UNIVERSITY OF GOTHENBURG
SCHOOL OF BUSINESS, ECONOMICS AND LAW

WORKING PAPERS IN ECONOMICS

No 573

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by

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September 2013

ISSN 1403-2473 (print)
ISSN 1403-2465 (online)

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On Refunding of Emission Taxes and Technology Diffusion*

Jessica Coria† Kristina Mohlin

Abstract

We analyze diffusion of an abatement technology in an imperfectly competitive industry under a standard emission tax compared to an emission tax which is refunded in proportion to output market share. The results indicate that refunding can speed up diffusion if firms do not strategically influence the size of the refund. If they do, it is ambiguous whether diffusion is slower or faster than under a non-refunded emission tax. Moreover, it is ambiguous whether refunding continues over time to provide larger incentives for technological upgrading than a non-refunded emission tax, since the effects of refunding dissipate as the overall industry becomes cleaner.

Keywords: emission tax, refund, abatement technology, technology diffusion, imperfect competition

JEL Classification: H23, O33, O38, Q52

1 Introduction

From a welfare point of view, the optimal rate of adoption of environmentally friendly technologies should balance the investment costs against the benefits of adoption in terms of reduced environmental damages and lower abatement costs. Nevertheless, the interplay of technology and environmental market failures implies that markets often underinvest in new technology. It is unlikely that environmental policy alone creates sufficient incentives for technological change - strengthening the case for second-best policies (Jaffe *et al.*, 2005).

*Research funding from the Swedish Energy Agency and from the research programme Instrument Design for Global Climate Mitigation (INDIGO) is gratefully acknowledged. We thank Katrin Millock, Magnus Hennlock, Carolyn Fischer and Thomas Sterner for valuable comments.

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In theory, a strong and stable price of emissions implemented through an emission tax should induce both investment in R&D and a "cost-effective" allocation among firms of the burden of achieving given levels of environmental protection. In reality, however, introducing such an emission tax may prove politically infeasible since regulated firms will often argue that they will lose international competitiveness. As well as job losses if firms relocate or close, an additional concern is the relocation of pollution, or so-called emission leakage in the case of transboundary pollution such as greenhouse gas emissions.

One potential way of making emission taxes more politically feasible is to refund the tax revenues to the regulated industry (Hagem *et al.*, 2012; Aidt, 2010; Fredriksson & Sterner, 2005). One method for such refunding is to refund the revenues in proportion to the output market share. This is the approach that Swedish policy makers used in 1992 when introducing a charge on emissions of nitrogen oxides (NO_x) from large combustion plants. The policy was explicitly intended to affect technology adoption. The refunding scheme enabled the introduction of an emission charge sufficiently high to induce abatement (Sterner & Höglund-Isaksson, 2006). This tax and refunding scheme, sometimes referred to as refunded emission payment (REP), has been extensively studied in the theoretical literature concerning the incentives for emission abatement and production and how it compares to optimal policy; see e.g., Fischer (2011), Cato (2010), Sterner & Höglund-Isaksson (2006) and Gersbach & Requate (2004)[1]. From the empirical side, Sterner & Turnheim (2009) study the effects of the Swedish refunded charge on NO_x emissions. Their results indicate that the charge had a very substantial role in explaining the sharp decrease in NO_x emission intensities; not only did the best plants make rapid progress in emission reductions, but there was also considerable catching up, such that today the majority of plants have lowered their emission intensities much more relative to the cleanest plants.

In this paper, we model the pattern of adoption of environmentally friendly technologies under a "standard" emission tax (hereinafter, emission tax) and an emission tax for which the revenues are returned to the aggregate of taxed firms in proportion to output (hereinafter,

[1] Gersbach& Requate (2004) and Sterner & Höglund-Isaksson (2006) analyze the incentives for abatement and production provided by an output based refunding scheme in markets characterized by imperfect and perfect competition, respectively. Cato (2010) studies the effects of refunding on market structure, showing that a refunding system might have to be complemented with an entry license to ensure that the system does not encourage too much market entry. Finally, Fischer (2011) studies the performance of refunding schemes when firms can strategically influence the size of the refund; since firms know that part of any emissions rents they create will be returned to them, refunding discourages large firms from abating emissions and subsidizes high emitters to a greater extent.

refunded tax)[2]. We consider the case of exogenous refunding, where firms take the size of the refund as given, vis-a-vis endogenous refunding, where firms recognize that a share of their emissions tax payments will be returned to them[3]. To the best of our knowledge, despite a growing body of literature analyzing the incentives for technological diffusion provided by different environmental policy instruments (see for instance van Soest (2005) and Coria (2009)), this is the first study investigating the effects of refunding an emission tax.

Like Coria (2009), our setting makes use of the framework by Reinganum (1981), who considers an industry composed of symmetric firms that engage in Cournot competition in the output market. When a technology that reduces the cost of compliance with an emission tax appears, each firm must decide when to adopt it, based in part upon the discounted cost of implementing it and in part upon the behavior of the rival firms. If a firm adopts a technology before its rivals, it can expect to make substantial profits at the expense of the other firms, since the cost advantage allows it to increase its output market share. On the other hand, the discounted sum of purchase price and adjustment costs may decline if the adjustment period lengthens, as various quasi-fixed factors become adjustable. Therefore, although waiting costs more in terms of forgone profits, it may save money on purchasing the new technology. Reinganum (1981) showed that diffusion, as opposed to immediate adoption, occurred purely due to strategic behavior in the output market, since adoptions that yield lower incremental benefits are deferred until they are justified by lower adoption costs.

Our results indicate that exogenous refunding of an emission tax based on output reinforces the mechanism described by Reinganum (1981). Hence, technology diffuses faster into an imperfectly competitive industry if the regulator refunds the emission tax revenues but the firms do not recognize the impact of adoption on the average emission intensity. The intuition behind this result is straightforward: if the refund is based on output, adopters receive a net refund as the system rewards those firms that are cleaner than average. However, the incremental effect of the refund over taxes decreases as more and more firms adopt because of the lower overall pollution intensity and thus lower refund.

[2] A distinction can be made between an emission tax and an emission charge where revenues from a tax go to the general budget and revenues from a charge are earmarked for a specific purpose (Sterner, 2003). Although refunding would make the emission tax a charge according to this definition, we will throughout the paper refer to the refunded charge as a refunded tax.

[3] Fischer (2011) refers to exogenous refunding as "fixed subsidy", and to an emission tax with an endogenous output-based rebate as the "refunded tax".

The paper is organized as follows. Section 2 introduces the model of technological diffusion. Section 3 and 4 analyze the adoption incentives provided by emission taxes with and without refunding, respectively. Section 5 analyzes technological catching up under the two policies. Section 6 presents numerical simulations and section 7 concludes.

2 The model

Assume an imperfectly competitive and stationary industry, where n firms choose their level of production simultaneously and compete in quantities. The inverse demand function is given by

$$P(Q) = a - bQ,$$

where $Q = \sum_{i=1}^{n} q^i$ and $a, b > 0$. The production technology exhibits constant returns to scale such that total variable costs are given by

$$C^i = c_0 q^i.$$

Production also generates emissions of a homogenous pollutant and emissions from firm i. e^i, are proportional to output q^i according to

$$e^i = \varepsilon_0 q^i.$$

To control emissions, the regulator has implemented a tax σ that each firm must pay for each unit of emission.

At date $t = 0$, an innovation in emissions abatement technology is announced. The new technology reduces the emission intensity from ε_0 to ε_1, i.e. $\varepsilon_1 < \varepsilon_0$, and also changes the marginal cost of production from c_0 to c_1[4]. Firms must now decide when to adopt the new technology, taking into account the effect of the competitors' adoption on pre- and post-adoption profit flows. Note that $c_0 + \sigma\varepsilon_0 > c_1 + \sigma\varepsilon_1$ by assumption to ensure that the rate of profit flow (quasi-rent) is higher with the new technology. Moreover, we assume that no future technical advance is anticipated.

Let $\pi_0(m_1)$ be the rate of (Cournot-Nash) profit flow for firm i when m_1 out of n firms

[4] As noted by Fischer (2011), this characterization is suitable for end-of-pipe technologies which scrub a certain proportion of emissions. It is also a good representation of a technology that improves fuel efficiency, which means that it reduces emissions per unit of electricity or useful heat of pollutants, which are highly correlated with fuel use (such as CO_2 and SO_2).

have adopted the cleaner technology and firm i has not. Next, let $\pi_1(m_1)$ be the rate of profit flow for firm i when m_1 firms have adopted the cleaner technology and firm i is among them. We assume that both $\pi_0(m_1)$ and $\pi_1(m_1)$ are known with certainty for all m_1.

Further, the following assumptions are made.

(1i) $\pi_0(m_1 - 1) \geq 0$ and $\pi_1(m_1) \geq 0$

(1ii) $\pi_1(m_1 - 1) - \pi_0(m_1 - 2) > \pi_1(m_1) - \pi_0(m_1 - 1) > 0$ for all $m_1 \leq n$.

Assumption (1ii) states that the increase in the profit rate from adopting as the $(m_1 - 1)$th firm should be higher than the increase in profit rate from adopting as the m_1th firm. This is to say, a firm that adopts earlier has a larger "relative" cost advantage than if it adopts later due to the strategic interaction in the output market.

Let τ_i denote firm i's date of adoption and let $p_1(\tau_i)$ be the present value of the investment cost for the new technology, including both purchase price and adjustment costs. We assume that $p_1(t)$ is a differentiable convex function with $p_1'(0) \leq \pi_0(0) - \pi_1(1)$ (2i), $\lim_{t\longrightarrow\infty} p_1'(t) > 0$ (2ii) and $p_1''(t) > re^{-rt}\left(\pi_1(1) - \pi_0(0)\right)$ (2iii). Assumption (2i) ensures that immediate adoption is too costly, while assumption 2(ii) ensures that the costs of adoption decrease over time, but do not decrease indefinitely. This implies that there is an efficient scale of adjustment beyond which adoption costs increase again. Moreover, assumption 2(iii) ensures that the objective function defining the optimal timing of adoption is locally concave on the choice of adoption dates.

Further, we define $V^i(\tau_1, ..., \tau_{i-1}, \tau_i, \tau_{i+1}, ..., \tau_n)$ to be the present value of firm i's profits net of any investment costs for the new technology when firm k adopts at τ_k, $k = 1, .., n$. Given an ordering of adoption dates $\tau_1 \leq \tau_2 \leq ... \leq \tau_n$, we can write the present value of firm i's profits as

$$V^i(\tau_1, ..., \tau_{i-1}, \tau_i, \tau_{i+1}, ..., \tau_n) = \sum_{m_1=0}^{i-1} \int_{\tau_{m_1}}^{\tau_{m_1+1}} \pi_0(m_1)e^{-rt}dt + \sum_{m_1=i}^{n} \int_{\tau_{m_1}}^{\tau_{m_1+1}} \pi_1(m_1)e^{-rt}dt - p_1(\tau_i),$$

where $\tau_0 = 0$ and $\tau_{n+1} = \infty$.

Maximization of V^i given the ordering $\tau_1 \leq \tau_2 \leq ... \leq \tau_n$ (and thus the restriction $\tau_{i-1} \leq \tau_i^* \leq \tau_{i+1}$) gives each firm i an optimal date of adoption, τ_i^*, and is implicitly defined by

$$\frac{\partial V^i}{\partial \tau_i} = \left(\pi_0(i-1) - \pi_1(i)\right) e^{-r\tau_i^*} - p_1'(\tau_i^*) = 0. \tag{1}$$

This first-order condition says that it is optimal to adopt the new technology on the date when the present value of the cost of waiting to adopt (the increase in profit rate due to adoption) is equal to the present value of the benefit of waiting to adopt (the decrease in investment cost). We define $\Delta\pi_i = \pi_1(i) - \pi_0(i-1)$ and (1) can then be written

$$\frac{\partial V^i}{\partial \tau_i} = -\Delta\pi_i e^{-r\tau_i^*} - p_1'(\tau_i^*) = 0,$$

$i = 1, ..., n$. Furthermore, V^i is strictly concave at τ_i^* for all i. As shown by Reinganum (1981), there are $n!$ sequences in which the adoption date defined by (1) is a Nash equilibrium (demonstration in Appendix A). This result holds regardless of firms being homogenous when the adoption decision is made at time 0 [5].

To further encourage adoption of new abatement technologies, the regulator has considered refunding the emission tax revenues to the firms in proportion to market share. In the following sections, we characterize one of the $n!$ sequences of adoption, analyzing the impact of refunding on the optimal date of adoption. That is, we analyze the difference in adoption profits $\Delta\pi_i$ between a standard emission tax and an emission tax refunded in proportion to output. A higher $\Delta\pi_i$ implies faster adoption (a lower τ_i^*) because of the concavity of $V^i(\tau_i^*)$ and vice versa.

3 Adoption incentives under an emission tax

If we have m_1 adopters of the new technology and rank the firms according to their order in the adoption sequence (taking it as given), we can write the profit rate maximization problem for the adopters as

$$\pi^j = \max_{q^j} \left[P(Q) - c_1 - \sigma\varepsilon_1\right] q^j,$$

for $j = 1, 2, ..., m_1 - 1, m_1$,

and the profit maximization problem for the $n - m_1$ non-adopters as

[5] To keep the analysis mathematically tractable and simple, we assume that firms are homogeneous in terms of their emissions intensity. Nevertheless, our results still hold if firms were heterogeneous. For example, following Coria (2009), we could have assumed that firms can be ordered according to their adoption profits from the firm with the highest to the firm with the lowest current emissions intensity. Under certain assumptions, such a setting would ensure a unique equilibrium for the adoption sequence. However, the comparison between refunded and non-refunded emission taxes would remain the same as the main driver behind technological diffusion in the model is the strategic interaction in the output market.

$$\pi^j = \max_{q^j} \left[P(Q) - c_0 - \sigma\varepsilon_0 \right] q^j,$$

for $j = m_1 + 1, m_1 + 2, ..., n - 1, n$.

The first order conditions for the adopters and non-adopters respectively are

$$P(Q) + P'(Q)q^j = c_1 + \sigma\varepsilon_1,$$

$j = 1, 2, ..., m_1 - 1, m_1,$

$$P(Q) + P'(Q)q^j = c_0 + \sigma\varepsilon_0,$$

$j = m_1 + 1, m_1 + 2, ..., n - 1, n.$

Thus, both types of firms set marginal revenue equal to marginal costs inclusive of the tax payment for the emissions embodied in an additional unit of output. Because marginal cost is lower for the adopters, they produce more than non-adopters.

We define the profit-maximizing level of production for the m_1 adopters under an emission tax to be q_1^T and the profit-maximizing level of production for the $n - m_1$ non-adopters to be q_0^T. We further assume that $q_0^T > 0$[6]. Now, if we let $\zeta_0^T = c_0 + \sigma\varepsilon_0$ denote marginal costs inclusive of emission tax payments under an emission tax before adoption of the new technology and let $\zeta_1^T = c_1 + \sigma\varepsilon_1$ denote marginal costs after adoption, the equilibrium output levels under an emission tax for adopters and non-adopters, respectively, are

$$q_1^T(m_1) = \frac{a - \zeta_1^T + [n - m_1] \left[\zeta_0^T - \zeta_1^T \right]}{b\,[n+1]},$$
$$q_0^T(m_1) = \frac{a - \zeta_0^T - m_1 \left[\zeta_0^T - \zeta_1^T \right]}{b\,[n+1]},$$

for which $q_1^T(m_1) > q_0^T(m_1) > 0$ and $q_1^T(m_1) - q_1^T(m_1 - 1) = q_0^T(m_1) - q_0^T(m_1 - 1) < 0 \vee m_1 \leq n$.

Furthermore, $q_1^T(m_1) > q_0^T(m_1 - 1) \vee m_1$. That is, adoption allows firms to increase their output. Moreover, it allows adopters to increase their market share since, due to strategic behavior in the output market, non-adopters reduce their output to offset the effect of an increased supply on the market price.

[6]From the equilibrium output level for technology 0 given below, it is clear that this assumption is satisfied for all $m_1 \leq n - 1$ if $a - n\,[c_0 + \sigma\varepsilon_0] + [n-1]\,[c_1 + \sigma\varepsilon_1] > 0$

Under an emission tax with m_1 adopters of the new technology, the equilibrium profit rate for adopters of the new technology is

$$\pi_1^T(m_1) = b\left[q_1^T(m_1)\right]^2,$$

and the equilibrium profit rate for the non-adopters

$$\pi_0^T(m_1) = b\left[q_0^T(m_1)\right]^2,$$

see Appendix B for derivation of equilibrium profits and output.

We can now find an expression for the increase in profit rate due to adoption for the firm that is the ith to adopt, under an emission tax.

$$\Delta\pi_i^T = b\left[\left[q_1^T(i)\right]^2 - \left[q_0^T(i-1)\right]^2\right]. \tag{2}$$

$\Delta\pi_i^T$ is positive but decreasing in i (in accordance with assumption 1ii and demonstrated in Appendix A.1).

4 Adoption incentives under a refunded tax

Under an emission tax which is refunded to the regulated firms in proportion to output market share, the profit rate maximization problem for the m_1 firms which have adopted the new technology is

$$\pi^j = \max_{q^j}\left[\left[P(Q) - c_1 - \sigma\varepsilon_1\right]q^j + \sigma E\frac{q^j}{Q}\right],$$

for $j = 1, 2, ..., m_1 - 1, m_1$,

and the profit maximization problem for the $n - m_1$ non-adopters

$$\pi^j = \max_{q^j}\left[P(Q) - c_0 - \sigma\varepsilon_0\right]q^j + \sigma E\frac{q^j}{Q},$$

$j = m_1 + 1, m_1 + 2, ..., n - 1, n$, with aggregate emissions (E) and aggregate output (Q) given by:

$$E = \sum_{i=1}^{n} e^i$$

$$Q = \sum_{i=1}^{n} q^i$$

and the average emission intensity $\bar{\varepsilon}(m_1)$ given by:

$$\bar{\varepsilon}(m_1) = \frac{m_1 \varepsilon_1 q_1 + [n - m_1]\, \varepsilon_0 q_0}{m_1 q_1 + [n - m_1]\, q_0} > 0 \ \vee m_1. \tag{3}$$

4.1 Exogenous Refunded Tax

With reference to the Swedish NO_x charge, we first focus on the case where the number of firms in the industry is large enough so that each firm considers its own impact on the average emission intensity (and therefore also the size of the refund) as neglible[7].

The first order conditions for the adopters and non-adopters respectively are then

$$P(Q) + P'(Q)q^j = c_1 + \sigma\left[\varepsilon_1 - \bar{\varepsilon}\right], \tag{4}$$

for $j = 1, 2, ..., m_1 - 1, m_1$,

$$P(Q) + P'(Q)q^j = c_0 + \sigma\left[\varepsilon_0 - \bar{\varepsilon}\right], \tag{5}$$

for $j = m_1 + 1, m_1 + 2, ..., n - 1, n$.

Thus both types of firms set marginal revenue equal to marginal costs inclusive of the emission tax minus the marginal refund. The marginal refund is given by the emission tax rate times the average emission intensity and works as an implicit output subsidy. Thus, just as under an emission tax, adopters produce more than non-adopters because of lower marginal cost. However, output will be higher for both adopters and non-adopters under a refunded tax because of the refund.

We define the profit-maximizing level of production for adopters under an emission tax with exogenous refunding to be q_1^X and the profit-maximizing level of production for non-adopters to be q_0^X. If $q_0^T > 0$, the equilibrium output levels under an exogenously refunded

[7] In the case of the Swedish NO_x charge, market power in the market for refunding is not a major concern. Although participants include large producers in industries that may not be perfectly competitive, in 2000 no plant had more than roughly 2% of the rebate market (Sterner & Höglund-Isaksson, 2006), since the tax-refund program includes several industries. Thus, by applying the program broadly, Sweden avoids the market-share issues that could arise with sector-specific programs (see Fischer 2011).

tax for adopters and non-adopters, respectively, are

$$q_1^X(m_1) = q_1^T(m_1) + \frac{\sigma\bar{\varepsilon}^X(m_1)}{b\,[n+1]}, \tag{6}$$

$$q_0^X(m_1) = q_0^T(m_1) + \frac{\sigma\bar{\varepsilon}^X(m_1)}{b\,[n+1]}, \tag{7}$$

where $\bar{\varepsilon}^X(m_1) = \frac{m_1\varepsilon_1 q_1^X + [n-m_1]\varepsilon_0 q_0^X}{m_1 q_1^X + [n-m_1] q_0^X} > 0$. Because the average emissions intensity decreases with the number of firms adopting the new technology[8], the difference in output with and without a refund decreases as m_1 increases. Equilibrium profit rates under a refunded tax with m_1 adopters of the new technology are

$$\pi_1^X(m_1) = b\left[q_1^X(m_1)\right]^2,$$

$$\pi_0^X(m_1) = b\left[q_0^X(m_1)\right]^2,$$

see Appendix B for derivation of equilibrium profits and output.

We can now find an expression for the increase in profit rate due to adoption for the firm, which is the ith to adopt, under an exogenous refunded tax.

$$\Delta\pi_i^X = b\left[\left[q_1^X(i)\right]^2 - \left[q_0^X(i-1)\right]^2\right].$$

Substituting in (6), we have that

$$\Delta\pi_i^X = b\left[\left[q_1^T(i) + \frac{\sigma\bar{\varepsilon}^X(i)}{b\,[n+1]}\right]^2 - \left[q_0^T(i-1) + \frac{\sigma\bar{\varepsilon}^X(i-1)}{b\,[n+1]}\right]^2\right]. \tag{8}$$

Since each firm considers its own impact on the average emission intensity as negligible, $\bar{\varepsilon}^X(i) = \bar{\varepsilon}^X(i-1)$ from the perspective of the firm, and hence (8) simplifies to

$$\Delta\pi_i^X = \Delta\pi_i^T + \frac{2\sigma\bar{\varepsilon}^X(i)}{[n+1]}\left[q_1^T(i) - q_0^T(i-1)\right].$$

The difference in the increase in profit rate from adoption under a standard emission tax compared to an exogenous refunded tax is then given by

[8] Let $s_1(m_1)$ to denote the market share of an individual adopter with m_1 adopters in the industry. The average emission intensity can be represented as $\bar{\varepsilon}(m_1) = \varepsilon_0 - m_1 s_1(m_1)\delta$,where $\delta = \varepsilon_0 - \varepsilon_1$.Note that $\bar{\varepsilon}(m_1) < \bar{\varepsilon}(m_1 - 1)$ if $[m_1-1]s_1(m_1-1) < m_1 s_1(m_1)$. That is to say, the average emission intensity decreases with adoption if the total output share of adopters increases with adoption.

$$\Delta\pi_i^X - \Delta\pi_i^T = 2\frac{n\left[\zeta_0^T - \zeta_1^T\right]}{b\left[n+1\right]^2}\sigma\bar{\varepsilon}^X(i), \tag{9}$$

since $q_1^T(i) - q_0^T(i-1) = \frac{n\left[\zeta_0^T - \zeta_1^T\right]}{b[n+1]} > 0$.

Under these assumptions, the following proposition holds:

Proposition 1 *A technology that reduces the emission intensity of production diffuses faster under an exogenously refunded than under a non-refunded emission tax.*

We see from (9) that, for the same tax per unit of emissions, σ, $\Delta\pi_i^X > \Delta\pi_i^T$. That is, the diffusion of the new technology is faster under the exogenous refunded tax. However, since the average emission intensity and the refund decreases as the technology diffuses into the industry, it is optimal for the late adopters to wait longer to adopt relative to the early adopters so that investment cost goes down further with time. The additional impact of the refund over taxes therefore diminishes for the firms later in the adoption sequence.

4.2 Endogenous Refunded Tax

So far we have assumed that each firm considers its own impact on the average emission intensity and thus the size of the refund as negligible. However, since firms in the present framework have market power in the output market and emissions are proportional to output, it is appropriate to also consider the case where firms have market power in the market for refunding. If firms take into account their influence on the size of the refund, the first order condition for the adopters are

$$P(Q) + P'(Q)q^j = c_1 + \sigma\left[\varepsilon_1 - \bar{\varepsilon}\right]\left[1 - \frac{q^j}{Q}\right], \tag{10}$$

for $j = 1, 2, ..., m_1 - 1, m_1$,
and for non-adopters

$$P(Q) + P'(Q)q^j = c_0 + \sigma\left[\varepsilon_0 - \bar{\varepsilon}\right]\left[1 - \frac{q^j}{Q}\right], \tag{11}$$

for $j = m_1 + 1, m_1 + 2, ..., n - 1, n$.

Let q_1^D and q_0^D be the profit-maximizing level of production for adopters and non-adopters, respectively, under endogenous refunding. Defining $Q^X(m_1) = m_1 q_1^X + [n - m_1]\, q_0^X$, $Q^D(m_1) =$

$m_1 q_1^D + [n - m_1]\, q_0^D$ and $\bar{\varepsilon}^D(m_1) = \frac{m_1 \varepsilon_1 q_1^D + [n - m_1] \varepsilon_0 q_0^D}{Q^D} > 0$, it can be shown from the equilibrium conditions in (4) and (5), and (10) and (11) (see Appendix C), that

$$Q^D(m_1) - Q^X(m_1) = \frac{n\sigma}{b\,[n+1]} \left[\bar{\varepsilon}^D(m_1) - \bar{\varepsilon}^X(m_1)\right],$$

i.e., total output under endogenous and exogenous refunding is the same only if the average emissions intensities $\bar{\varepsilon}^D(m_1)$ and $\bar{\varepsilon}^X(m_1)$ are the same. Thus, comparing the FOCs that define the profit-maximizing level of production for adopters and non-adopters under exogenous and endogenous refunding (i.e., equations (4)-(10) for adopters and (5)-(11) for non-adopters), we can say that, for equivalent average emission intensity, $q_1^X > q_1^D \; \forall m_1 < n$ and $q_0^X < q_0^D \; \forall m_1 > 0$. Hence, more production is shifted toward non-adopters under endogenous refunding compared to exogenous refunding for equivalent average emission intensity (see also, Fischer 2011, pp 223). Furthermore, $q_1^X(n) = q_1^D(n)$ and $q_0^X(0) = q_0^D(0)$ since the net tax is zero when the firms are homogenous.

As shown in Appendix B, equilibrium profit rates under an endogenous refunded tax with m_1 adopters of the new technology are

$$\pi_1^D(m_1) = b\left[1 - \frac{\sigma}{bQ^D(m_1)}\left[\varepsilon_1 - \bar{\varepsilon}^D(m_1)\right]\right]\left[q_1^D(m_1)\right]^2,$$
$$\pi_0^D(m_1) = b\left[1 - \frac{\sigma}{bQ^D(m_1)}\left[\varepsilon_0 - \bar{\varepsilon}^D(m_1)\right]\right]\left[q_0^D(m_1)\right]^2.$$

The increase in profit rate due to adoption for the firm that is the ith to adopt, under a refunded tax with firm influence on the size of the refund, is then given by

$$\begin{aligned} \Delta\pi_i^D = {} & b\left[\left[q_1^D(i)\right]^2 - \left[q_0^D(i-1)\right]^2\right] \\ & + \sigma\left[\frac{[\varepsilon_0 - \bar{\varepsilon}^D(i-1)]}{Q^D(i-1)}\left[q_0^D(i-1)\right]^2 - \frac{[\varepsilon_1 - \bar{\varepsilon}^D(i)]}{Q^D(i)}\left[q_1^D(i)\right]^2\right]. \end{aligned} \tag{12}$$

By using equation (3), and that $\varepsilon_0 = \varepsilon_1 + \delta$ with $\delta > 0$, we can write:

$$\begin{aligned} \varepsilon_0 - \bar{\varepsilon}^D(m_1) &= m_1 s_1^D(m_1)\delta, \\ \varepsilon_1 - \bar{\varepsilon}^D(m_1) &= -\left[n - m_1\right] s_0^D(m_1)\delta, \end{aligned} \tag{13}$$

where $s_1^D(m_1)$ and $s_0^D(m_1)$ represent the market shares of an individual adopter and non-adopter, respectively, with m_1 adopters in the industry.

Substituting (13) into (12) yields:

$$\begin{aligned}\Delta\pi_i^D = b\left[\left[q_1^D(i)\right]^2 - \left[q_0^D(i-1)\right]^2\right] \\ + \sigma\delta\left[[i-1]\, s_0^D(i-1)s_1^D(i-1)q_0^D(i-1) + [n-i]\, s_0^D(i)s_1^D(i)q_1^D(i)\right].\end{aligned} \tag{14}$$

Unfortunately, equation (14) cannot be easily compared to (2) or (8) since output levels and emission intensities are endogenous. Nevertheless, to be able to say something about the impact of firms' strategically influencing the size of the refund and the adoption decision, we follow the approach in Fischer (2011) and compare adoption incentives between exogenous and endogenous refunding for an equivalent average emission intensity. That is to say, we compare adoption profits under exogenous vs. endogenous refunding for the firms which are the first and last to adopt. This yields:

$$\Delta\pi_1^D - \Delta\pi_1^X = b\left[\left[q_1^D(1)\right]^2 - \left[q_1^X(1)\right]^2\right] + \left[\sigma\delta\,[n-1]\, s_0^D(1)s_1^D(1)q_1^D(1)\right], \tag{15}$$

and

$$\begin{aligned}\Delta\pi_n^D - \Delta\pi_n^X = b\left[\left[q_0^X(n-1)\right]^2 - \left[q_0^D(n-1)\right]^2\right] \\ + \left[\sigma\delta\,[n-1]\, s_0^D(n-1)s_1^D(n-1)q_0^D(n-1)\right].\end{aligned} \tag{16}$$

Note that the first term (in brackets) on the right hand side of equations (15) and (16) gives account of the differences in profits due to output. In turn, the second term (in brackets) on the right hand side of equations (15) and (16) gives account of the differences in profits due to the size of the refund. As stated before, for equivalent average emissions intensities, production is shifted toward non-adopters under endogenous refunding (i.e., $q_1^D(1) < q_1^X(1)$ and $q_0^X(n-1) < q_0^D(n-1)$). Consequently, this production shifting lowers the benefit of adoption under endogenous versus exogenous refunding for the firms which are the first and last to adopt. However, because production is shifted toward non-adopters, the average emission intensity is larger under endogenous refunding, and so is the refund, which increases the benefits of adoption under endogenous versus exogenous refunding.

Therefore, equations (15) and (16) indicate that it is ambiguous whether adoption will be slower under endogenous than under exogenous refunding because of the existence of two counteracting effects: a negative ”output” effect and a positive ”refunding” effect. Overall, we expect the magnitude of the ”output” effect to be larger[9], and hence, adoption profits to be larger under exogenous refunding. However, the larger the number of firms in the industry, the smaller should be the difference between exogenous and endogenous refunding, because the strategic interaction between firms in the output market is reduced in such a case. Note also that the ”refunding” effect depends critically on the effect of adoption on emissions per unit of output, i.e., the larger is δ, the larger the increase in emissions from shifting production toward non-adopters, and the larger is the ”refunding” effect. These observations lead to the following proposition.

Proposition 2 *A technology that reduces the emission intensity of production tends to diffuse more slowly under an endogenously vs. an exogenously refunded emission tax the more concentrated the industry is.*

Next, we compare the adoption incentives under an endogenous refunded tax and an emission tax for the firm which is first to adopt and the firm which is the last, nth, firm to adopt. This yields:

$$\Delta\pi_1^D - \Delta\pi_1^T = \left[\Delta\pi_1^D - \Delta\pi_1^X\right] + 2\frac{n\left[\zeta_0^T - \zeta_1^T\right]}{b\left[n+1\right]^2}\sigma\varepsilon_0,$$

and

$$\Delta\pi_n^D - \Delta\pi_n^T = \left[\Delta\pi_n^D - \Delta\pi_n^X\right] + 2\frac{n\left[\zeta_0^T - \zeta_1^T\right]}{b\left[n+1\right]^2}\sigma\varepsilon_1.$$

The difference in profit increase for endogenous refunding versus a non-refunded emission tax is given by the sum of the difference between endogenous and exogenous refunding (the first term), and the difference between exogenous refunding and an emission tax (the second term). As discussed previously, the first term is on the net likely to be negative while the second is positive. Hence, compared to exogenous refunding, it is clear that taxes are less likely to induce a faster diffusion than endogenous refunding. Nevertheless, it is still the case that the ”output” effect should dominate the ”refunding” effect if the number of firms in the industry is small, to the extent that diffusion is likely to be slower under endogenous refunding. These observations lead to the following proposition.

[9] This is consistent with the assumption that refunding of emission taxes is not the main source of revenue for the firms.

Proposition 3 *A technology that reduces the emission intensity of production tends to diffuse more slowly under an endogenously refunded vs. a non-refunded emission tax the more concentrated the industry is.*

5 Incentives for continuous technological upgrading

In the previous sections, we showed under what conditions exogenous refunding helps to speed up the path of technology adoption. However, this positive effect of refunding dissipates as the average emission intensity of the industry decreases. In order to analyze to what extent refunding provides continuous increased incentives for technological upgrading, we consider the case when further technological advance occurs at some point in the future. This new technology, which we will call technology 2, unexpectedly arrives at some time t_2 after k^T and k^X firms would have already adopted technology 1 under an emission tax and an exogenous refunded tax, respectively. As shown in the previous sections, since the exogenous refund induces a faster adoption than the emission tax, $k^X \geq k^T$.

We study the difference in adoption incentives for the new technology provided by these instruments for three groups: (1) the *laggards* - those firms that would not have adopted technology 1 at t_2 either under the emission tax or the refunded tax (i.e., $n - k^X$ firms), (2) the *intermediates* - those firms that would have adopted technology 1 at t_2 under refunding, but would not have adopted under an emission tax (i.e., $k^X - k^T$ firms), and finally, (3) the *early adopters* - those firms that would have adopted technology 1 at t_2 under both schemes (i.e., k^T firms). If refunding provides a continuous and larger incentive to technological upgrading than taxes, we should expect the difference in the increase in profit rate from adoption with and without refunding to be positive for all groups. Moreover, if refunding produces a "catching up" effect - understood as an increased incentive for firms dirtier than average to adopt new technologies, we should expect the difference in profit increase for the *laggards* to be unambiguously positive.

Technology 2 is characterized by a marginal production cost c_2 and emission intensity ε_2, with $\varepsilon_2 < \varepsilon_1 < \varepsilon_0$. Let $\zeta_2^T = c_2 + \sigma\varepsilon_2$. By assumption, we have that $\zeta_0^T > \zeta_1^T > \zeta_2^T$. Now let m_1 be the number of adopters of technology 1 and m_2 be the number of adopters of technology 2. At time t_2, we thus have $m_1 = k$ and $m_2 = 0$. Further, let $\pi_2(m_1, m_2)$ be the profit rate for firm j when m_1 firms have adopted technology 1, m_2 firms have adopted technology 2, and firm j is among the adopters of technology 2. We define $\pi_1(m_1, m_2)$ and $\pi_0(m_1, m_2)$ accordingly. The firm which has not adopted technology 1 at time t_2 now has the choice between two technologies. However, for simplicity, we assume that $p_2(t)$, the present value cost at time t_2 of investing in technology 2 at t, is not larger than the cost of investing in technology 1 at t, i.e., $p_2(t) \leq p_1(t)e^{rt_2}$ for $t \geq t_2$. This implies that it will never be profitable to adopt technology 1 once technology 2 has appeared[10].

The lower marginal costs imply higher profit rates with technology 2 compared to both technology 1 and technology 0. The increase in profit rates from adoption of technology 2 will thus be higher for a firm which produces with technology 0 than for a firm which has already adopted technology 1. I.e., the following conditions apply: $\pi_2(m_1, m_2) > \pi_1(m_1, m_2) > \pi_0(m_1, m_2)$ as well as $\pi_2(m_1, m_2 + 1) - \pi_0(m_1, m_2) > \pi_2(m_1 - 1, m_2 + 1) - \pi_1(m_1, m_2)$ for all m_1, m_2 for which $m_1 + m_2 < n$. Furthermore, we assume that $p_2(t)$ (defined for $t \geq t_2$) is a differentiable convex function for which $p_2'(t_2) \leq \pi_0(k, 0) - \pi_2(k, 1)$, $\lim_{t \longrightarrow \infty} p_2'(t) > 0$ and $p_2''(t) > re^{-rt} \left(\pi_2(k, 1) - \pi_0(k, 0)\right)$. Lastly, we define $\Delta\pi_{02,j} = \pi_2(k, j) - \pi_0(k, j - 1)$ and $\Delta\pi_{12,j} = \pi_2(n - j, j) - \pi_1(n - j + 1, j - 1)$.

We can now determine the optimal adoption dates for technology 2 for the three groups of firms from first order conditions similar to (1) (see more details on the results in this section in Appendix D). The $n - k$ firms which produce with technology 0 at t_2 will first find it profitable to adopt technology 2 at τ_j^*, implicitly defined by

$$\Delta\pi_{02,j}\, e^{-r\left[\tau_j^* - t_2\right]} - p_2'(\tau_j^*) = 0$$

for $j = 1, 2, ..., m_1 - 1, n - k,$, and the k firms which produce with technology 1 at t_2 will adopt technology 2 at τ_j^*, implicitly defined by

$$\Delta\pi_{12,j}\, e^{-r\left[\tau_j^* - t_2\right]} - p_2'(\tau_j^*) = 0$$

for $j = n - k + 1, n - k + 2, ..., n - 1, n$.

To analyze the schedule of adoption dates for technology 2, we again need to analyze the difference in the increase in profit rate from adoption with and without refunding for each position in the adoption sequence.

[10] This is not a necessary condition for technology 2 to always be preferred. What is required is that the net present value of adopting technology 2 at some point in time after t_2 is always greater than the net present value of adopting technology 1.

Under an emission tax, equilibrium output and profit levels for the three technologies are[11]

$$q_0^T(m_1, m_2) = \frac{a - \zeta_0^T - m_1 \left[\zeta_0^T - \zeta_1^T\right] - m_2 \left[\zeta_0^T - \zeta_2^T\right]}{b\,[n+1]},$$

$$q_1^T(m_1, m_2) = \frac{a - \zeta_1^T - [n - m_1 - m_2] \left[\zeta_1^T - \zeta_0^T\right] - m_2 \left[\zeta_1^T - \zeta_2^T\right]}{b\,[n+1]},$$

$$q_2^T(m_1, m_2) = \frac{a - \zeta_2^T - [n - m_1 - m_2] \left[\zeta_2^T - \zeta_0^T\right] - m_1 \left[\zeta_2^T - \zeta_1^T\right]}{b\,[n+1]},$$

and

$$\pi_0^T(m_1, m_2) = b\left[q_0^T(m_1, m_2)\right]^2,$$

$$\pi_1^T(m_1, m_2) = b\left[q_1^T(m_1, m)\right]^2,$$

$$\pi_2^T(m_1, m_2) = b\left[q_2^T(m_1, m_2)\right]^2.$$

Under the exogenously refunded tax, the expressions corresponding to the case with two technologies are

$$q_0^X(m_1, m_2) = q_0^T(m_1, m_2) + \frac{\sigma\bar{\varepsilon}^X(m_1, m_2)}{b\,[n+1]},$$

$$q_1^X(m_1, m_2) = q_1^T(m_1, m_2) + \frac{\sigma\bar{\varepsilon}^X(m_1, m_2)}{b\,[n+1]},$$

$$q_2^X(m_1, m_2) = q_2^T(m_1, m_2) + \frac{\sigma\bar{\varepsilon}^X(m_1, m_2)}{b\,[n+1]},$$

and

$$\pi_0^X(m_1, m_2) = b\left[q_0^X(m_1, m_2)\right]^2 = b\left[q_0^T(m_1, m_2) + \frac{\sigma\bar{\varepsilon}^X(m_1, m_2)}{b\,[n+1]}\right]^2,$$

$$\pi_1^X(m_1, m_2) = b\left[q_1^X(m_1, m_2)\right]^2 = b\left[q_1^T(m_1, m_2) + \frac{\sigma\bar{\varepsilon}^X(m_1, m_2)}{b\,[n+1]}\right]^2,$$

$$\pi_2^X(m_1, m_2) = b\left[q_2^X(m_1, m_2)\right]^2 = b\left[q_2^T(m_1, m_2) + \frac{\sigma\bar{\varepsilon}^X(m_1, m_2)}{b\,[n+1]}\right]^2.$$

where

$$\bar{\varepsilon}^X(m_1, m_2) = \frac{m_2 \varepsilon_2 q_2^X(m_1, m_2) + m_1 \varepsilon_1 q_1^X(m_1, m_2) + [n - m_1 - m_2]\,\varepsilon_0 q_0^X(m_1, m_2)}{m_2 q_2^X(m_1, m_2) + m_1 q_1^X(m_1, m_2) + [n - m_1 - m_2]\,q_0^X(m_1, m_2)}.$$

[11] As seen from the expression below, $q_0^T > 0$ if $a - \zeta_0 - m_1\left[\zeta_0 - \zeta_1\right] - m_2\left[\zeta_0 - \zeta_2\right] > 0$

Laggards

Let us first analyze the difference in the increase in profit rate from adoption of technology 2 with and without refunding for the *laggards* which would not have adopted technology 1 by t_2 under either policy and are therefore producing with technology 0. Because $\bar{\varepsilon}^R(k^R, j) = \bar{\varepsilon}^R(k^R, j-1)$ from the perspective of the firm under exogenous refunding, the difference in the profit rate increase from adoption of technology 2 under the exogenous refunded tax compared to the emission tax is

$$\Delta\pi^X_{02,j} - \Delta\pi^T_{02,j} = 2\frac{n\left[\zeta^T_0 - \zeta^T_2\right]}{b\left[n+1\right]^2}\left[\left[k^T - k^X\right]\left[\zeta^T_0 - \zeta^T_1\right] + \sigma\bar{\varepsilon}^X(k^X, j)\right], \tag{17}$$

for $j = 1, 2, ..., n-k^X-1, n-k^X$.

If $k^X = k^T$, we have from (17) that, analogous to the result with two technologies, $\Delta\pi^X_{02,j} > \Delta\pi^T_{02,j}$. Hence, the adopters of technology 2 switching from technology 0 would invest earlier under the refunded tax than under an emission tax. However, if $k^X > k^T$, the sign of this expression is ambiguous. A negative sign would indicate faster diffusion of technology 2 under an emission tax than a refunded tax. The explanation for this possible outcome is simple: switching to technology 2 from technology 0 under the emission tax can be more profitable if there are fewer competitors with technology 1 and instead more competitors with technology 0. The sign of (17) is negative and adoption is faster under an emission tax if the difference in profit increase coming from higher output under an emission tax is larger than the profit increase coming from the refund.

Intermediates

Let us now examine the difference in profits for the *intermediates*, which only exist if the number of firms which would have adopted technology 1 by t_2 under the emission tax is lower than the number of adopters of technology 1 at t_2 under the exogenous refunded tax, i.e., $k^T < k^X$. The jth adopter, for which $j \in \left[n-k^X+1, n-k^T\right]$, would switch from technology 0 under an emission tax, and from technology 1 under a refunded tax. In the eyes of the firms, $\bar{\varepsilon}^X(n-j, j) = \bar{\varepsilon}^X(n-j+1, j-1)$. Therefore, the difference between the policies in adoption time is determined by the following:

$$\Delta\pi^X_{12,j} - \Delta\pi^T_{02,j} = \frac{n\left[\zeta^T_0 - \zeta^T_1\right]}{b\left[n+1\right]^2}\left[2k^T\left[\zeta^T_0 - \zeta^T_2\right] - [n-2j]\left[\zeta^T_0 + \zeta^T_1 - 2\zeta^T_2\right] - 2\left[a + \zeta^T_2\right]\right]$$
$$+ 2\frac{n[\zeta^T_1 - \zeta^T_2]}{b\left[n+1\right]^2}\sigma\bar{\varepsilon}^X(n-j,j), \tag{18}$$

for $j \in \left[n - k^X + 1, n - k^T\right]$.

The sign of (18) is ambiguous, so the *intermediates* would adopt either earlier or later under an exogenous refunded tax compared to a standard emission tax.

Early adopters

Finally, let us analyze the incentives to adopt technology 2 under the emission tax and the refunded tax for those firms that would have adopted technology 1 by t_2 under both policies, i.e., the *early adopters*. When the first of the firms with technology 1 invests in technology 2, there is no longer any firm using technology 0. This means that there are again only two production technologies in the market and that results are comparable to the ones in section 4.1. Because $\bar{\varepsilon}^X(n-j,j) = \bar{\varepsilon}^X(n-j+1,j-1)$ from the perspective of the firm, the difference in profit rate increase is given by:

$$\Delta\pi^X_{12,j} - \Delta\pi^T_{12,j} = \frac{2n\left[\zeta^T_1 - \zeta^T_2\right]}{b\left[n+1\right]^2}\sigma\bar{\varepsilon}^X(n-j,j) \tag{19}$$

for $j = n - k^T + 1, n - k^T + 2, ..., n-1, n$.

(19) is positive. This indicates that the jth adopter of technology 2, which would switch from technology 1 under both policies, invests earlier under the refunded tax than under a standard emission tax.

In sum, our results indicate that, although exogenous refunding provides continuous incentives for technological upgrading, these incentives are not unambiguously larger than those provided by an emission tax. This is particularly the case for firms that are dirtier than average (the so- called *laggards*). In relative terms, the gains of investing in a new technology, in terms of increased output and refunding, dissipates as the overall industry becomes cleaner. The previous findings can be summarized in the following Proposition.

Proposition 4 *A technology that reduces the emission intensity of production does not unambiguously diffuse faster under an exogenously refunded tax than under a non-refunded emission tax* *among those firms that are dirtier than average.*

6 Numerical illustrations

In the following, we present simulations on the diffusion patterns and welfare effects under a standard emission tax as well as exogenous and endogenous refunding.

6.1 Diffusion

To illustrate the diffusion patterns under the policies and how the patterns are affected by the degree of market concentration, we present numerical simulations for an industry composed of 5 and 15 firms, respectively. For the simulations, we assume the following function for the present value of the investment cost

$$p_1(t) = K_1 e^{-[\theta+r]t}$$

where $\theta > 0$ captures drivers such as learning and technological progress which lead to decreasing investment costs over time (here assumed exogenous and generating a constant rate of decrease in costs). We assume $\theta = 3\%$, $r = 6\%$ and $K_1 = 20$ and for the remaining parameters $a = 10$, $b = 1$, $\varepsilon_0 = 1$, $\varepsilon_1 = 0.5$, $c_0 = c_1 = 1$ and $\sigma = 1$.

Figures 1 and 2 illustrate the adoption times for each firm in the sequence. We see from Figure 1 with $n = 5$ firms that, for this set of parameters, the exogenous refunded tax induces a faster diffusion than the non-refunded emission tax, just as discussed in section 4.1. However, with endogenous refunding, the firms would adopt later than under exogenous refunding, as well as later than they would under a non-refunded emission tax. Figure 3 illustrates the contribution from the "output" and "refunding" effects to the difference between endogenous and exogenous refunding. As discussed in section 4.2, the output effect dominates the refunding effect, such that, on net, the difference is negative for each adopter in the adoption sequence. We also see that, even though the additional difference between exogenous refunding and a non-refunded tax is positive, the net difference between endogenous refunding and an emission tax is still negative.

With $n = 15$ firms in Figure 2, diffusion takes longer since gains from adoption are lower. Here, also, the exogenous refunded tax induces faster diffusion than the non-refunded emission tax. However, with endogenous refunding, the first firm would adopt at a point in time very close to but later than the adoption time under the emission tax, while the last firm would adopt earlier than under an emission tax and at a point in time very close to the adoption time under the exogenous refunded tax. With $n = 15$ firms, differences in adoption times are, however, relatively small. This illustrates that, as the number of firms increases, the diffusion pattern under a refunded tax also approaches the pattern under a standard emission tax.

In Figure 4, the difference in profit increase between endogenous and exogenous refunding is disaggregated into "output" and "refunding" effects with 15 firms in the industry. It is still true that the output effect dominates the refunding effect such that diffusion is slower under endogenous versus exogenous refunding for each firm in the sequence. However, the relatively larger difference in profit increase between exogenous refunding and an emission tax implies that, on net, endogenous refunding induces faster adoption than an emission tax for all but the first firm in the adoption sequence, as also noted from Figure 2. Figure 4 also illustrates that, for $n = 15$, the outcome under endogenous refunding is well approximated by the outcome under exogenous refunding for firms later in the adoption sequence.

6.2 Welfare

The policies have different effects on welfare because of the different patterns of adoption. Faster diffusion of the cost-reducing technology raises consumer surplus and lowers environmental damages in present value terms for the whole diffusion period but also raises total investment costs. Welfare effects are also different under the policies because, even with the same number of adopters at a certain point in time, equilibrium output and aggregate emissions differ[12].

With m_1 adopters of the new technology, consumer surplus is given by

$$CS(m_1) = \frac{b}{2}[Q(m_1)]^2$$

We assume that the emitted substance is a flow pollutant which causes damages only in the current period and has a constant value of marginal damage from emissions $\delta = 1$. Total

[12]The welfare comparison is made between outcomes under the two policies for the same level of the emission tax. Because of the refund, equilibrium output and aggregate emissions differ. From a welfare comparison perspective, one could argue that the relevant comparison is between different tax rates under the two policies which induce the same level of aggregate emissions. However, for this model, there is no emission tax level other than zero that induces the same level of emissions under the two policies before diffusion has started and after the technology has completely diffused into the industry.

environmental damages D at a point in time with m_1 adopters of the new technology is then given by

$$D(m_1) = \delta E(m_1)$$

Net tax revenues are $TR(m_1) = \sigma E(m_1)$ under the emission tax. In contrast, $TR(m_1) = 0$ under the refunded tax since all the tax revenues are refunded back to the firms and included in firm profits.

The welfare rate (or instantaneous welfare), $w(m_1)$, excluding investment costs, with m_1 adopters of the new technology is the sum of consumer surplus, firm profits and tax revenues minus environmental damages and is given by

$$w(m_1) = CS(m_1) + [n - m_1]\,\pi_0(m_1) + m_1\pi_1(m_1) + TR(m_1) - D(m_1)$$

Total discounted welfare W net of investment costs can now be written

$$W = \sum_{m_1=0}^{n}\left[\int_{\tau^*_{m_1}}^{\tau^*_{m_1+1}} w(m_1)e^{-rt}dt\right] - \sum_{m_1=1}^{n} p(\tau^*_{m_1})$$

with $\tau^*_0 = 0$ and $\tau^*_{n+1} = \infty$.

Tables 1 and 2 show the welfare levels over time under an emission tax, an exogenous refunded tax and an endogenous refunded tax with 5 and 15 firms, respectively. Adoption times are the same as in the previous section, with $\tau^*_{m_1}$ determining the start of the m_1th period with current value of the welfare rate $w(m_1)$ at each point in time. We see from table 1 that, for $n = 5$, discounted welfare is similar under exogenous and endogenous refunding. It appears that the benefit of reaching higher welfare rates with the faster diffusion in the first case is matched by the benefit of lower investment cost with slower diffusion in the second.

Discounted welfare is lower under the emission tax compared to both refunding situations. This is not driven by differences in how early clean production is traded for lower investment cost but by a difference in the level of welfare. This welfare difference comes from the fact that we have assumed that consumer surplus is quadratic in aggregate production while environmental damage is linear in aggregate emissions. This leads to higher welfare rates with a refund since more production is valued more highly than less emissions at the margin. Had we assumed that environmental damages were quadratic in aggregate emissions, the opposite would have been true, i.e., welfare rates would have been higher without refunding.

Table 2 shows the welfare outcomes with $n = 15$ firms. Comparing outcomes for the same policy with $n = 5$ and $n = 15$, consumer surplus and emissions are higher and firm profits lower for all three policy situations. With more competition in the industry, the benefits of adoption for an individual firm are significantly lower and therefore diffusion is slower than with only five firms in the industry. Both welfare rates and adoption times are so similar with 15 firms that there is, in practice, no difference in the value of discounted welfare across policies.

Note that, when it comes to output, our simulations indicate that non-adopters do produce slightly more and adopters slightly less with endogenous refunding compared to the case with exogenous refunding in line with Fischer (2011) and as discussed in section 4.2. However, at the aggregate level, output does not differ significantly between the two refunding situations, which explains why consumer surplus is almost the same in both cases.

Figures 5 and 6 illustrates how the level of aggregate emissions develops over time under the different policies. The figures show that the difference in the level of aggregate emissions between the policies is smaller after the new technology has been completely diffused into the industry. This is driven by the fact that the additional output under the refunded tax is then produced with lower emission intensity, and also because the difference in aggregate output is smaller between the two policies.

7 Conclusions

The main conclusion is that a refunded emission tax speeds up diffusion in an imperfectly competitive industry relative to a non-refunded emission tax if firms do not strategically influence the size of the refund. If they do, diffusion is, in contrast, likely to be slower than under a non-refunded emission tax if the industry is highly concentrated.

It is straightforward to see that, as the number of firms increases and the equilibrium comes closer to the outcome under perfect competition, the difference in diffusion patterns with and without refunding goes to zero. However, our findings are only valid in the context of an output market that is not perfectly competitive. If there is perfect competition, diffusion is not an equilibrium since, in that case, adoption would yield the same incremental benefits to all firms.

These results should apply to end-of-pipe technologies that convert a certain proportion of emissions. For energy production, the findings also should be valid for fuel efficiency improving technologies when it comes to pollutants such as CO_2 and SO_2. The implications of refunding for other types of abatement technologies is a potential area for future research.

Our results are based on the assumption that firms do not anticipate the appearance of a more efficient technology farther into the future. Allowing for such anticipation should delay optimal adoption times but, for this to alter the main comparative results, the effect of refunding would have to interact with the anticipation effect.

We have focused only on the incentives to technological diffusion provided by output-based refunding. Refunding might also be based on investments in abatement technologies, like the Norwegian NO_x fund from which emission fee revenues are refunded in proportion to abatement expenditure (see Hagem *et al.*, 2012). Such a case is outside the scope of our study, and further research is needed to understand the incentives provided by that type of scheme.

The welfare implications of the differences in diffusion patterns under our particular assumptions appear to be small. There could be a more relevant difference from a welfare point of view if faster diffusion also speeds up learning and endogenously lowers investment costs. There should also be larger benefits to faster diffusion if emissions are a stock pollutant.

The fact that the rate of technology adoption is influenced by (exogenous) refunding is potentially good news for a regulator, who has political constraints on the level of the tax to be imposed, but wants to promote faster uptake of existing abatement technologies as a way to speed up the pace of emission reductions.

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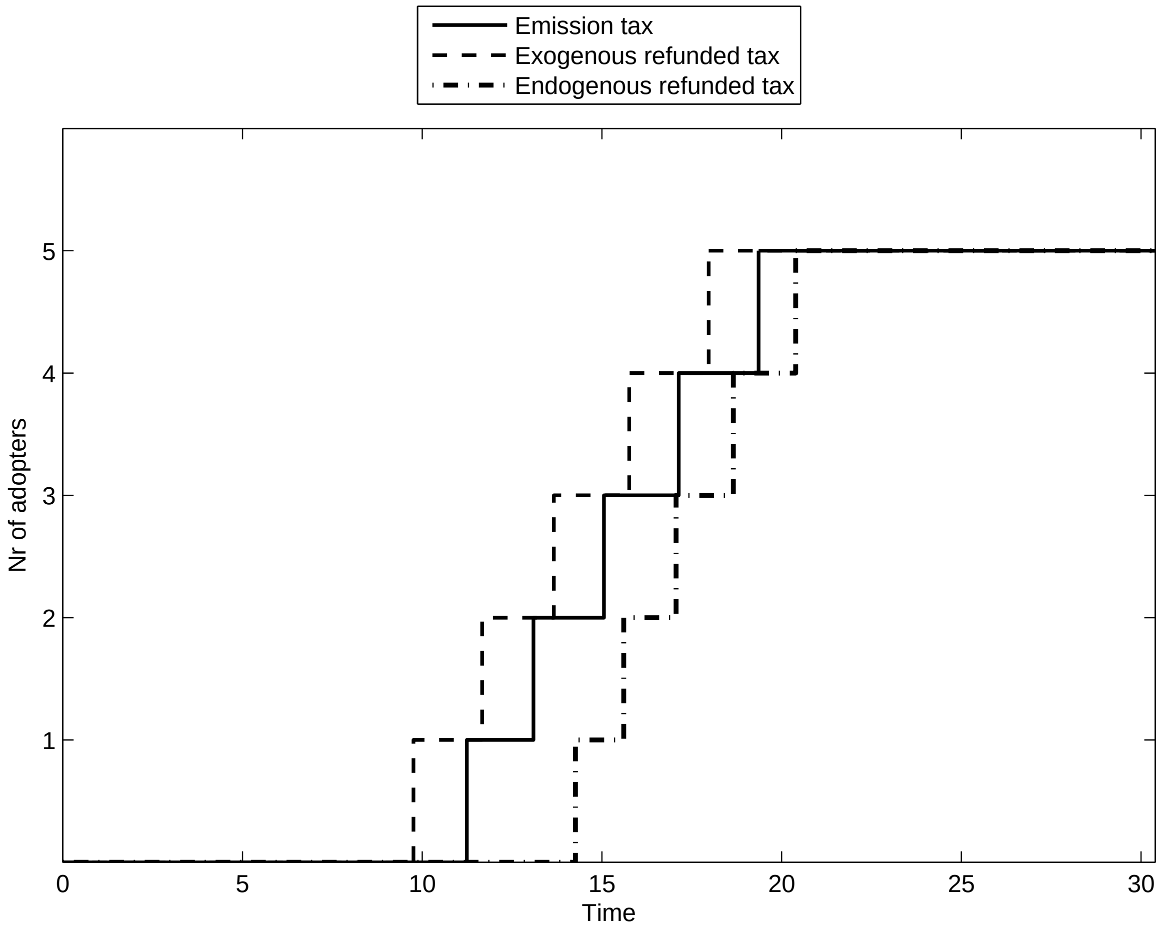

Figure 1: Diffusion with 5 firms in the industry

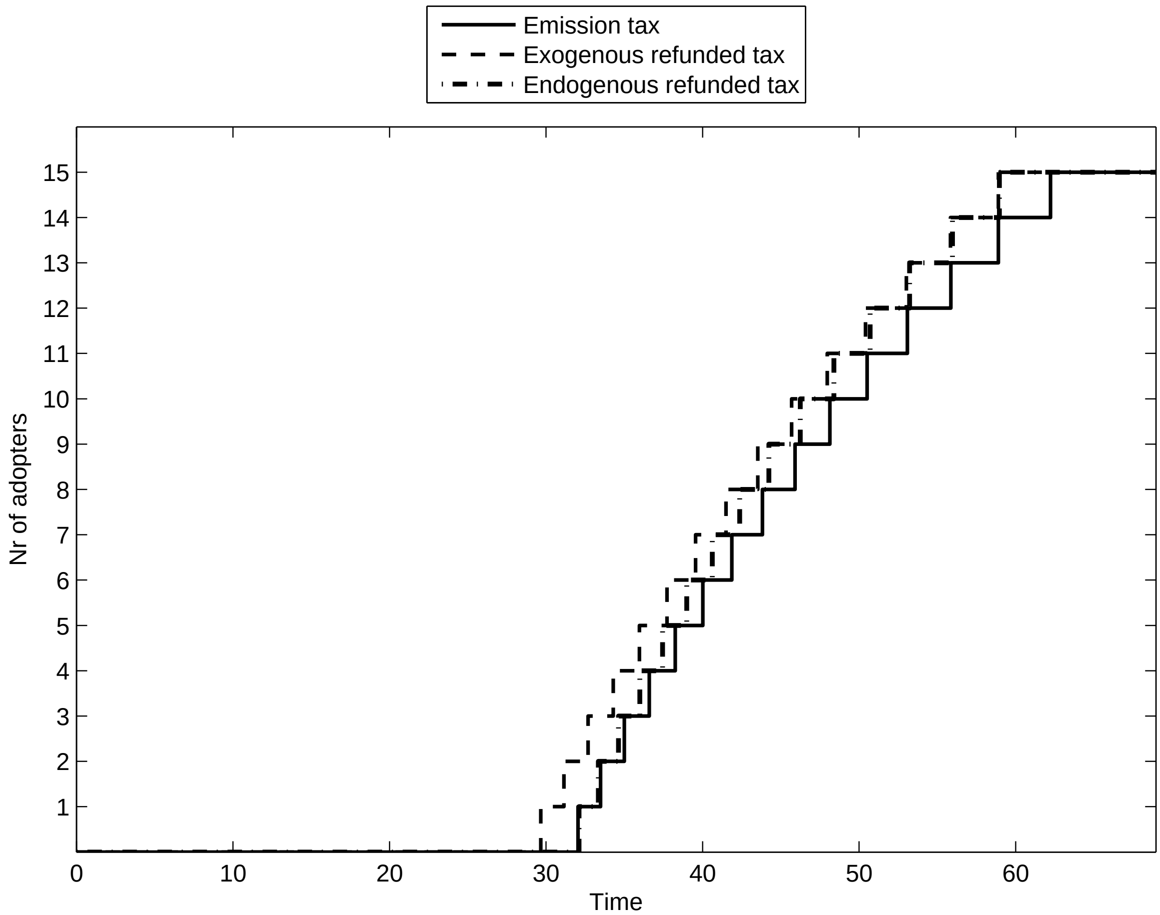

Figure 2: Diffusion with 15 firms in the industry

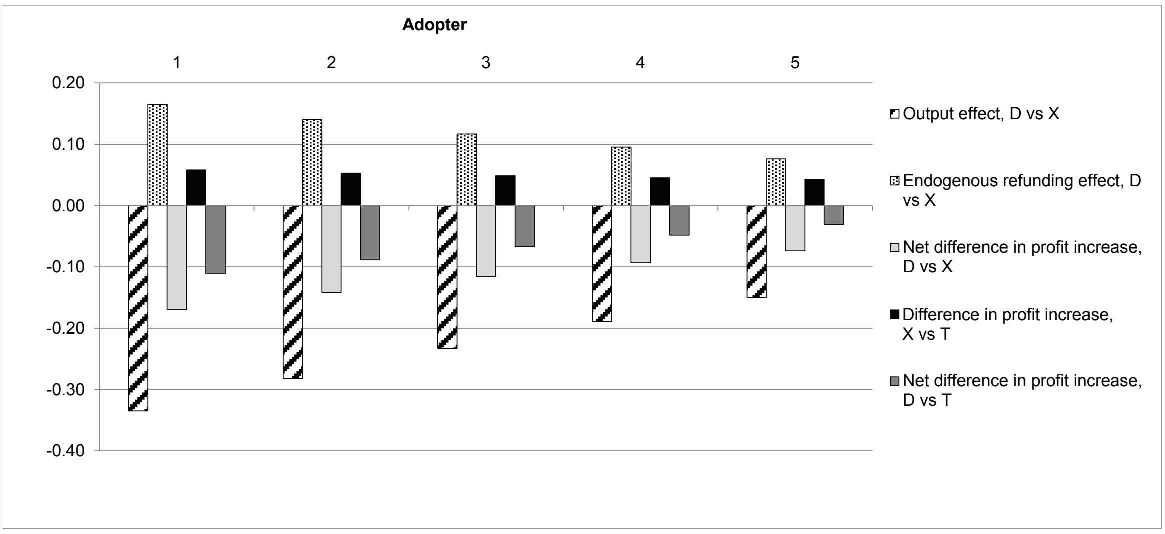

Figure 3: Output and endogenous refunding effects explaining net differences in profit increase from adoption with 5 firms in the industry. T refers to emission tax, X to exogenous refunded tax and D to endogenous refunded tax.

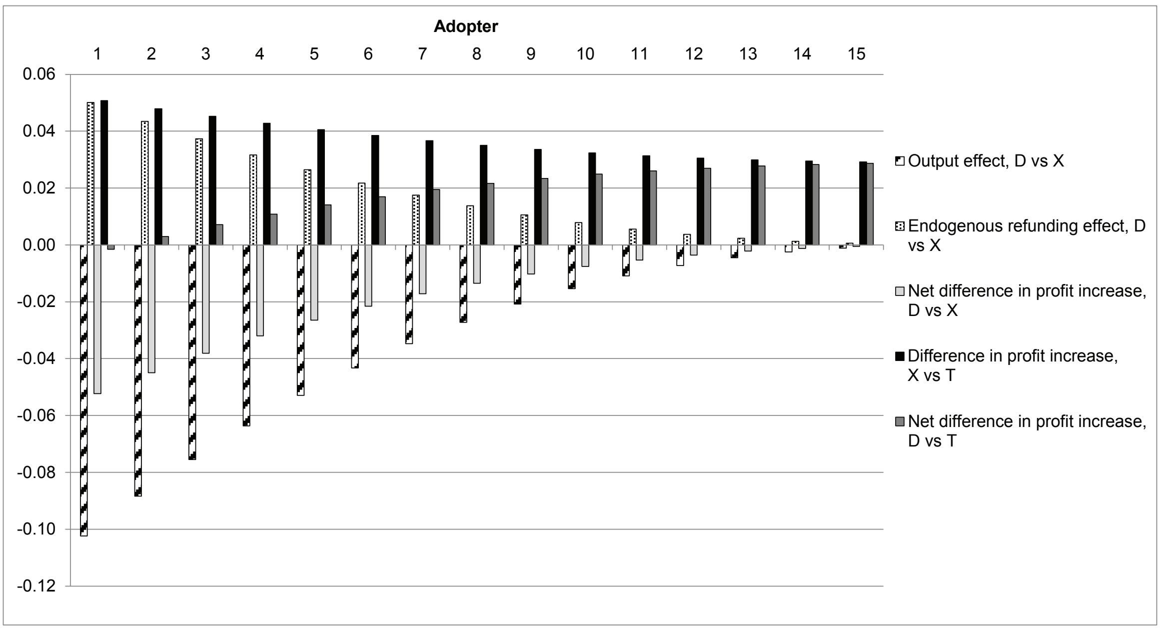

Figure 4: Output and endogenous refunding effects explaining net differences in profit increase from adoption with 15 firms in the industry. T refers to emission tax, X to exogenous refunded tax and D to endogenous refunded tax.

Table 1: Welfare estimates with 5 firms in the industry.

Period/number of adopters	0	1	2	3	4	5	Total all 6 periods
Emission tax							
Start of period/date of adoption	0.0	11.2	13.1	15.1	17.1	19.4	
Present value investment cost	0.0	7.3	6.2	5.2	4.3	3.5	
Current value consumer surplus rate	22.2	22.8	23.3	23.9	24.5	25.1	
Current value firms' profit rate	8.9	9.3	9.6	9.9	10.0	10.0	
Current value tax revenue rate	6.7	5.9	5.2	4.5	4.0	3.5	
Current value environmental damage rate	6.7	5.9	5.2	4.5	4.0	3.5	
Current value welfare rate (excl investment)	31.1	32.1	33.0	33.8	34.5	35.1	
Present value total period welfare	254.4	21.4	21.7	21.7	21.4	179.7	**520**
Exogenous refunded tax							
Start of period/date of adoption	0.0	9.8	11.7	13.7	15.8	18.0	
Present value investment cost	0.0	8.3	7.0	5.8	4.8	4.0	
Current value consumer surplus rate	28.1	28.0	27.9	27.9	28.0	28.1	
Current value firms' profit rate	11.3	11.4	11.4	11.4	11.4	11.3	
Current value tax revenue rate	0.0	0.0	0.0	0.0	0.0	0.0	
Current value environmental damage rate	7.5	6.5	5.7	4.9	4.3	3.8	
Current value welfare rate (excl investment)	31.9	32.8	33.7	34.4	35.1	35.6	
Present value total period welfare	235.5	24.6	24.4	24.0	23.4	198.0	**530**
Endogenous refunded tax							
Start of period/date of adoption	0.0	14.3	15.6	17.1	18.7	20.4	
Present value investment cost	0.0	5.5	4.9	4.3	3.7	3.2	
Current value consumer surplus rate	28.1	28.0	27.9	27.9	28.0	28.1	
Current value firms' profit rate	11.3	11.4	11.4	11.4	11.4	11.3	
Current value tax revenue rate	0.0	0.0	0.0	0.0	0.0	0.0	
Current value environmental damage rate	7.5	6.6	5.7	5.0	4.3	3.7	
Current value welfare rate (excl investment)	31.9	32.8	33.6	34.3	35.0	35.6	
Present value total period welfare	305.5	12.4	13.5	14.4	15.1	171.5	**532**

Table 2: Welfare estimates with 15 firms in the industry.

Period/number of adopters	0	1	2	3	4	5	10	15	Total all 16 periods
Emission tax									
Start of period/date of adoption	0.0	32.0	33.5	35.0	36.6	38.3	48.1	62.2	
Present value investment cost	0.0	1.1	1.0	0.9	0.7	0.6	0.3	0.1	
Current value consumer surplus rate	28.1	28.4	28.6	28.8	29.1	29.3	30.5	31.8	
Current value firms' profit rate	3.8	4.0	4.2	4.4	4.6	4.7	4.9	4.2	
Current value tax revenue rate	7.5	7.0	6.6	6.2	5.9	5.5	4.4	4.0	
Current value environmental damage rate	7.5	7.0	6.6	6.2	5.9	5.5	4.4	4.0	
Current value welfare rate (excl investment)	31.9	32.4	32.8	33.3	33.7	34.1	35.4	36.0	
Present value total period welfare	453.5	5.5	5.4	5.3	5.2	5.1	4.1	14.3	**531**
Exogenous refunded tax									
Start of period/date of adoption	0.0	29.7	31.1	32.7	34.3	36.0	45.7	59.0	
Present value investment cost	0.0	1.4	1.2	1.1	0.9	0.8	0.3	0.1	
Current value consumer surplus rate	35.6	35.4	35.2	35.0	34.9	34.8	34.8	35.6	
Current value firms' profit rate	4.7	5.0	5.1	5.3	5.4	5.5	5.5	4.7	
Current value tax revenue rate	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Current value environmental damage rate	8.4	7.9	7.4	6.9	6.5	6.1	4.7	4.2	
Current value welfare rate (excl investment)	31.9	32.4	32.9	33.4	33.8	34.2	35.6	36.1	
Present value total period welfare	442.1	6.4	6.3	6.1	6.0	5.8	4.6	17.4	**531**
Endogenous refunded tax									
Start of period/date of adoption	0.0	32.1	33.3	34.6	36.0	37.4	46.2	59.0	
Present value investment cost	0.0	1.1	1.0	0.9	0.8	0.7	0.3	0.1	
Current value consumer surplus rate	35.6	35.4	35.2	35.1	35.0	34.9	34.8	35.6	
Current value firms' profit rate	4.7	4.9	5.1	5.2	5.3	5.4	5.4	4.7	
Current value tax revenue rate	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Current value environmental damage rate	8.4	7.9	7.4	7.0	6.6	6.2	4.8	4.2	
Current value welfare rate (excl investment)	31.9	32.4	32.9	33.3	33.7	34.1	35.5	36.1	
Present value total period welfare	454.3	4.5	4.5	4.6	4.6	4.6	4.2	17.4	**531**

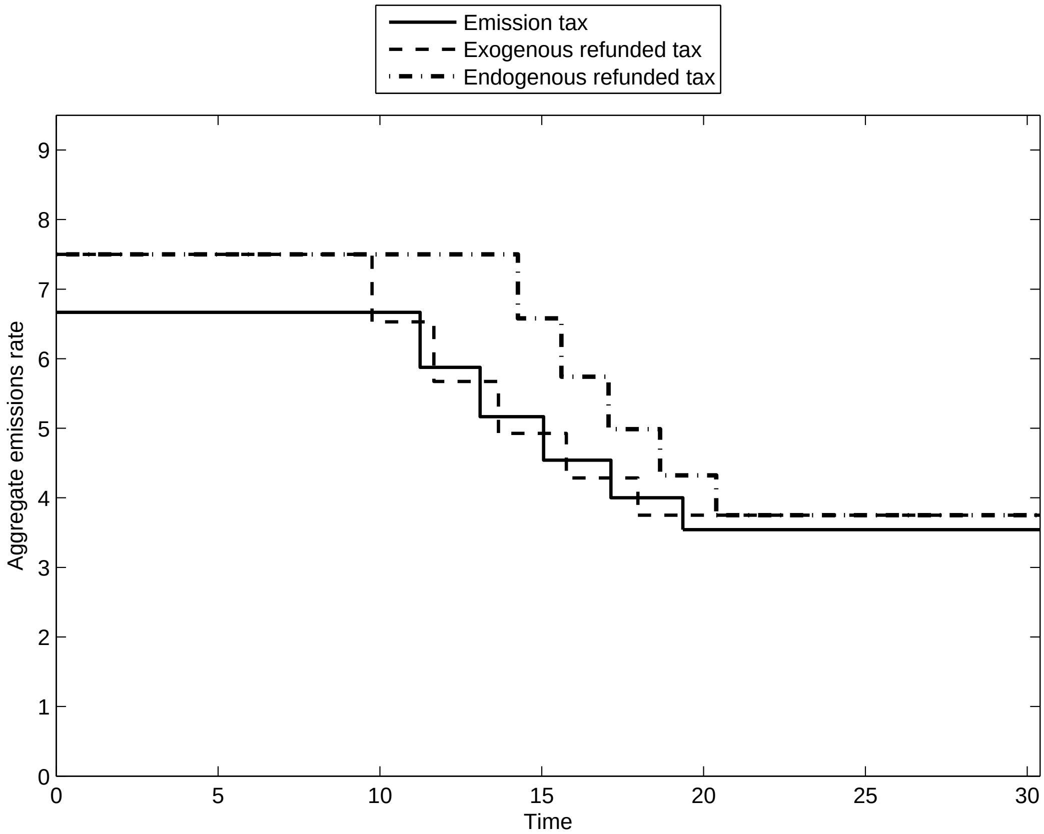

Figure 5: Aggregate emissions over time with 5 firms in the industry.

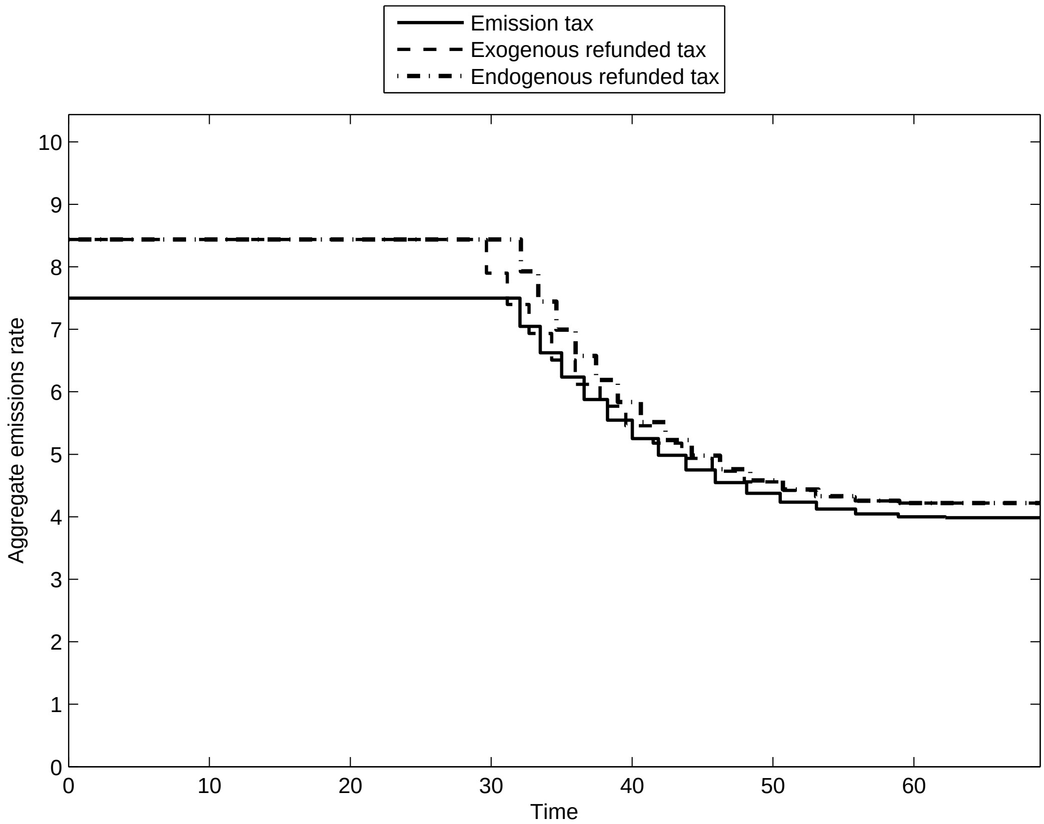

Figure 6: Aggregate emissions over time with 15 firms in the industry.

Appendices

A Demonstration of Nash equilibrium - Reinganum (1981)

(1i) $\pi_0(m-1) \geq 0$ and $\pi_1(m) \geq 0$

(1ii) $\pi_1(m-1) - \pi_0(m-2) > \pi_1(m) - \pi_0(m-1) > 0$ for all $m < n$.

(2i) $p'(0) \leq \pi_0(0) - \pi_1(1)$

(2ii) $\lim_{t \longrightarrow \infty} p'(t) > 0$

(2iii) $p''(t) > re^{-rt}(\pi_1(1) - \pi_0(0))$

Demonstration very similar to Reinganum (1981).

Proposition Given a weak ordering of adoption dates $\tau_1 \leq \tau_2 \leq ... \leq \tau_n$, each firm has a unique optimal adoption date τ_i^* such that $0 \leq \tau_1^* < \tau_2^* < .. < \tau_n^* < \infty$.

Proof From assumption 1 and 2iii, V^i is strictly concave in τ_i for $\tau_i \in (\tau_{i-1}, \tau_{i+1})$, so first-order conditions are necessary and sufficient for finding an optimal date of adoption τ_i^*.

Furthermore, by assumption 2i $\frac{\partial V^1}{\partial \tau_1}_{\tau_1=0} = \pi_0(0) - \pi_1(1) - p'(0) \geq 0$ and thus $\tau_1^* \geq 0$. By assumption 2ii $\lim_{t \longrightarrow \infty} p'(t) > 0$, it also follows that $\lim_{\tau_n \longrightarrow \infty} \frac{\partial V^n}{\partial \tau_n} = -p'(\tau_n) < 0$ which implies that $\tau_n^* < \infty$.

We also need to show that $\tau_i^* \in (\tau_{i-1}^*, \tau_{i+1}^*)$. If we evaluate $\frac{\partial V^i}{\partial \tau_i}$ at $\tau_i = \tau_{i-1}^*$, we get

$$\begin{aligned}\frac{\partial V^i}{\partial \tau_i}_{\tau_i=\tau_{i-1}^*} &= (\pi_0(i-1) - \pi_1(i))\, e^{-r\tau_{i-1}^*} - p'(\tau_{i-1}^*) \\ &= (\pi_0(i-1) - \pi_1(i))\, e^{-r\tau_{i-1}^*} - (\pi_0(i-2) - \pi_1(i-1))\, e^{-r\tau_{i-1}^*}\end{aligned}$$

which is strictly positive by assumption 1ii.

Similarly, we evaluate $\frac{\partial V^i}{\partial \tau_i}$ at $\tau_i = \tau_{i+1}^*$

$$\begin{aligned}\frac{\partial V^i}{\partial \tau_i}_{\tau_i=\tau_{i+1}^*} &= (\pi_0(i-1) - \pi_1(i))\, e^{-r\tau_{i+1}^*} - p'(\tau_{i+1}^*) \\ &= (\pi_0(i-1) - \pi_1(i))\, e^{-r\tau_{i-1}^*} - (\pi_0(i) - \pi_1(i+1))\, e^{-r\tau_{i-1}^*}\end{aligned}$$

which is strictly negative by assumption 1ii.

Since V^i is strictly concave in τ_i and $\frac{\partial V^i}{\partial \tau_i}_{\tau_i=\tau_i^*} = 0$, the unique maximum is achieved at

$\tau_i^* \in (\tau_{i-1}^*, \tau_{i+1}^*)$. *Q.E.D.*

We also need to demonstrate that $\tau^* = (\tau_1^*, \tau_2^*, .., \tau_n^*)$ is a Nash equilibrium.

Proposition $\tau^* = (\tau_1^*, \tau_2^*, .., \tau_n^*)$ as defined by (1) is a Nash equilibrium in adoption dates.

Proof If $\tau^* = (\tau_1^*, \tau_2^*, .., \tau_n^*)$ is a Nash equilibrium it must be that, given $\tau_1^*, \tau_2^*, .., \tau_{i-1}^*, \tau_{i+1}^*, ..., \tau_n^*$, i will prefer τ_i^* to any other date T. First, suppose i chooses a $T \in \left[\tau_{k-1}^*, \tau_k^*\right]$ where $k < i$

$$\begin{aligned} V^i(\tau_1^*, \tau_2^*, .., \tau_{i-1}^*, \tau_{i+1}^*, ..., \tau_n^*, T) = & \sum_{m=0}^{k-2} \int_{\tau_m^*}^{\tau_{m+1}^*} \pi_0(m) e^{-rt} dt + \int_{\tau_{k-1}^*}^{T} \pi_0(k-1) e^{-rt} dt \\ & + \int_{T}^{\tau_k^*} \pi_1(k) e^{-rt} dt + \sum_{m=k}^{i-2} \int_{\tau_m^*}^{\tau_{m+1}^*} \pi_1(m+1) e^{-rt} dt \\ & + \int_{\tau_{i-1}^*}^{\tau_{i+1}^*} \pi_1(i) e^{-rt} dt + \sum_{m=i+1}^{n} \int_{\tau_m^*}^{\tau_{m+1}^*} \pi_1(m) e^{-rt} dt - p(T) \end{aligned}$$

Maximizing with respect to T gives

$$(\pi_0(k-1) - \pi_1(k))\, e^{-rT^*} - p'(T^*) = 0$$

That is $T^* = \tau_k^*$. That is, in each interval $\left[\tau_{k-1}^*, \tau_k^*\right]$, with $k < i$, V^i reaches its maximum at the right boundary τ_k^*.

Next, suppose i chooses a $T \in \left[\tau_k^*, \tau_{k+1}^*\right]$ where $k > i$

$$\begin{aligned} V^i(\tau_1^*, \tau_2^*, .., \tau_{i-1}^*, \tau_{i+1}^*, ..., \tau_n^*, T) = & \sum_{m=0}^{i-2} \int_{\tau_m^*}^{\tau_{m+1}^*} \pi_0(m) e^{-rt} dt + \int_{\tau_{i-1}^*}^{\tau_{i+1}^*} \pi_0(i-1) e^{-rt} dt \\ & + \sum_{m=i}^{k-2} \int_{\tau_m^*}^{\tau_{m+1}^*} \pi_0(m) e^{-rt} dt + \int_{\tau_k^*}^{T} \pi_0(k-1) e^{-rt} dt \\ & + \int_{T}^{\tau_{k+1}^*} \pi_1(k) e^{-rt} dt + \sum_{m=k+1}^{n} \int_{\tau_m^*}^{\tau_{m+1}^*} \pi_1(m) e^{-rt} dt - p(T) \end{aligned}$$

Maximizing with respect to T gives

$$(\pi_0(k-1) - \pi_1(k))\, e^{-rT^*} - p'(T^*) = 0$$

That is, $T^* = \tau_k^*$. That is, in each interval $\left[\tau_k^*, \tau_{k+1}^*\right]$, with $k > i$, V^i reaches its maximum at the left boundary τ_k^*. Thus, the maximum of V^i must be in $\left[\tau_{i-1}^*, \tau_{i+1}^*\right]$. We already know from the previous demonstration that the maximum on that interval is τ_i^*. We have thus demonstrated that, given $\tau_1^*, \tau_2^*, .., \tau_{i-1}^*, \tau_{i+1}^*, ..., \tau_n^*$, i will prefer $T = \tau_i^*$ to all other $T \in [0, \infty)$. $\tau^* = (\tau_1^*, \tau_2^*, .., \tau_n^*)$ is therefore a Nash equilibrium. *Q.E.D*

A.1 Assumption 1ii)

For the existence of a Nash equilibrium, we need to check that assumption 1ii holds under the different policies.

A.1.1 Emission tax

Let us consider first the case of taxes. Let $\zeta_1^T = c_1 + \sigma\varepsilon_1$, $\zeta_0^T = c_0 + \sigma\varepsilon_0$ and $\rho = \frac{1}{b[n+1]^2}$. Then,

$$\begin{aligned}
\pi_1(m_1 - 1) &= \rho \left[a - [n - m_1 + 2]\, \zeta_1^T + [n - m_1 + 1]\, \zeta_0^T\right]^2, \\
\pi_0(m_1 - 2) &= \rho \left[a + [m_1 - 2]\, \zeta_1^T - [m_1 - 1]\, \zeta_0^T\right]^2,
\end{aligned}$$

and thus $\Delta\pi_{m_1-1}^T = \pi_1(m_1 - 1) - \pi_0(m_1 - 2)$ is equal to:

$$\Delta\pi_{m_1-1}^T = \rho \left[\zeta_1^T + \zeta_0^T\right] \left[n^2 \left[\zeta_1^T + \zeta_0^T\right] - 2n \left[a + [m_1 - 2]\, \zeta_1^T + [m_1 - 1]\, \zeta_0^T\right]\right].$$

By analogy, $\Delta\pi_{m_1}^T = \pi_1(m_1) - \pi_0(m_1 - 1)$ is equal to:,

$$\Delta\pi_{m_1}^T = \rho \left[\zeta_1^T + \zeta_0^T\right] \left[n^2 \left[\zeta_1^T + \zeta_0^T\right] - 2n \left[a + [m_1 - 1]\, \zeta_1^T + m_1\zeta_0^T\right]\right].$$

and hence:

$$\Delta\pi_{m_1-1}^T - \Delta\pi_{m_1}^T = 2n\rho \left[\zeta_1^T + \zeta_0^T\right]^2 > 0 \ \vee \forall m_1 \geq 2.$$

That is, assumption 1ii holds under the emission tax.

A.1.2 Exogenous refunded tax

Since under the exogenously refunded tax $\bar{\varepsilon}^X(m_1) = \bar{\varepsilon}^X(m_1-1)$, $\Delta\pi^X_{m_1-1} - \Delta\pi^X_{m_1}$ can be represented as:

$$\Delta\pi^X_{m_1-1} - \Delta\pi^X_{m_1} = \Delta\pi^T_{m_1-1} - \Delta\pi^T_{m_1} + \tag{20}$$

$$\frac{2\sigma\bar{\varepsilon}^X(m_1)}{b\,[n+1]}\left[\left[q^T_1(m_1-1) - q^T_0(m_1-2)\right] - \left[q^T_1(m_1) - q^T_0(m_1-1)\right]\right], \tag{21}$$

Since $q^T_1(m_1) - q^T_0(m_1-1) = \frac{n[\zeta^T_1 - \zeta^T_0]}{b[n+1]}$, equation (20) simplifies to:

$$\Delta\pi^X_{m_1-1} - \Delta\pi^X_{m_1} = 2n\rho\left[\zeta^T_1 + \zeta^T_0\right]^2 > 0 \;\vee m_1 \geq 2.$$

A.1.3 Endogenous refunded tax

$$\begin{aligned}
\Delta\pi^D_{m_1-1} - \Delta\pi^D_{m_1} = {} & b\left[1 - \frac{\sigma}{bQ^D(m_1-1)}\left[\varepsilon_1 - \bar{\varepsilon}^D(m_1-1)\right]\right]\left[q^D_1(m_1-1)\right]^2 \\
& - b\left[1 - \frac{\sigma}{bQ^D(m_1-2)}\left[\varepsilon_0 - \bar{\varepsilon}^D(m_1-2)\right]\right]\left[q^D_0(m_1-2)\right]^2 \\
& - b\left[1 - \frac{\sigma}{bQ^D(m_1)}\left[\varepsilon_1 - \bar{\varepsilon}^D(m_1)\right]\right]\left[q^D_1(m_1)\right]^2 \\
& + b\left[1 - \frac{\sigma}{bQ^D(m_1-1)}\left[\varepsilon_0 - \bar{\varepsilon}^D(m_1-1)\right]\right]\left[q^D_0(m_1-1)\right]^2.
\end{aligned}$$

Since $\varepsilon_0 - \bar{\varepsilon}^D(m_1) = m_1 s^D_1(m)\delta$, and $\varepsilon_1 - \bar{\varepsilon}^D(m_1) = -[n-m_1]\,s^D_0(m_1)\delta$, this equation can be represented as:

$$\begin{aligned}
\Delta\pi^D_{m_1-1} - \Delta\pi^D_{m_1} = {} & b\left[1 + \frac{\sigma\delta\,[n-m_1+1]\,s^D_0(m_1-1)}{bQ^D(m_1-1)}\right]\left[q^D_1(m_1-1)\right]^2 \\
& - b\left[1 - \frac{\sigma\delta\,[m_1-2]\,s^D_1(m_1-2)}{bQ^D(m_1-2)}\right]\left[q^D_0(m_1-2)\right]^2 \\
& - b\left[1 + \frac{\sigma\delta\,[n-m_1]\,s^D_0(m_1)}{bQ^D(m_1)}\right]\left[q^D_1(m_1)\right]^2 \\
& + b\left[1 - \frac{\sigma\delta\,[m_1-1]\,s^D_1(m_1-1)}{bQ^D(m_1-1)}\right]\left[q^D_0(m_1-1)\right]^2.
\end{aligned}$$

$\Delta\pi^D_{m_1-1} - \Delta\pi^D_{m_1} > 0 \; \forall m_1 \geq 2$ if and only if:

$$
\begin{aligned}
& b\left[\left[q_1^D(m_1-1)\right]^2 - \left[q_1^D(m_1)\right]^2\right] \\
& + \sigma\delta\left[n-m_1\right]\left[s_0^D(m_1-1)s_1^D(m_1-1)q_1^D(m_1-1) - s_0^D(m_1)s_1^D(m_1)q_1^D(m_1)\right] \\
& + \sigma\delta s_0^D(m_1-1)s_1^D(m_1-1)q_1^D(m_1-1) \\
& > \\
& b\left[\left[q_0^D(m_1-2)\right]^2 - \left[q_0^D(m_1-1)\right]^2\right] \\
& + \sigma\delta\left[m_1-1\right]\left[s_0^D(m_1-1)s_1^D(m_1-1)q_0^D(m_1-1) - s_0^D(m_1-2)s_1^D(m_1-2)q_0^D(m_1-2)\right] \\
& + \sigma\delta s_0^D(m_1-2)s_1^D(m_1-2)q_0^D(m_1-2).
\end{aligned}
$$

We have that $s_0^D(m_1-1)s_1^D(m_1-1)q_j^D(m_1-1) \simeq s_0^D(m_1)s_1^D(m_1)q_j^D(m_1) \; \forall m_1 \neq 1, n \;\&\; j \in \{0,1\}$[13] and thus this expression simplifies to:

$$
\begin{aligned}
& b\left[\left[q_1^D(m_1-1)\right]^2 - \left[q_0^D(m_1-2)\right]^2\right] + \sigma\delta s_0^D(m_1-1)s_1^D(m_1-1)q_1^D(m_1-1) \\
& > \\
& b\left[\left[q_1^D(m_1)\right]^2 - \left[q_0^D(m_1-1)\right]^2\right] + \sigma\delta s_0^D(m_1-2)s_1^D(m_1-2)q_0^D(m_1-2).
\end{aligned}
$$

Finally, if $q_1^D(m_1) > q_0^D(m_1-1) \vee m_1 \geq 2$, we expect this condition to be satisfied.

B Cournot equilbrium with two technologies

We leave the completely analogous derivation of the equiilbrium for three technologies to the interested reader.

B.1 Emission tax

Let $\zeta_0^T = c_0 + \sigma\varepsilon_0$ denote marginal costs inclusive of emission tax payments under an emission tax before adoption of the new technology and let $\zeta_1^T = c_1 + \sigma\varepsilon_1$ denote marginal costs after adoption. If we have m_1 adopters of the new technology and rank the firms according to their order in the adoption sequence (taking it as given), we can write the profit rate maximization problem for the adopters as

[13] Note that $s_1^D(0) = 0$, and $s_0^D(n) = 0$.

$$\pi^j = \max_{q^j} \left[P(Q) - \zeta_1^T \right] q^j,$$

for $j \leq m_1$,

and the profit maximization problem for the $n - m_1$ non-adopters as

$$\pi^j = \max_{q^j} \left[P(Q) - \zeta_0^T \right] q^j,$$

for $j > m_1$

Substituting in $P(Q) = a - b \sum_{i=1}^n q^i$, the first order condition for the adopters is

$$q^j = \frac{a - b \sum_{i \neq j} q^i - \zeta_1^T}{2b},$$

and the first order condition for the non-adopters

$$q^j = \frac{a - b \sum_{i \neq k} q^i - \zeta_0^T}{2b}.$$

Since the m_1 adopters are symmetric they will all have the same profit-maximizing level of production. We denote this profit-maximizing level q_1^T. Similarly, the level of production is the same for all $n - m_1$ non-adopters and we denote this profit-maximizing level q_0^T. We thus have the following equilibrium conditions

$$q_1^T = \frac{a - b \left[[m_1 - 1] q_1^T + [n - m_1] q_0^T \right] - \zeta_1^T}{2b},$$

$$q_0^T = \frac{a - b \left[m_1 q_1^T + [n - m_1 - 1] q_0^T \right] - \zeta_0^T}{2b}.$$

Solving for q_1^T and q_0^T, we find the levels of equilibrium output for adopters and non-adopters, respectively

$$q_1^T(m) = \frac{a - \zeta_1^T + [n - m_1] \left[\zeta_0^T - \zeta_1^T \right]}{b [n + 1]},$$

$$q_0^T(m) = \frac{a - \zeta_0^T - m_1 \left[\zeta_0^T - \zeta_1^T \right]}{b [n + 1]}, \tag{22}$$

yielding equilibrium price

$$P^T(m) = \frac{a + m_1 \zeta_1^T + [n - m_1] \zeta_0^T}{[n + 1]},$$

and equilibrium profits for adopters and non-adopters, respectively,

$$\pi_1^T(m_1) = \left[P^T(m_1) - \zeta_1^T\right] q_1^T(m_1) = \left[\frac{a + m_1\zeta_1^T + [n - m_1]\,\zeta_0^T}{[n+1]} - \zeta_1\right] q_1^T(m_1) = b\left[q_1^T(m_1)\right]^2.$$

$$\pi_0^T(m_1) = \left[P^T(m_1) - \zeta_0^T\right] q_0^T(m_1) = \left[\frac{a + m_1\zeta_1^T + [n - m_1]\,\zeta_0^T}{[n+1]} - \zeta_0\right] q_0^T(m_1) = b\left[q_0^T(m_1)\right]^2.$$

For interior solutions with $q_0^T(m_1) > 0$ for all $m_1 < n$, we see from (22) that this requires $a - \zeta_0 - [n-1]\,[\zeta_0 - \zeta_1] > 0$ to be true.

B.2 Exogenously refunded tax

Similarly, under an exogenously refunded tax, the profit maximization problems for the adopters and non-adopters, respectively, are

$$\pi^j = \max_{q^j}\left[[P(Q) - c_1 - \sigma\varepsilon_1]\,q^j + \sigma E\frac{q^j}{Q}\right] = \max_{q^j}\left[P(Q) - \zeta_1^T + \sigma\bar{\varepsilon}\right] q^j, \tag{23}$$

for $j = 1, 2, ..., m_1 - 1, m_1$,

$$\pi^j = \max_{q^j}\,[P(Q) - c_0 - \sigma\varepsilon_0]\,q^j + \sigma E\frac{q^j}{Q} = \max_{q^j}\left[P(Q) - \zeta_0^T + \sigma\bar{\varepsilon}\right] q^j, \tag{24}$$

for $j = m_1 + 1, m_1 + 2, ..., n - 1, n$.

with aggregate emissions (E) and aggregate output (Q) are given by:

$$E = \sum_{i=1}^{n} \varepsilon^i q^i.$$
$$Q = \sum_{i=1}^{n} q^i.$$

First-order conditions for the adopters and non-adopters are

$$q^j = \frac{a - b\sum_{i\neq j} q^i - \zeta_1^T + \sigma\bar{\varepsilon}}{2b},$$

for $j = 1, 2, ..., m_1 - 1, m_1$, and

$$q^j = \frac{a - b\sum_{i\neq j} q^i - \zeta_0^T + \sigma\bar{\varepsilon}}{2b},$$

for $j = m_1 + 1, m_1 + 2, ..., n - 1, n$.

Substituting in the profit-maximizing levels q_1^X for the m_1 adopters and q_0^X for the $n - m_1$ non-adopters, we can write

$$q_1^X(m_1) = \frac{a - \zeta_1^T + [n - m_1]\left[\zeta_0^T - \zeta_1^T\right] + \sigma\bar{\varepsilon}^X(m_1)}{b\,[n+1]} = q_1^T(m_1) + \frac{\sigma\bar{\varepsilon}^X(m_1)}{b\,[n+1]},$$
$$q_0^X(m_1) = \frac{a - \zeta_0^T - m_1\left[\zeta_0^T - \zeta_1^T\right] + \sigma\bar{\varepsilon}^X(m_1)}{b\,[n+1]} = q_0^T(m_1) + \frac{\sigma\bar{\varepsilon}^X(m_1)}{b\,[n+1]}.$$

and the average emission intensity is $\bar{\varepsilon}^X(m_1) = \frac{m_1\varepsilon_1 q_1^X + [n-m_1]\varepsilon_0 q_0^X}{m_1 q_1^X + [n-m_1] q_0^X} > 0$.

$$P^X(m) = \frac{a + m_1\zeta_1^T + [n - m_1]\,\zeta_0^T - \sigma n\bar{\varepsilon}^X(m_1)}{[n+1]}$$

Equilibrium profits for adopters and non-adopters, respectively,

$$\pi_1^X(m_1) = \left[P^X(m_1) - \zeta_1^T + \sigma\bar{\varepsilon}^X(m_1)\right] q_1^X(m_1) = \left[\frac{a - \zeta_1^T + [n - m_1]\left[\zeta_0^T - \zeta_1^T\right] + \sigma\bar{\varepsilon}^X(m_1)}{[n+1]}\right] q_1^X(m_1),$$
$$= b\left[q_1^X(m_1)\right]^2,$$
$$\pi_0^X(m_1) = \left[P^X(m_1) - \zeta_0^T + \sigma\bar{\varepsilon}^X(m_1)\right] q_0^X(m_1) = \left[\frac{a - \zeta_0^T + m_1\left[\zeta_1^T - \zeta_0^T\right] + \sigma\bar{\varepsilon}^X(m_1)}{[n+1]}\right] q_0^x(m_1),$$
$$= b\left[q_0^X(m_1)\right]^2.$$

B.3 Endogenously refunded tax

Under an endogenously refunded tax, the profit maximization problems for the adopters and non-adopters are the same as the ones for the exogenously refunded tax found in (23) and (24), respectively. However, when the firm recognizes that it can influence the size of the refund, the first-order conditions are

$$q^j = \frac{a - b\sum_{i\neq j} q^i - c_1 - \sigma\left[\varepsilon_1 - \bar{\varepsilon}\right]}{\left[2b - \sigma\left[\varepsilon_1 - \bar{\varepsilon}\right]\frac{1}{Q}\right]},$$

for $j = 1, 2, ..., m_1 - 1, m_1$,

$$q^j = \frac{a - b\sum_{i\neq j} q^i - c_0 - \sigma\left[\varepsilon_0 - \bar{\varepsilon}\right]}{\left[2b - \sigma\left[\varepsilon_0 - \bar{\varepsilon}\right]\frac{1}{Q}\right]},$$

for $j = m_1 + 1, m_1 + 2, ..., n - 1, n$.

Substituting in the profit-maximizing levels q_1^D for the m_1 adopters and q_0^D for the $n - m_1$ non-adopters, and suppressing the argument of m_1 for clarity, we can write

$$q_1^D = \frac{\left[1 - \frac{\sigma}{bQ^D}\left[\varepsilon_0 - \bar{\varepsilon}^D\right]\right]\left[a - \zeta_1^T + \sigma\bar{\varepsilon}^D\right] + \left[n - m_1\right]\left[\zeta_0^T - \zeta_1^T\right]}{\phi}, \tag{25}$$

$$q_0^D = \frac{\left[1 - \frac{\sigma}{bQ^D}\left[\varepsilon_1 - \bar{\varepsilon}^D\right]\right]\left[a - \zeta_0^T + \sigma\bar{\varepsilon}^D\right] - m_1\left[\zeta_0^T - \zeta_1^T\right]}{\phi}, \tag{26}$$

where

$$\phi = b\left[n+1\right] + \frac{1}{b}\left[\frac{\sigma}{Q^D}\right]^2\left[\varepsilon_1 - \bar{\varepsilon}^D\right]\left[\varepsilon_0 - \bar{\varepsilon}^D\right] - \frac{\sigma}{Q^D}\left[\left[\varepsilon_1 - \bar{\varepsilon}^D\right]\left[n - m_1 + 1\right] + \left[\varepsilon_0 - \bar{\varepsilon}^D\right]\left[m_1 + 1\right]\right] > 0$$
$\vee\, m$.

Substituting (25) and (26) into $P^D = a - bQ^D$ with $Q^D = m_1 q_1^D + \left[n - m_1\right] q_0^D$, we get

$$\begin{aligned}\pi_1^D &= \left[P^D - \zeta_1^T + \sigma\bar{\varepsilon}^D\right] q_1^D, \\ &= b\left[1 - \frac{\sigma}{bQ^D}\left[\varepsilon_1 - \bar{\varepsilon}^D\right]\right]\left[q_1^D\right]^2.\end{aligned}$$

$$\begin{aligned}\pi_0^D &= \left[P^D - \zeta_0^T + \sigma\bar{\varepsilon}^D\right] q_0^D, \\ &= b\left[1 - \frac{\sigma}{bQ^D}\left[\varepsilon_0 - \bar{\varepsilon}^D\right]\right]\left[q_0^D\right]^2.\end{aligned}$$

C Comparison of endogenous versus exogenous refunding

Rewriting the equilibrium conditions (10) for the m_1 adopters as

$$a - bQ^D(m_1) - bq_1^D(m_1) = c_1 + \sigma\left[\varepsilon_1 - \bar{\varepsilon}^D(m_1)\right]\left[1 - \frac{q_1^D(m_1)}{Q^D}\right],$$

and (11) for the $n - m_1$ adopters as

$$a - bQ^D(m_1) - bq_0^D(m_1) = c_0 + \sigma\left[\varepsilon_0 - \bar{\varepsilon}^D(m_1)\right]\left[1 - \frac{q_0^D(m_1)}{Q^D}\right],$$

we can sum over all n conditions to get

$$m_1\left[a-bQ^D(m_1)-bq_1^D(m_1)\right]+[n-m_1]\left[a-bQ^D(m_1)-bq_0^D(m_1)\right]$$
$$=m_1\left[c_1+\sigma\left[\varepsilon_1-\bar{\varepsilon}^D(m_1)\right]\left[1-\frac{q_1^D(m_1)}{Q^D}\right]\right]+[n-m_1]\left[c_0+\sigma\left[\varepsilon_0-\bar{\varepsilon}^D(m_1)\right]\left[1-\frac{q_0^D(m_1)}{Q^D}\right]\right]$$

This simplifies to

$$\begin{aligned} na-[n+1]\,bQ^D(m_1) &= m_1\zeta_1^T+[n-m_1]\,\zeta_0^T-n\sigma\bar{\varepsilon}^D(m_1) \\ &\quad -\sigma\left[m_1\varepsilon_1\frac{q_1^D(m_1)}{Q^D}+[n-m_1]\,\varepsilon_0\frac{q_0^D(m_1)}{Q^D}\right] \\ &\quad +\sigma\bar{\varepsilon}^D(m_1)\left[m_1\frac{q_1^D(m_1)}{Q^D}+[n-m_1]\,\frac{q_0^D(m_1)}{Q^D}\right] \end{aligned}$$

yielding

$$Q^D(m_1)=\frac{na-m_1\zeta_1^T-[n-m_1]\,\zeta_0^T+n\sigma\bar{\varepsilon}^D(m_1)}{b\,[n+1]}.$$

Similarly, using the n equilibrium conditions in (4) and (5), we get

$$Q^X(m_1)=\frac{na-m_1\zeta_1^T-[n-m_1]\,\zeta_0^T+n\sigma\bar{\varepsilon}^X(m_1)}{b\,[n+1]}.$$

Hence,

$$Q^D(m_1)-Q^X(m_1)=\frac{n\sigma\left[\bar{\varepsilon}^D(m_1)-\bar{\varepsilon}^X(m_1)\right]}{b\,[n+1]},$$

The first-order conditions under policy $k\in\{T,X,D\}$ and technology $j\in\{0,1\}$ can also be written

$$a-bQ^k-bq_j^k=\psi_j^k.$$

where ψ_j^k denotes the marginal cost inclusive of the costs of the emissions policy. We drop the argument of m_1 for clarity. We can then write

$$q_j^k=\frac{a-\psi_j^k}{b}-Q^k,$$

with

$$\psi_j^T=\zeta_j^T,$$
$$\psi_j^X=c_j+\sigma\left[\varepsilon_j-\bar{\varepsilon}^R\right],$$
$$\psi_j^D=c_j+\sigma\left[\varepsilon_j-\bar{\varepsilon}^R\right]\left[1-\frac{q_j^D}{Q^D}\right].$$

Comparing equilibrium quantities under exogenous and endogenous refunding for adopters, we can write

$$
\begin{aligned}
q_1^X - q_1^D &= \frac{\psi_1^D - \psi_1^X}{b} + Q^D - Q^X, \\
&= \frac{c_1 + \sigma\left[\varepsilon_1 - \bar{\varepsilon}^D\right]\left[1 - \frac{q_1^D}{Q^D}\right] - \left[c_1 + \sigma\left[\varepsilon_1 - \bar{\varepsilon}^X\right]\right]}{b} + \frac{n\sigma}{b\left[n+1\right]}\left[\bar{\varepsilon}^D - \bar{\varepsilon}^X\right], \\
&= \sigma\frac{\left[\bar{\varepsilon}^D - \varepsilon_1\right] q_1^D\left[n+1\right] - \left[\bar{\varepsilon}^D - \bar{\varepsilon}^X\right] Q^D}{b\left[n+1\right] Q^D} > 0,
\end{aligned}
$$

since $\left[\bar{\varepsilon}^D\left(m_1\right) - \varepsilon_1\right] > \left[\bar{\varepsilon}^D\left(m_1\right) - \bar{\varepsilon}^X\left(m_1\right)\right]$ and $q_1^D\left(m_1\right)\left[n+1\right] > Q^D\left(m_1\right)$ for $0 < m_1 < n$.

Furthermore, for non-adopters, we can write

$$
\begin{aligned}
q_0^X - q_0^D &= \frac{\psi_0^D - \psi_0^X}{b} + Q^D - Q^X, \\
&= \frac{\left[c_0 + \sigma\left[\varepsilon_0 - \bar{\varepsilon}^D\right]\left[1 - \frac{q_0^D}{Q^D}\right]\right] - \left[c_0 + \sigma\left[\varepsilon_0 - \bar{\varepsilon}^X\right]\right]}{b} + \frac{n\sigma}{b\left[n+1\right]}\left[\bar{\varepsilon}^D - \bar{\varepsilon}^X\right], \\
&= \frac{-\sigma\left[\varepsilon_0 - \bar{\varepsilon}^D\right] q_0^D\left[n+1\right] + \sigma\left[\bar{\varepsilon}^X - \bar{\varepsilon}^D\right] Q^D}{b\left[n+1\right] Q^D}. \\
&= \frac{-\sigma m_1 \delta s_1^D\left[n+1\right] q_0^D - \sigma\left[s_1^X - s_1^D\right] m_1 \delta Q^D}{b\left[n+1\right] Q^D}.
\end{aligned}
$$

which implies that $q_0^X < q_0^D \vee s_1^X \geq s_1^D$.

D Optimal adoption times with three technologies

Given an ordering of adoption dates $\tau_1 \leq \tau_2 \leq ... \leq \tau_j \leq ... \leq \tau_n$ for technology 2, where the first $n-k$ adopters switch from technology 0 and the following k adopters switch from technology 1, we can write the present value of adopting technology 2 for firm j at τ_j as

$$
\begin{aligned}
V_2^j(\tau_1, ..., \tau_{j-1}, \tau_j, \tau_{j+1}, ..., \tau_n) = &\sum_{m_2=0}^{j-1} \int_{\tau_{m_2}}^{\tau_{m_2+1}} \pi_0(k, m_2) e^{-r[\,t-t_2]} dt \\
&+ \sum_{m_2=j}^{n-k} \int_{\tau_{m_2}}^{\tau_{m_2+1}} \pi_2(k, m_2) e^{-r[\,t-t_2]}\, dt \\
&+ \sum_{m_2=n-k+1}^{n} \int_{\tau_{m_2}}^{\tau_{m_2+1}} \pi_2(n-m_2, m_2) e^{-r[\,t-t_2]}\, dt - p_2(\tau_j)
\end{aligned}
$$

for $j = 1, 2, ..., n-k$ and

$$V_2^j(\tau_1, ..., \tau_{j-1}, \tau_j, \tau_{j+1}, ..., \tau_n) = \sum_{m_2=0}^{n-k-1} \int_{\tau_{m_2}}^{\tau_{m_2+1}} \pi_1(k, m_2) e^{-r[\ t-t_2]}\, dt$$
$$+ \sum_{m_2=n-k}^{j-1} \int_{\tau_{m_2}}^{\tau_{m_2+1}} \pi_1(n-m_2, m_2) e^{-r[\ t-t_2]}\, dt$$
$$+ \sum_{m_2=j}^{n} \int_{\tau_{m_2}}^{\tau_{m_2+1}} \pi_2(n-m_2, m_2) e^{-r[\ t-t_2]}\, dt - p_2(\tau_j)$$

for $j = n-k+1, n-k+2, ..., n-1, n$ and where $\tau_0 = t_2$ and $\tau_{n+1} = \infty$.

From the assumptions that $\pi_2(m_1, m_2) > \pi_1(m_1, m_2) > \pi_0(m_1, m_2) \geq 0$, $\pi_2(m_1, m_2 + 1) - \pi_0(m_1, m_2) > \pi_2(m_1 - 1, m_2 + 1) - \pi_1(m_1, m_2)$ for all m_1, m_2 for which $m_1 + m_2 < n$ and $p_2''(t) > re^{-rt}(\pi_2(k,1) - \pi_0(k,0))$, V_2^j is strictly concave in τ_j for $\tau_j \in [\tau_{j-1}, \tau_{j+1}]$, which implies that first-order conditions are necessary and sufficient conditions for determining τ_j^*. The first-order conditions are

$$\frac{\partial V_2^j}{\partial \tau_j} = [\pi_0(k, j-1) - \pi_2(k, j)]\, e^{-r[\ \tau_j^* - t_2]} - p_2'(\tau_j^*) = 0 \tag{27}$$

for $j = 1, 2, ..., n-k$ and

$$\frac{\partial V_2^j}{\partial \tau_j} = [\pi_1(n-j+1, j-1) - \pi_2(n-j, j)]\, e^{-r[\ \tau_j^* - t_2]} - p_2'(\tau_j^*) = 0 \tag{28}$$

for $j = n-k+1, ..., n-1, n$.

We now define $\Delta\pi_{02,j} = \pi_2(k, j) - \pi_0(k, j-1)$ and $\Delta\pi_{12,j} = \pi_2(n-j, j) - \pi_1(n-j+1, j-1)$ and we can then write (27) and (28) as

$$\frac{\partial V_2^j}{\partial \tau_j} = -\Delta\pi_{02,j} e^{-r[\ \tau_j^* - t_2]} - p_2'(\tau_j^*) = 0$$

for $j = 1, 2, ..., n-k$ and

$$\frac{\partial V_2^j}{\partial \tau_j} = -\Delta\pi_{12,j} e^{-r[\ \tau_j^* - t_2]} - p_2'(\tau_j^*) = 0$$

for $j = n-k+1, ..., n-1, n$.

From the assumptions that $p_2(t) < p_1(t)e^{rt_2}$ and $c_2 + \sigma\varepsilon_2 < c_1 + \sigma\varepsilon_1$, we know that firms which have not adopted technology 1 by date t_2 will not have an incentive to adopt it after technology 2 has appeared at t_2. Therefore, at t_2, the firms only face the decision of when to adopt technology 2. (A demonstration of a Nash equilibrium in the adoption times implicitly defined by (27) and (28) is available upon request.)

For the *laggards*, the increase in profit rate under the emission tax, $\Delta\pi^T_{02,j}$, for the firm which is the jth to adopt technology 2 and switches from technology 0 under a refunded tax, is given by:

$$\Delta\pi^T_{02,j} = \pi^T_2(k^T, j) - \pi^T_0(k^T, j-1) = b\left[q^T_2(k^T, j)\right]^2 - b\left[q^T_0(k^T, j-1)\right]^2$$

for $j = 1, 2., ..., n - k^T - 1, n - k^T$,
and the increase in profit rate under the exogenously refunded tax, $\Delta\pi^X_{02,j}$, by:

$$\begin{aligned}\Delta\pi^X_{02,j} &= \pi^X_2(k^X, j) - \pi^X_0(k^X, j-1) \\ &= b\left[q^T_2(k^X, j) + \frac{\sigma\bar{\varepsilon}^X(k^X, j)}{b\,[n+1]}\right]^2 - b\left[q^T_0(k^X, j-1) + \frac{\sigma\bar{\varepsilon}^X(k^X, j-1)}{b\,[n+1]}\right]^2\end{aligned}$$

for $j = 1, 2, ..., n - k^X - 1, n - k^X$.

The difference in the increase in profit rate from adoption of technology 2 under the exogenous refunded tax compared to the emission tax for the jth adopter of technology 2, which would switch from technology 0 under both policies, is thus equal to:

$$\begin{aligned}\Delta\pi^X_{02,j} - \Delta\pi^T_{02,j} &= b\left[q^T_2(k^X, j) + \frac{\sigma\bar{\varepsilon}^X(k^X, j)}{b\,[n+1]}\right]^2 - b\left[q^T_0(k^X, j-1) + \frac{\sigma\bar{\varepsilon}^X(k^X, j-1)}{b\,[n+1]}\right]^2 \\ &\quad - \left[b\left[q^T_2(k^T, j)\right]^2 - b\left[q^T_0(k^T, j-1)\right]^2\right],\end{aligned}$$

for $j = 1, 2, ..., n - k^X - 1, n - k^X$. If, as before, we assume that one firm switching from technology 0 to technology 2 considers its own impact on the refund as negligible, i.e., $\bar{\varepsilon}^X(k^X, j) = \bar{\varepsilon}^X(k^X, j-1)$, and use that

$$q^T_2(k^X, j) - q^T_2(k^T, j) = q^T_0(k^X, j-1) - q^T_0(k^T, j-1) = \frac{[k^T - k^X][\zeta^T_0 - \zeta^T_2]}{b[n+1]},$$

and

$$q^T_2(k^X, j) - q^T_0(k^X, j-1) = q^T_2(k^T, j) - q^T_0(k^T, j-1) = \frac{n\,[\zeta^T_0 - \zeta^T_2]}{b\,[n+1]},$$

the difference in profit rate increase for the *laggards* simplifies to:

$$\Delta\pi^X_{02,j} - \Delta\pi^T_{02,j} = 2\frac{n\left[\zeta^T_0 - \zeta^T_2\right]}{b\left[n+1\right]^2}\left[\left[k^T - k^X\right]\left[\zeta^T_0 - \zeta^T_1\right] + \sigma\bar{\varepsilon}^X(k^X, j)\right].$$

The *intermediates* exist only if the number of firms which would have adopted technology 1 by t_2 under the emission tax is lower than the number of adopters of technology 1 at t_2 under the exogenous refunded tax, i.e., $k^T < k^X$. The jth adopter, for which $j \in \left[n - k^X + 1, n - k^T\right]$, would switch from technology 0 under an emission tax, and from technology 1 under a refunded tax. The difference in adoption time between the policies is then determined by the following difference:

$$\begin{aligned}
\Delta\pi^X_{12,j} - \Delta\pi^T_{02,j} = {} & b\left[q^T_2(n-j,j) + \frac{\sigma\bar{\varepsilon}^X(n-j,j)}{b\left[n+1\right]}\right]^2 \\
& - b\left[q^T_1(n-j+1,j-1) + \frac{\sigma\bar{\varepsilon}^X(n-j+1,j-1)}{b\left[n+1\right]}\right]^2 \\
& - \left[b\left[q^T_2(k^T,j)\right]^2 - b\left[q^T_0(k^T,j-1)\right]^2\right]
\end{aligned}$$

Since $\bar{\varepsilon}^X(n-j,j) = \bar{\varepsilon}^X(n-j+1,j-1)$ from the perspective of the firm, we have

$$\begin{aligned}
q^T_2(n-j,j) - q^T_1(n-j+1,j-1) &= \frac{n\left[\zeta^T_1 - \zeta^T_2\right]}{b\left[n+1\right]} \\
q^T_2(n-j,j) + q^T_1(n-j+1,j-1) &= \frac{2a - \left[n - 2\left[j+1\right]\right]\zeta^T_2 + \left[n-2j\right]\zeta^T_1}{b\left[n+1\right]} \\
q^T_2(k^T,j) + q^T_0(k^T,j-1) &= \frac{2a + \left[n-2j\right]\left[\zeta^T_0 - \zeta^T_2\right] - 2k^T\left[\zeta^T_0 - \zeta^T_1\right] - 2\zeta^T_2}{b\left[n+1\right]}
\end{aligned}$$

, so that we can simplify the difference in profit rate increase to

$$\begin{aligned}
\Delta\pi^X_{12,j} - \Delta\pi^T_{02,j} = {} & \frac{n\left[\zeta^T_0 - \zeta^T_1\right]}{b\left[n+1\right]^2}\left[2k^T\left[\zeta^T_0 - \zeta^T_2\right] - \left[n-2j\right]\left[\zeta^T_0 + \zeta^T_1 - 2\zeta^T_2\right] - 2\left[a + \zeta^T_2\right]\right] \\
& + 2\frac{n\left[\zeta^T_1 - \zeta^T_2\right]}{b\left[n+1\right]^2}\sigma\bar{\varepsilon}^X(n-j,j)
\end{aligned}$$

For the *early adopters* the increase in profit rate from adoption of technology 2 under an emission tax is

$$\begin{aligned}\Delta\pi^T_{12,j} &= \pi^T_2(n-j,j) - \pi^T_1(n-j+1,j-1)\\ &= b\left[q^T_2(n-j,j)^2 - \left[q^T_1(n-j+1,j-1)\right]^2\right]\end{aligned}$$

for $j = n-k^T+1, n-k^T+2, ..., n-1, n$,

and under an exogenous refunded tax:

$$\begin{aligned}\Delta\pi^X_{12,j} &= \pi^X_2(n-j,j) - \pi^X_1(n-j+1,j-1)\\ &= b\left[q^T_2(n-j,j) + \frac{\sigma\bar{\varepsilon}^X(n-j,j)}{b\,[n+1]}\right]^2\\ &- b\left[q^T_1(n-j+1,j-1) + \frac{\sigma\bar{\varepsilon}^X(n-j+1,j-1)}{b\,[n+1]}\right]^2\end{aligned}$$

for $j = n-k^X+1, n-k^X+2, ..., n-1, n$. Since $\bar{\varepsilon}^X(n-j,j) = \bar{\varepsilon}^X(n-j+1,j-1)$, the difference in profit rate increase is given by:

$$\Delta\pi^X_{12,j} - \Delta\pi^T_{12,j} = 2b\left[q^T_2(n-j,j) - q^T_1\,(n-j+1,j-1)\right]\frac{\sigma\bar{\varepsilon}^X(n-j,j)}{b\,[n+1]}$$

for $j = n-k^T+1, n-k^T+2, ..., n-1, n$.

Using similar tricks as before, this becomes:

$$\Delta\pi^X_{12,j} - \Delta\pi^T_{12,j} = \frac{2n\left[\zeta^T_1 - \zeta^T_2\right]}{b\,[n+1]^2}\sigma\bar{\varepsilon}^X(n-j,j)$$

for $j = n-k^T+1, n-k^T+2, ..., n$.