing in abatement costs.

(c) For all abatement cost levels $r^{no} < r$: Aggregate output (which all is dirty) and total emissions are determined by condition (2) alone which is independent of abatement costs.

B.2 Proof of Proposition 2

Under tradable permits the market equilibrium in the downstream industry is determined by

$$\begin{aligned} P(Y) &= C'(Y) + \lambda, && if \quad Y^{di} > 0, && \text{(B.1)} \\ P(Y) &= C'(Y) + r + e \cdot \lambda, && if \quad Y^{cl} > 0, && \text{(B.2)} \\ \hat{E} &= Y^{di} + e \cdot Y^{cl}, && && \text{(B.3)} \end{aligned}$$

where λ is the equilibrium permit price. Depending on the permit quantity set in stage one, there are three cases to be distinguished: no, full and partial diffusion of the abatement technology.

- None of the abatement devices is used if the marginal costs of clean output exceed those of dirty output. Using (B.1) and (B.2) this is the case if $r > (1-e)\lambda^{no}$ where $\lambda^{no} = P\left(\hat{E}\right) - C'\left(\hat{E}\right)$.
- Full diffusion occurs if the marginal costs of clean output are lower than those of dirty output, i.e. if $r < (1-e)\lambda^{full}$ where $\lambda^{full} = \frac{P(\hat{E}/e) - C'(\hat{E}/e) - r}{e}$.
- Partial diffusion is an equilibrium if clean and dirty output are equally attractive to downstream firms ($r = (1-e)\lambda$).

In the first stage the government sets $\hat{E}$.

- If no diffusion is optimal it sets $\hat{E} = Y^{di^*}$. Hence, $\lambda = D'\left(\hat{E}\right) = P\left(\hat{E}\right) - C'\left(\hat{E}\right)$ and using condition (4), the government can implement the social optimum whenever no adoption is socially optimal.
- If full diffusion is optimal it sets $\hat{E} = e \cdot Y^{cl^*}$. Hence, $\lambda = D'\left(\hat{E}\right) = \frac{P(\hat{E}/e) - C'(\hat{E}/e) - r}{e}$ and using condition (5), the government can implement the social optimum whenever full diffusion is socially optimal.
- If partial diffusion is optimal it sets $\hat{E} = Y^{di^*} + e \cdot Y^{cl^*}$. Hence, $\lambda = D'\left(\hat{E}\right) = P\left(\hat{E}\right) - C'\left(\hat{E}\right)$ and using $r = (1-e)D'(E^*)$, the government can implement the social optimum whenever partial diffusion is socially optimal.

This completes the proof that permits can implement the social optimum if the upstream industry is competitive.

Under taxes the market equilibrium in the downstream industry is determined by

$$\begin{aligned} P(Y) &= C'(Y) + \tau, && if \quad Y^{di} > 0, && \text{(B.4)} \\ P(Y) &= C'(Y) + r + e \cdot \tau, && if \quad Y^{cl} > 0, && \text{(B.5)} \end{aligned}$$

where τ is the emission tax rate. Depending on the tax rate set in stage one, there are three cases to be distinguished: no, full and partial diffusion of the abatement technology.

- None of the abatement devices is used if the marginal costs of clean output exceed those of dirty output. Using (B.4) and (B.5) this is the case if $r > (1-e)\tau$.
- Full diffusion occurs if the marginal costs of clean output are lower than those of dirty output, i.e. if $r < (1-e)\tau$.
- Partial diffusion is an equilibrium if clean and dirty output are equally attractive to downstream firms ($r = (1-e)\tau$). Note that the rate of diffusion is undetermined since marginal costs for clean and dirty output are exactly the same and independent of the rate of diffusion.

In the first stage the government sets τ.

- If no diffusion is optimal it sets $\tau = P\left(Y^{di^*}\right) - C'\left(Y^{di^*}\right)$. Hence, using condition (4), the government can implement the social optimum whenever no adoption is socially optimal.
- If full diffusion is optimal it sets $\tau = P\left(Y^{cl^*}\right) - C'\left(Y^{cl^*}\right)$. Hence, using condition (5), the government can implement the social optimum whenever full diffusion is socially optimal.
- If partial diffusion is optimal the government faces the problem of multiple equilibria in the market clearing stage. One of them is efficient if $\tau = r/(1-e)$. It can either 'take a gamble' or implement second-best full or no diffusion outcomes. Which one it prefers depends on its beliefs over the probability distribution over the continuum of equilibria.

This completes the proof for taxes.

B.3 Proof of condition (16)

Implicitly differentiating (11) w.r.t. M, and using condition (13) yields $\frac{\partial Y^{cl}_{pa}}{\partial M} = \frac{1}{(1-e)^2[P'-C'']} < 0$ where C'' is the second derivative of $C(Y)$ with respect to aggregate output Y. Substituting this, (11) and (13) into the first-order condition (15) and rearranging gives (16).

B.4 Proof of the Second-Order Condition

The second-order condition for a profit maximum is

$$\frac{\partial^2 \pi^{up}}{\partial M^2} = 2 \cdot \frac{\partial Y^{cl}_{pa}}{\partial M}\left(\hat{E}, M\right) + M \cdot \frac{\partial^2 Y^{cl}_{pa}}{\partial M^2}\left(\hat{E}, M\right) < 0. \tag{B.6}$$

Recall that $\frac{\partial Y^{cl}_{pa}}{\partial M} = \frac{1}{(1-e)^2[P'-C'']} < 0$ and hence $\frac{\partial^2 Y^{cl}_{pa}}{\partial M^2} = -\frac{P''-C'''}{(1-e)^2[P'-C'']^2} \cdot \frac{\partial Y^{cl}_{pa}}{\partial M}$. Substituting this and (16) into the second-order condition (B.6) yields (18).

B.5 Proof that $Y^{cl}_{pa} = Y_{pe}\ \forall E \leq \hat{E}^{corn}(r)\ \forall r \in \left[r^{eff}, r^{full\_sb}\right]$

If an increase in $\hat{E}$ would render the left-hand side of (16) negative, then the full diffusion condition ($Y = \hat{E}/e$) imposes an upper bound on the permit quantity. $E \leq \hat{E}^{corn}(r)$ would therefore impose an upper bound on the permit quantity compatible with full diffusion.

Taking the first derivative of the left-hand side of (16) with respect to $\hat{E}$ evaluated at $\hat{E}^{sb}$ yields the following result. The left-hand side of (16) is negative if and only if

$$P'' - C''' < -\frac{2 \cdot e \cdot [P' - C'']}{(1-e)\hat{E}},$$

which given full diffusion of the abatement technology ($Y = \hat{E}/e$) coincides with (18). Hence, it holds in all cases considered here.

B.6 Proof of Proposition 3

Part (a)
In order to achieve both full diffusion of the abatement technology and the socially optimal output level the following condition has to hold (see(17))

$$-\frac{(1-e)\left[P(Y^*) - C'(Y^*)\right] - r}{(1-e)^2\left[P' - C''\right] Y^*} \geq 1$$

which defines r^{eff} when it holds as an equality. Hence, for all $r \leq r^{eff}$ it holds that $Y = Y^{cl} = Y^* = e \cdot E^*$.

Aggregate output and emissions are decreasing in abatement costs since total differentiating of (3) yields

$$\frac{dY^{cl}}{dr} = \frac{1}{P' - C'' - e^2 \cdot D''} < 0.$$

Part (b)

Emissions: Since diffusion is full ($r < r^{full\_sb}$), the socially optimal output not feasible ($r > r^{eff}$) and $\hat{E}^{corn}(r)$ imposes an upper bound on the permit quantity that is consistent with full diffusion, the government chooses the permit quantity that is as close as possible to the social optimum but still ensures full diffusion, i.e. $\hat{E}^{sb} = \hat{E}^{corn}(r) < E^*(r)$.

Partial derivative of second-best emissions w.r.t. r: The effect of an increase in r on the second-best permit quantity is implicitly defined by (16). Note that since all downstream firms use the abatement device (16) simplifies to

$$-\frac{(1-e)\left[P(Y) - C'(Y)\right] - r}{(1-e)^2\left[P' - C''\right] \cdot Y} = 1. \tag{B.7}$$

Total differentiation of (B.7) yields

$$\frac{dY}{dr} = \frac{(P' - C'') \cdot Y}{(1-e)(P' - C'')^2 \cdot Y - (1-e)(P - C')\left[(P'' - C''')\,Y + P' - C''\right]}, \tag{B.8}$$

which is negative if and only if the denominator is positive. This yields condition

$$P'' - C''' < (P' - C'') \cdot \frac{(P' - C'') \cdot Y - (P' - C'')}{(P' - C'')Y}. \tag{B.9}$$

Comparing (B.9) to the second-order condition for a profit maximum (18) yields $P - C' > \frac{r}{1-e}$ which always holds in the range $r \in \left[r^{eff}, r^{full\_sb}\right]$. Second-best output and hence emissions are therefore decreasing in r.

Part (c)

Emissions: This case is characterised by partial diffusion and hence an interior solution to the upstream firm's profit maximisation problem. Using $\frac{dY^{cl}_{pa}}{d\hat{E}} = \frac{1}{1-e}\left[\frac{\partial Y_{pe}}{\partial \hat{E}} - 1\right]$ the first-order condition of the welfare maximisation problem (19) yields (21) which determines the second-best permit quantity $\hat{E}^{sb}$ under partial diffusion of the abatement technology.

Since some but not all output should be clean, i.e. $r \in [r^{full}, r^{no}]$, it follows from the first-order conditions of the social optimum (2) and (3) that $r = (1-e)D'(E^*)$ is a condition for a first-best outcome. However, the latter is not satisfied since there is a positive mark-up on the abatement device, $M\left(\hat{E}\right) > 0$. Hence, if aggregate output is increasing in the number of permits issued, $\frac{\partial Y_{pe}}{\partial \hat{E}} > 0$, the first term on the left-hand side in (21) is positive. Since $D'' > 0$ the second-best permit quantity $\hat{E}^{sb}$ is larger than first-best emissions E^*.

Next we check whether total output is indeed increasing in the permit quantity ($\frac{\partial Y_{pe}}{\partial \hat{E}} > 0$). Total differentiation of (16) and rearranging yields

$$P'' - C''' < -\frac{2 \cdot \left[P' - C''\right]}{Y - \hat{E}},$$

which is always satisfied given that the second-order condition for a profit maximum of the upstream monopolist holds (see (18)).

By continuity, the second-best permit quantity for abatement costs close to r^{full_sb} are smaller than socially optimal emissions. Hence, somewhere in the range $r \in \left[r^{full\_sb}, r^{full}\right]$ second-best and first-best emissions are equal.

Aggregate output: For all $r \in \left[r^{full}, r^{no}\right]$ the socially optimal aggregate output is determined by $P(Y) - C'(Y) = D'(E^*) = \frac{r}{1-e}$. However, in the second-best optimum total output under partial diffusion is given by (11). Since M is strictly positive and $P(Y) - C'(Y)$ decreasing in Y it follows that $Y^{sb}(r) < Y^*(r)$ for all $r \in \left[r^{full}, r^{no}\right]$.

For all r that are sufficiently close to r^{full_sb} such that $\hat{E}^{sb}(r) < E^*(r)$ it has to hold that $Y^{sb}(r) < Y^*(r)$ since diffusion is less than in the social optimum (and hence less output is produced per permit). However, there is a range of abatement costs for which $\hat{E}^{sb}(r) > E^*(r)$ but $r < r^{full}$. Hence, the lower diffusion rate could be compensated by additional permits and aggregate output might - potentially - exceed the social optimum. However, this effect is largest for $r = r^{full}$ (since second-best emissions are furthest above E^*) but it has been shown above that $Y^{sb}(r^{full}) < Y^*(r^{full})$. Hence, $Y^{sb}(r) < Y^*(r)$ for all $r \in \left[r^{full\_sb}, r^{no}\right]$.

Diffusion: Diffusion is less than socially optimal for all $r \in \left[r^{full\_sb}, r^{full}\right]$ because not all downstream firms use the abatement device in the second-best optimum. For all $r \in \left[r^{full}, r^{no}\right]$ the equilibrium clean output is given by (13). Since $Y^{sb}(r) < Y^*(r)$ and $\hat{E}^{sb}(r) > E^*(r)$ it follows that $Y^{cl\_sb}(r) < Y^{cl^*}(r)$.

Partial derivative of second-best emissions w.r.t. r: Total differentiation of (21) yields

$$\frac{d\hat{E}}{dr} = -\frac{1}{\frac{\partial^2 Y_{pe}}{\partial \hat{E}^2} \cdot M + \frac{\partial Y_{pe}}{\partial \hat{E}} \frac{\partial M}{\partial E} - (1-e)D''} > 0.$$

Note that $\frac{\partial^2 Y_{pe}}{\partial \hat{E}^2} = -\frac{1}{1-e} \cdot \frac{1}{\left[-2(P'-C'')+(P''-C''')\cdot(Y-E)\right]^2} < 0$.

Part (d)

Substituting $r^{no} = (1-e) \cdot D'(E^*)$ into $\overline{M} = (1-e) \cdot \lambda - r$ yields

$$\overline{M} = (1-e) \cdot \left[\lambda - D'(E^*)\right].$$

Using the definition of the first-best output level Y^{di^*} and (8) it follows that $\overline{M} = 0$. Hence there will be no distortion due to market power, the abatement technology is not used and output is optimal due to $\hat{E} = E^*$. According to (2) E^* and Y^* are independent of r in this case.

B.7 Proof of Proposition 4

The government maximises social welfare

$$W^{tax}(\tau) = \int_{z=0}^{Y_{tax}(\tau)} P(z)dz - C\left(Y_{tax}(\tau)\right) - r \cdot Y_{tax}^{cl}\left(\tau, M(\tau)\right) - D\left(Y_{tax}^{di}(\tau) + eY_{tax}^{cl}(\tau)\right).$$

anticipating the outcome of the mark-up and market clearing stages, it realises that

$$\begin{array}{rll} Y_{tax}^{cl}\left(\tau, M(\tau)\right) = 0 & if & \tau < \frac{r}{1-e} \vee \left(\tau = \frac{r}{1-e} \wedge M > 0\right) \\ Y_{tax}^{di} + Y_{tax}^{cl} = Y_{tax}(\tau) & if & \tau = \frac{r}{1-e} \wedge M = 0 \\ Y_{tax}^{di}(\tau) = 0 & if & \tau > \frac{r}{1-e}. \end{array}$$

For all $r > r^{no}$, the social optimum is implemented by setting $\tau = D'(Y^{di^*})$ which satisfies $\tau < \frac{r}{1-e}$. For all $r < r^{full}$, the social optimum is implemented by setting $\tau = r + eD'(Y^{cl^*})$. This satisfies $\tau > \frac{r}{1-e}$. Since $\overline{M} = e\left[(1-e)D'(Y^{cl^*}) - r\right] > 0$ it also guarantees efficiency in the market clearing stage ($P(Y^{cl^*}) = C'(Y^{cl^*}) + r + e\tau + M = C'(Y^{cl^*}) + r + eD'(eY^{cl^*})$).

For $r \in \left[r^{full}, r^{no}\right]$, aggregate output is socially optimal if and only if $\tau = \frac{r}{1-e}$. In this case $\overline{M} = 0$. Hence the monopolist is indifferent between all non-negative mark-ups. If and only if $M = 0$, there is a continuum of equilibria that differ only in the diffusion rate. Only one of these is socially optimal. If $M > 0$, then $Y^{cl}_{tax} = 0$. Both the downstream firms and the monopolist are indifferent between all equilibria. If the government has access to a mechanism allowing to select the equilibrium in stages two and three (e.g. a small monetary reward), then taxes can always implement the social optimum.

In the absence of such a mechanism, the government's beliefs are crucial. Assume that beliefs are independent of r. For partial diffusion under $\tau = \frac{r}{1-e}$ to be relevant to the government, the belief about $M = 0$, ρ has to be strictly positive. If that is the case the distribution function $\phi(Y^{cl}/Y^*)$ representing the conditional belief over the diffusion rate given $M = 0$, determines the desirability of $\tau = \frac{r}{1-e}$ versus full or no adoption.

For any $\phi(Y^{cl}/Y^*)$ that attaches at least some weight to both extreme outcomes (i.e. $Y^{cl}_{tax} = 0$ and $Y^{di}_{tax} = 0$, Proposition 4 (b) holds. This is the case since for r just above r^{full} the socially optimal rate of diffusion is almost one. A tax rate $\tau = \frac{r}{1-e} + \epsilon$ can (approximately) implement the socially optimal aggregate output level and a diffusion rate of one. 'Taking a gamble' ensures the socially optimal aggregate output level, but with a strictly positive probability that the diffusion rate is way off the social optimum. Welfare is therefore higher under $\tau = \frac{r}{1-e} + \epsilon$ than expected welfare under $\tau = \frac{r}{1-e}$ for r sufficiently close to r^{full}. The same reasoning holds for abatement levels just below r^{no}.

It is possible that $\underline{r}^{tax}\left(\rho, \phi(Y^{cl}/Y^*)\right) = \overline{r}^{tax}\left(\rho, \phi(Y^{cl}/Y^*)\right)$ and hence the government switches from $\tau = \frac{r}{1-e} + \epsilon$ directly to $\tau = \frac{r}{1-e} - \epsilon$. Take the example where $\rho > 0$ and a specific $\phi(Y^{cl}/Y^*)$ that assigns probability $\frac{1}{3}$ to full and probability $\frac{2}{3}$ to no diffusion. In this case the government is always better off with implementing one extreme for sure than with taking a gamble.

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