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On Refunding of Emission Taxes and Technology Diffusion

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ABSTRACT

We analyze the impacts on technology diffusion of an emission tax refunded in proportion to output market share — a policy modeled after existing systems in Sweden and France — and compare to the diffusion of an abatement technology under a standard emission tax. 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 nonrefunded emission tax. Moreover, it is ambiguous whether refunding continues over time to provide larger incentives for technological upgrades than a nonrefunded emission tax, since the effects of refunding dissipate as the industry becomes cleaner. The overall conclusion is that the effects of refunding on technology diffusion critically depends on the regulated industry's prior technological composition and its market structure.

Keywords: Emission tax; refund; abatement technology; technology diffusion; imperfect competition

JEL Codes: H23, O33, O38, Q52

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Introduction

The impact of environmental policy on technological change may be the greatest determinant of the long-run cost of emissions abatement, and hence, perhaps one of the most important criteria on which to judge its success. How to control and limit polluting emissions caused by our growing consumption of fossil fuels and to develop alternative clean energy sources are among the most pressing policy challenges facing the world today. In theory, a strong and stable price of emissions implemented through an emission tax should induce both investment in R&D and cost-effective investment by polluting firms in already existing technologies that reduce emissions (Acemoglu *et al.*, 2012). In reality, however, introducing such an emission tax is typically difficult politically because regulated firms will often argue that they will lose international competitiveness. 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 (Aidt, 2010; Fredriksson and Sterner, 2005). One method for such refunding is to refund the revenues in proportion to the output market share, sometimes referred to as refunded emission payment (REP). Under such an approach, firms with above-average emission intensity make net payments to the cleaner-than-average firms. Thus, REP is designed to affect technology investment since firms that outperform their peers may become net receivers of the refund, while those who under-perform become net payers (Sterner and Höglund-Isaksson, 2006). REP therefore has both a carrot and a stick feature which makes it appealing to policy makers. A country with long experience with REP is Sweden where a high but refunded charge on NO_x emissions from large combustion plants was introduced in 1992. Similar systems (such as feebates or Bonus-Malus) have been implemented in France to reduce vehicle emissions by providing incentives for individuals to purchase more energy efficient vehicles by means of a fee on cars with high CO_2 emission intensity and a rebate on cars with low emission intensity (see, e.g., d'Haultfoeuille *et al.* 2014).

In this paper, we analyze diffusion of an abatement technology under a "standard" emission tax (hereinafter, emission tax) compared to an emission tax for which the revenues are returned to the aggregate of taxed firms in proportion to output (hereinafter, refunded tax). 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.[1]

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; Coria 2009; Kerr and Newell 2003; van Soest 2005), this is the first study investigating the effects of refunding an emission tax. Previous studies on refunded emission taxes have analyzed the incentives for emission abatement and production and how they compare to optimal policy. For instance, Gersbach and Requate (2004) show that refunding is non-optimal in the case of perfect competition since in order to achieve a higher share of refunds firms would choose output such that marginal costs of production exceed the competitive price. In contrast, refunding can alleviate output underprovision in markets characterized by imperfect competition. When it comes to the incentives to abatement, the results are reversed: refunding does not distort abatement incentives under perfect competition (Sterner and Höglund-Isaksson, 2006). However, under imperfect competition, it discourages firms from abating emissions since pollution reduction reduces the rents from emissions that will be returned to firms through the refund.

In the long run, refunding not only affects output and emissions but also the equilibrium number of firms operating in an industry. Hence, if the regulator is to ensure that refunding will be returned to firms through the refund (Fischer, 2011), refunding must be complemented with an entry license (Cato, 2010).

Refunding can also induce firms to reveal their private valuation of common pool resources. For instance, Montero (2008) proposes a mechanism that builds upon a conventional uniform-price sealed-bid auction. Part of the auction revenues are returned to firms, not as lump sum transfers but in a way that firms would have incentives to bid truthfully. Furthermore, refunding can be used to solve the so called hold-up problem, i.e., that the regulator is unable to precommit to

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

a regulatory scheme when enforcement is deemed too costly if firms do not make investments to reduce their emissions. Gersbach (2002) shows that a self-financing tax-subsidy scheme designed to benefit the investing firms can solve this problem. Similar to the outcome in the unique subgame perfect equilibrium demonstrated by Gersbach (2002), where no actual implementation of taxes and subsidies is required, under the refunded emission tax we analyze the net tax is zero for all firms in the long run equilibrium, i.e., when all firms have invested. Actual implementation of the refunding scheme is however required to drive technology diffusion towards this long-run equilibrium.[2]

To study diffusion of an abatement technology, we follow 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 and firms take the size of the refund as given. The intuition behind this result

[2] From the empirical side, Sterner and Turnheim (2009) study the effects of the Swedish refunded charge on NO_x emissions (REP). Their results indicate that the charge had a very substantial role in explaining the sharp decrease in NO_x emission intensities. Moreover, Bonilla *et al.* (2015) show that REP had a significant effect on the diffusion of NOx abatement post-combustion technologies.

is straightforward: if the refund is based on output, adoption provides firms with a competitive advantage as the lower cost of production allows them to increase their output, market share, and total refund. 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. In contrast, adoption incentives are reduced when firms take into account their influence on the size of the refund. In such a setting, adoption incentives come from the combination of two effects: one on output and another on refunding. The "output effect" accounts for the fact that more production is shifted towards nonadopters since they receive a higher implicit output subsidy than adopters. Hence, compared to exogenous refunding, adopters produce less and have lower adoption benefits from increased output. The counteracting "refunding effect" accounts for the fact that because production is shifted towards nonadopters, the average emission intensity is larger under endogenous refunding and so is the refund. After accounting for these two effects, we find that endogenous refunding offers lower incentives to technology diffusion than exogenous refunding, because the output effect dominates the refunding effect. Finally, we also analyze whether a refunded tax continuously provide larger incentives to technological upgrading than an emission tax. Our results indicate that the answer critically depends on the stock of cleaner technologies that are already installed when a new technology arrives.

The paper is organized as follows. The following section introduces the model of technological diffusion. The next two sections analyze the adoption incentives provided by emission taxes with and without refunding, respectively. The last but one section analyzes technological catching up under the two policies. The last section concludes.

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

$$P(Q) = a - bQ, \tag{1}$$

where $Q = \sum_{i=1}^{n} q^i$ and $a, b > 0$. The production technology exhibits constant returns to scale. In the absence of the new technology, the total variable costs are given by $c_0 q^i$ for firm i. Production also generates emissions of a homogenous pollutant from firm i. The emissions in the absence of the new technology, e_0^i, are proportional to output q^i and equal to $\varepsilon_0 q^i$.

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, that is, $\varepsilon_1 < \varepsilon_0$, and also changes the marginal cost of production from c_0 to c_1.[3] Firms must now decide when to adopt the new technology, taking into account the effect of the competitors' adoption on pre- and postadoption profit flows. Note that $c_0 + \sigma\varepsilon_0 > c_1 + \sigma\varepsilon_1$ by assumption to ensure that the rate of profit flow is higher with the new technology. Moreover, we assume that no future technical advance is anticipated.[4]

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

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[3] 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 and thereby reduces emissions which are highly correlated with fuel use (such as CO_2 and SO_2).

[4] If firms anticipate that a better technology will arrive at an uncertain date, they must consider suspending the current adoption process in light of the expectations of future technological improvements. The suspension of the current process provides the firm with an option to purchase the future technology when it becomes available. The value of the option to suspend must be equal to the expected net present value of the future technology. So, the profitability threshold required in order to adopt the current best technology increases, delaying the entire sequence of adoption. However, unless there is an interaction between refunding and the option value, the relative ranking of the policies in our analysis is unaffected.

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 further assume, in line with Reinganum (1981), that

(2i) $p_1(t)$ is a differentiable convex function with $p_1'(0) \leq \pi_0(0) - \pi_1(1)$,

(2ii) $\lim_{t \longrightarrow \infty} p_1'(t) > 0$, and

(2iii) $p_1''(t) > re^{-rt}(\pi_1(1) - \pi_0(0))$.

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 $V^i(\tau_1, \ldots, \tau_{i-1}, \tau_i, \tau_{i+1}, \ldots, \tau_n)$ 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, $k = 1, \ldots, n$. Given an ordering of adoption dates $\tau_1 \leq \tau_2 \leq \cdots \leq \tau_n$, we can write the present value of firm i's profits as

$$\begin{aligned} V^i&(\tau_1, \ldots, \tau_{i-1}, \tau_i, \tau_{i+1}, \ldots, \tau_n) \\ &= \sum_{m_1=0}^{i-1} \int_{\tau_{m_1}}^{\tau_{m_1+1}} \pi_0(m_1) e^{-rt} dt \\ &\quad + \sum_{m_1=i}^{n} \int_{\tau_{m_1}}^{\tau_{m_1+1}} \pi_1(m_1) e^{-rt} dt - p_1(\tau_i), \end{aligned} \tag{2}$$

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

Maximization of V^i given the sequence of adoption $\tau_1 \leq \tau_2 \leq \cdots \leq \tau_n$ (which as shown by Reinganum (1981) is a sub-game perfect equilibrium) gives each firm i an optimal date of adoption, τ_i^*, and is implicitly defined by

$$\frac{\partial V^i}{\partial \tau_i} = \left(\pi_0(i-1) - \pi_1(i)\right) e^{-r\tau_i^*} - p_1'(\tau_i^*) = 0. \tag{3}$$

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 Equation (3) can then be written

$$\frac{\partial V^i}{\partial \tau_i} = -\Delta\pi_i \mathrm{e}^{-r\tau_i^*} - p_1'(\tau_i^*) = 0, \tag{4}$$

$i = 1, \ldots, n$. Furthermore, V^i is strictly concave at τ_i^* for all i. Thus, despite firms being homogenous at the time when the new technology arrives, there are $n!$ sequences in which the adoption date defined by (3) is a Nash equilibrium. In the following sections, we characterize one of the $n!$ sequences of adoption, analyzing the impact of refunding on the optimal date of adoption.[5] That is, we analyze the difference in adoption profits $\Delta\pi_i$ between an emission tax and a refunded tax for which the revenues are returned to the aggregate of taxed firms in proportion to output. Because of the concavity of $V^i(\tau_i^*)$, a higher $\Delta\pi_i$ implies an earlier date of adoption τ_i^*. In what follows, we refer to "faster" diffusion under one policy as the situation where τ_i^* is lower than the optimal time to adoption under another policy for each adopter in the sequence.

Adoption Incentives Under an Emission Tax

Let $\zeta_0^T = c_0 + \sigma\varepsilon_0$ denote the cost per unit of output (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 the cost per unit of output

[5] Note that this paper focuses on technology diffusion and compares the timing of adoption for different policies and thereby differs from the theoretical literature on technology adoption which instead compares the number of adopters at a given point in time. While our results can be used to also make the latter comparison, our focus is explicitly on timing and the pattern of diffusion.

after adoption. Since these costs are constant they also correspond to the marginal costs of production. If we have m_1 adopters of the new technology and rank the firms according to their order in the adoption sequence, we can write the profit rate maximization problem for the adopters as

$$\pi^j = \max_{q^j} \left[P(Q) - \zeta_1^T \right] q^j, \tag{5}$$

for $1 \leq j \leq m_1$.

The problem of the $n - m_1$ nonadopters is analogous to problem (5); the main difference is that the per unit production cost is given by ζ_0^T instead of ζ_1^T.

$$\pi^j = \max_{q^j} \left[P(Q) - \zeta_0^T \right] q^j, \tag{6}$$

for $m_1 < j \leq n$.

The first-order conditions (FOCs) for the adopters and nonadopters, respectively, are:

$$P(Q) + P'(Q)q^j = \zeta_1^T \quad \forall\ 1 \leq j \leq m_1, \tag{7}$$

$$P(Q) + P'(Q)q^j = \zeta_0^T \quad \forall\, m_1 < j \leq n \tag{8}$$

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 nonadopters. This is to say, 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, nonadopters reduce their output to offset the effect of an increased supply on the market price.

Since the m_1 adopters are symmetric they will all have the same profit-maximizing level of production in equilibrium that we denote as q_1^T. Similarly, the level of production is the same for all $n - m_1$ nonadopters and we denote this profit-maximizing level q_0^T. Substituting $P(Q) = a - b[[n - m_1]q_0^T + m_1 q_1^T]$ in Equations (7) and (8), and solving for q_1^T and q_0^T yields:

$$q_1^T(m_1) = \frac{a - \zeta_1^T + [n - m_1]\left[\zeta_0^T - \zeta_1^T\right]}{b\,[n+1]}, \tag{9}$$

$$q_0^T(m_1) = \frac{a - \zeta_0^T - m_1\left[\zeta_0^T - \zeta_1^T\right]}{b\,[n+1]}, \tag{10}$$

for which $q_1^T(m_1) > q_0^T(m_1) > 0$.[6]

Finally, substituting the profit-maximizing levels of production into Equations (5) and (6) yields equilibrium profits for adopters and non-adopters, respectively,

$$\pi_1^T(m_1) = b\left[q_1^T(m_1)\right]^2, \tag{11}$$

$$\pi_0^T(m_1) = b\left[q_0^T(m_1)\right]^2. \tag{12}$$

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

$$\Delta\pi_i^T = b\left[\left[q_1^T(i)\right]^2 - \left[q_0^T(i-1)\right]^2\right]. \tag{13}$$

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

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

$$\pi^j = \max_{q^j}\left[\left[P(Q) - \zeta_1^T\right]q^j + \sigma E\frac{q^j}{Q}\right], \tag{14}$$

for $1 \leq j \leq m_1$, where E and Q correspond to aggregate emissions and output, respectively. The first term on the right-hand side (RHS) of Equation (14) corresponds to net revenues while the second term is the refund (which is the product of the total refunds σE times firm j's output share q^j/Q).

[6] We further assume that $q_0^T > 0$. From the equilibrium output level for technology 0 discussed later, it is clear that this assumption is satisfied for all $m_1 \leq n-1$ if $a - n[c_0 + \sigma\varepsilon_0] + [n-1][c_1 + \sigma\varepsilon_1] > 0$.

By analogy, the profit maximization problem of the $n - m_1$ nonadopters corresponds to

$$\pi^j = \max_{q^j} \left[\left[P(Q) - \zeta_0^T \right] q^j + \sigma E \frac{q^j}{Q} \right], \tag{15}$$

for $m_1 < j \leq n$.

Finally, the average emission intensity $\overline{\varepsilon}(m_1)$ corresponds to the ratio between aggregate emissions and aggregate output and is given by:

$$\overline{\varepsilon}(m_1) = \frac{E}{Q} = \frac{\sum_{i=1}^n e^i}{\sum_{i=1}^n q^i} = \frac{m_1 \varepsilon_1 q_1 + [n - m_1] \varepsilon_0 q_0}{m_1 q_1 + [n - m_1] q_0}. \tag{16}$$

This is to say, the average emission intensity is a weighted average of adopters' and nonadopters' emissions, where $\varepsilon_1 < \overline{\varepsilon} < \varepsilon_0$ for all m_1 for which $1 \leq m_1 < n$.

Exogenous Refunded Tax

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 FOCs for the adopters and nonadopters, respectively, are then

$$P(Q) + P'(Q)q^j = \zeta_1^T - \sigma\overline{\varepsilon}, \tag{17}$$

for $1 \leq j \leq m_1$,

$$P(Q) + P'(Q)q^j = \zeta_0^T - \sigma\overline{\varepsilon}, \tag{18}$$

for $m_1 < j \leq n$.

Thus both types of firms set marginal revenue equal to marginal costs inclusive of the emission tax minus the marginal refund. Note that the marginal refund is given by the emission tax rate times the average emission intensity and works as an implicit output subsidy. Thus, just

[7]Such a description is consistent with the case of the Swedish NO_x charge, where 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 and 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).

as under an emission tax, adopters produce more than nonadopters because of lower marginal cost. However, output will be higher for both adopters and nonadopters because the refund reduces the marginal cost of production of all firms by an amount equal to $\sigma\bar{\varepsilon}$.

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. Substituting $P(Q) = a - b[[n - m_1]q_0^X + m_1 q_1^X]$ in Equations (17) and (18), and solving for q_1^X and q_0^X yields:

$$q_1^X(m_1) = q_1^T(m_1) + \frac{\sigma\bar{\varepsilon}^X(m_1)}{b[n+1]}, \tag{19}$$

$$q_0^X(m_1) = q_0^T(m_1) + \frac{\sigma\bar{\varepsilon}^X(m_1)}{b[n+1]}, \tag{20}$$

where $\bar{\varepsilon}^X(m_1)$ corresponds to the average emissions intensity under exogenous refunding. Because the average emissions intensity decreases with the number of firms adopting the new technology, the difference in output with and without a refund decreases as m_1 increases.[8] Finally, substituting the profit-maximizing levels of production into Equations (14) and (15) yields equilibrium profits for adopters and non-adopters, respectively,

$$\pi_1^X(m_1) = b[q_1^X(m_1)]^2, \tag{21}$$

$$\pi_0^X(m_1) = b[q_0^X(m_1)]^2. \tag{22}$$

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.

$$\Delta\pi_i^X = b\left[\left[q_1^X(i)\right]^2 - \left[q_0^X(i-1)\right]^2\right]. \tag{23}$$

Given Equations (19) and (20), $\Delta\pi_i^X$ can be represented as

$$\Delta\pi_i^X = b\left[\left[q_1^T(i) + \frac{\sigma\bar{\varepsilon}^X(i)}{b\,[n+1]}\right]^2 - \left[q_0^T(i-1) + \frac{\sigma\bar{\varepsilon}^X(i-1)}{b\,[n+1]}\right]^2\right]. \tag{24}$$

[8]Let $s_1(m_1)$ 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.

Finally, we assume that each firm considers its own impact on the average emission intensity as negligible, implying that $\overline{\varepsilon}^X(i) = \overline{\varepsilon}^X(i-1)$, and hence, using (13), (24) simplifies to

$$\Delta\pi_i^X = \Delta\pi_i^T + \frac{2\sigma\overline{\varepsilon}^X(i)}{[n+1]}\left[q_1^T(i) - q_0^T(i-1)\right]. \tag{25}$$

Since $q_1^T(i) - q_0^T(i-1) = n[\zeta_0^T - \zeta_1^T]/b[n+1] > 0$, the difference in the increase in profit rate from adoption under a standard emission tax compared to an exogenous refunded tax is positive and given by

$$\Delta\pi_i^X - \Delta\pi_i^T = 2\frac{n\left[\zeta_0^T - \zeta_1^T\right]}{b\left[n+1\right]^2}\sigma\overline{\varepsilon}^X(i) > 0. \tag{26}$$

We now define τ_i^X to be the optimal time of adoption for adopter i under an exogenously refunded emission tax and τ_i^T the optimal time of adoption for adopter i under a nonrefunded emission tax. From (26), we see that for the same tax σ per unit of emissions $\Delta\pi_i^X > \Delta\pi_i^T$. Hence, we have from Equation (3) and the strict concavity of the present value function V that $\tau_i^X < \tau_i^T$.

Thus we can enunciate the following proposition

Proposition 1. *For the same tax per unit of emissions, a technology that reduces the emission intensity of production diffuses faster under an exogenously refunded than under a nonrefunded emission tax.*

As stated earlier, the refunding works as an implicit output subsidy that allows adopters to produce more compared to the nonrefunded emission tax. Hence, the intuition behind Proposition 1 is that for each adopter in the sequence, the refund creates further gains from adopting the technology compared to the nonrefunded emission tax by increasing the output of adopters. The larger gains from adopting in turn shift the optimal date of adoption forward in time. However, since the average emission intensity and the refund decreases as the technology diffuses into the industry, the increased profits of exogenous refunding over taxes therefore diminishes for the firms later in the adoption sequence. This is to say, in relative terms, the effects of refunding on the time of adoption are larger for the early adopters than for the late adopters.

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

$$P(Q) + P'(Q)q^j = \zeta_1^T - \sigma\bar{\varepsilon} - \sigma\left[\varepsilon_1 - \bar{\varepsilon}\right]\frac{q^j}{Q}, \tag{27}$$

for $1 \leq j \leq m_1$, and for nonadopters

$$P(Q) + P'(Q)q^j = \zeta_0^T - \sigma\bar{\varepsilon} - \sigma\left[\varepsilon_0 - \bar{\varepsilon}\right]\frac{q^j}{Q}, \tag{28}$$

for $m_1 < j \leq n$.

Since $\varepsilon_1 < \bar{\varepsilon} < \varepsilon_0$ for $1 \leq m_1 < n$, it holds that $[\varepsilon_1 - \bar{\varepsilon}] < 0$ and $[\varepsilon_0 - \bar{\varepsilon}] > 0$. Thus, with regards to the case of exogenous refunding, adopters' marginal costs in Equation (27) are augmented. In contrast, from Equation (28) we can see that nonadopters' marginal costs are reduced under endogenous refunding. Hence, the implicit output subsidy is higher for nonadopters than for adopters. Moreover, the implicit output subsidy decreases (increases) with increased output and market share in the case of adopters (nonadopters). Therefore, more production is shifted toward nonadopters under endogenous refunding compared to exogenous refunding since in relative terms they receive a larger subsidy for their output. The shift in production also has an effect on aggregate emissions and on the magnitude of the refund; aggregate emissions and total tax revenues to be refunded is larger under endogenous refunding.

Let q_1^D and q_0^D be the profit-maximizing level of production for adopters and nonadopters, respectively. Moreover, let Q^D and $\bar{\varepsilon}^D$ be aggregate output and average emission intensity under endogenous refunding. Substituting $P(Q) = a - b[[n - m_1]q_0^D + m_1 q_1^D]$ in Equations (27) and (28), and solving for q_1^D and q_0^D yields:

$$q_1^D(m_1) = \frac{[1 - \frac{\sigma}{bQ^D}[\varepsilon_0 - \overline{\varepsilon}^D]][a - \zeta_1^T + \sigma\overline{\varepsilon}^D] + [n - m_1][\zeta_0^T - \zeta_1^T]}{\phi}, \tag{29}$$

$$q_0^D(m_1) = \frac{[1 - \frac{\sigma}{bQ^D}[\varepsilon_1 - \overline{\varepsilon}^D]][a - \zeta_0^T + \sigma\overline{\varepsilon}^D] - m_1[\zeta_0^T - \zeta_1^T]}{\phi}, \tag{30}$$

where $\phi > 0$ and is given by

$$\begin{aligned}\phi &= b[n+1] + \frac{1}{b}\left[\frac{\sigma}{Q^D}\right]^2 \left[\varepsilon_1 - \overline{\varepsilon}^D\right]\left[\varepsilon_0 - \overline{\varepsilon}^D\right] \\ &\quad - \frac{\sigma}{Q^D}\left[\left[\varepsilon_1 - \overline{\varepsilon}^D\right][n - m_1 + 1] + \left[\varepsilon_0 - \overline{\varepsilon}^D\right][m_1 + 1]\right].\end{aligned} \tag{31}$$

Finally, substituting the profit-maximizing levels of production into Equations (14) and (15) yields equilibrium profits for adopters and nonadopters, respectively,

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

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

The increase in profit rate due to adoption for the firm which is the ith to adopt is then given by

$$\begin{aligned}\Delta\pi_i^D &= b[[q_1^D(i)]^2 - [q_0^D(i-1)]^2] \\ &\quad + \sigma\left[\frac{[\varepsilon_0 - \overline{\varepsilon}^D(i-1)]}{Q^D(i-1)}[q_0^D(i-1)]^2 + \frac{[\overline{\varepsilon}^D(i) - \varepsilon_1]}{Q^D(i)}[q_1^D(i)]^2\right].\end{aligned} \tag{32}$$

Comparing an Endogenous Refunded Tax to an Exogenous Refunded Tax

Let us compare adoption incentives between exogenous and endogenous refunding:

$$\begin{aligned}\Delta\pi_i^X - \Delta\pi_i^D = {} & b[[q_1^X(i)]^2 - [q_1^D(i)]^2] \\ & + b[[q_0^D(i-1)]^2 - [q_0^X(i-1)]^2] \\ & - \sigma\left[\frac{[\varepsilon_0 - \overline{\varepsilon}^D(i-1)]}{Q^D(i-1)}[q_0^D(i-1)]^2\right] \\ & - \sigma\left[\frac{[\overline{\varepsilon}^D(i) - \varepsilon_1]}{Q^D(i)}[q_1^D(i)]^2\right]. \end{aligned} \tag{33}$$

The first two terms on the RHS of Equation (33) is positive. The first accounts for the larger level of production by adopters under exogenous refunding. As stated earlier, production is shifted toward nonadopters under endogenous refunding making the second term positive. Consequently, this production shifting, or "output effect," lowers the benefit of adoption under endogenous versus exogenous refunding. The third and fourth terms on the RHS of Equation (33) are negative. Because production is shifted toward nonadopters, the average emission intensity is larger under endogenous refunding, and so is the refund. This "refunding effect" increases the benefits of adoption under endogenous versus exogenous refunding.

The sign of Equation (33), which depends on the relative magnitudes of the output and the refund effect, cannot be easily determined since output levels and emission intensities are endogenous. Nevertheless, to be able to say something about the relative magnitude of the output and refund effect, we follow the approach in Fisher (2011) and compare adoption incentives between exogenous and engogenous refunding for an equivalent average emission intensity. That is, we compare adoption profits under exogenous versus endogenous refunding for the firms which are the first and last to adopt because the average emission intensity is the same under exogenous and endogenous refunding when no firms have adopted and when all firms have adopted. For comparison of profits for the cases where emission intensities are not the same under the two refunding schemes, see Appendix B.

From the equilibrium conditions in Equations (17) and (18), and (27) and (28), it can be shown that:

$$Q^D(m_1) - Q^X(m_1) = \frac{n\sigma}{b\,[n+1]}\left[\bar{\varepsilon}^D(m_1) - \bar{\varepsilon}^X(m_1)\right], \tag{34}$$

that is, 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 (see Appendix B for details). Thus, comparing the FOCs that define the profit-maximizing level of production for adopters and nonadopters under exogenous and endogenous refunding (i.e., Equations (17) vs (27) for adopters and (18) vs (28) for nonadopters), we can say that, for equivalent average emission intensity, $q_1^X > q_1^D \; \forall\, m_1 < n$ and $q_0^X < q_0^D \; \forall\, m_1 \geq 1$. Hence, as discussed earlier, more production is shifted toward nonadopters under endogenous refunding compared to exogenous refunding. 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, this yields

$$\Delta\pi_1^X - \Delta\pi_1^D > 0,$$
$$\Delta\pi_n^X - \Delta\pi_n^D > 0,$$

implying that the output effect is larger than the refunding effect and adoption profits under exogenous refunding are larger than those under endogenous refunding.

Proposition 2. *For the same tax per unit of emissions, a technology that reduces the emission intensity of production diffuses faster under an exogenously refunded than under an endogenously refunded emission tax.*

Because the output effect dominates, a technology that reduces the emission intensity of production tends to diffuse faster under an exogenously refunded than under an endogenously refunded emission tax. The intuition behind this result is that, relative to exogenous refunding, endogenous refunding creates an incentive for adopters to produce less and the nonadopters to produce more because the implicit output subsidy is higher for nonadopters. This output effect in turn reduces the gains from adoption compared to exogenous refunding. Smaller gains from adopting shifts the optimal date of adoption to a later date because the benefits of waiting in terms of decreases in adoption costs also decrease over time.

Comparing an Endogenous Refunded Tax to a Nonrefunded Emission Tax

Next, we compare the adoption incentives under a nonrefunded emission tax and an endogenous refunded tax:

$$\begin{aligned}\Delta\pi_i^T - \Delta\pi_i^D = {} & b[[q_1^T(i)]^2 - [q_0^T(i-1)]^2] \\ & - b[[q_1^D(i)]^2 - [q_0^D(i-1)]^2] \\ & - \sigma\left[\frac{[\varepsilon_0 - \bar{\varepsilon}^D(i-1)]}{Q^D(i-1)}[q_0^D(i-1)]^2\right] \\ & - \sigma\left[\frac{[\bar{\varepsilon}^D(i) - \varepsilon_1]}{Q^D(i)}[q_1^D(i)]^2\right]. \end{aligned} \quad (35)$$

Note first that — as discussed earlier — endogenous refunding provides adopters and nonadopters with an implicit output subsidy. Hence, not surprisingly it is easy to show that $q_1^T < q_1^D \ \forall m_1 < n$ and $q_0^T < q_0^D \ \forall m_1 \geq 1$. This is to say, output by adopters and nonadopters under an endogenous refunded tax is larger than output under a nonrefunded tax. However, $q_1^T(i) - q_0^T(i-1) > q_1^D(i) - q_0^D(i-1) \ \forall i$, implying that adoption leads to a larger increase in output under a nonrefunded emission tax than under an endogenous refunded tax (see Appendix C for details). The difference in profit increase for a nonrefunded tax versus endogenous refunding is, just as in the preceding section, given by the sum of the output and refunding effect. Similar to the previous section, the output effect is positive and accounts for the larger level of production by adopters under a nonrefunded tax. In contrast, the refunding effect is negative and accounts for the fact that the refund increases the benefits of adoption under an endogenous refunded compared to a nonrefunded tax.

Note also that since adopters' and non-adopters' output levels under a nonrefunded tax are lower than under exogenous refunding, the magnitude of the output effect is smaller when comparing endogenous refunding to a nonrefunded tax rather than to exogenous refunding as in the previous section. Hence, while exogenous refunding induces faster diffusion than endogenous refunding, an emission tax is less likely to induce faster diffusion than endogenous refunding due to the smaller output effect.[9] For instance, we can analyze the difference in adoption profits for the firms which are the first and last to adopt. As shown in Appendix C, a sufficient condition for $\Delta\pi_1^T - \Delta\pi_1^D > 0$ is:

$$\varepsilon_0 \frac{q_0^T(0) + q_0^D(0)}{q_1^T(1) + q_1^D(1)} > \overline{\varepsilon}^D(1). \tag{36}$$

Note that if the industry is concentrated (i.e., the number of firms is small), the firms have greater opportunity to influence the average (endogenous) emission intensity $\overline{\varepsilon}^D$, making the gains from adoption smaller under an endogenous refunded tax compared to a nonrefunded emission tax.

As also shown in Appendix C, a sufficient condition for $\Delta\pi_n^T - \Delta\pi_n^D > 0$ is:

$$\overline{\varepsilon}^D(n-1) \frac{q_0^T(n-1) + q_0^D(n-1)}{q_1^T(n) + q_1^D(n)} \geq \overline{\varepsilon}^D(n). \tag{37}$$

These observations lead to the following proposition.

Proposition 3. *For the same tax per unit of emissions, a technology that reduces the emission intensity of production diffuses more slowly under an endogenously refunded versus a non-refunded emission tax, the more concentrated the industry is.*

The intuition behind this result is that relative to an emission tax, refunding provides an enhanced incentive for adoption because it increases the value of the additional output of the clean firms. However, with endogenous refunding, there is a counteracting effect since the implicit subsidy makes nonadopters produce more and adopters less because this increases the size of the refund. If the number of firms is small (i.e., the market shares large), the firms have greater opportunity to influence the size of the refund so that the latter distorting effect of the endogenous refund dominates and makes the gains from adoption smaller under an endogenous refunded tax compared to a nonrefunded emission tax. If the number of firms is larger, the firms have less influence and the distorting effect of the endogenous refund becomes

[9] Indeed, note that $\Delta\pi_i^T - \Delta\pi_i^D = \Delta\pi_i^X - \Delta\pi_i^D - [2[(n[\zeta_0^T - \zeta_1^T])/(b[n+1]^2)]]\sigma\overline{\varepsilon}^X(i)$. This is to say, $\Delta\pi_i^T - \Delta\pi_i^D < \Delta\pi_i^X - \Delta\pi_i^D$.

smaller. Instead the effect of the refund as an output subsidy becomes dominating and makes it more likely that gains from adoption are larger under an endogenous refunded tax than under a nonrefunded emission tax — in line with the results for an exogenous refunded tax. A numerical example in Appendix E supports this point.

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 (hereinafter G_2), unexpectedly arrives at some time t_2 after k^T and k^X firms would have already adopted technology 1 (hereinafter G_1) under an emission tax and an exogenous refunded tax, respectively. As shown in the previous sections, $k^X \geq k^T$ since the exogenous refund induces a faster adoption than the emission tax.

We study the difference in adoption incentives for the new technology provided by these instruments for three groups:

(1) the *laggards* — those $n - k^X$ firms that would not have adopted G_1 by t_2 neither under the emission tax nor under the refunded tax,

(2) the *intermediates* — those $k^X - k^T$ firms that would have adopted G_1 by t_2 under the refunded tax, but would not have adopted under an emission tax, and finally,

(3) the *early adopters* — those k^T firms that would have adopted G_1 by t_2 under both policies.

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.

G_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 G_1 and m_2 be the number of adopters of G_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 G_1, m_2 firms have adopted G_2, and firm j is among the adopters of G_2. We define $\pi_1(m_1, m_2)$ and $\pi_0(m_1, m_2)$ accordingly. The firm which has not adopted G_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 G_2 at t, is not larger than the cost of investing in G_1 at t, that is, $p_2(t) \leq p_1(t)e^{rt_2}$ for $t \geq t_2$.[10] This implies that it will never be profitable to adopt G_1 once G_2 has appeared.

The lower marginal costs imply higher profit rates with G_2 compared to both G_1 and G_0. To ensure that the increase in profit rates from adoption of G_2 would be higher for a firm which produces with G_0 than for a firm which has already adopted G_1 the following conditions apply:

$$\pi_2(m_1, m_2) > \pi_1(m_1, m_2) > \pi_0(m_1, m_2), \tag{38}$$

$$\pi_2(m_1, m_2 + 1) - \pi_0(m_1, m_2) > \pi_2(m_1 - 1, m_2 + 1) - \pi_1(m_1, m_2), \tag{39}$$

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 $p_2''(t) > re^{-rt}(\pi_2(k, 1) - \pi_0(k, 0))$. 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 G_2 for the three groups of firms from first-order conditions similar to (3). The $n-k$ firms which produce with G_0 at t_2 will first find it profitable to adopt G_2 at τ_j^*, implicitly defined by

$$-\Delta\pi_{02,j}\, e^{-r[\tau_j^* - t_2]} - p_2'(\tau_j^*) = 0, \tag{40}$$

[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.

for $1 \leq j \leq n-k$, and the k firms which produce with G_1 at t_2 will adopt G_2 at τ_j^*, implicitly defined by

$$-\Delta\pi_{12,j}\, e^{-r[\tau_j^* - t_2]} - p_2'(\tau_j^*) = 0, \tag{41}$$

for $n-k+1 \leq j \leq n$.

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. In line with section “adoption incentives under an emission tax”, the FOC determining the optimal choice of output of adopters of technology 2 under emission taxes corresponds to:

$$P(Q) + P'(Q)q^j = \zeta_2^T, \quad \forall\ 1 \leq j \leq m_2 \tag{42}$$

We define the profit-maximizing level of production for adopters of G_2 to be $q_2^T(m_1, m_2)$. Substituting $P(Q) = a - b[[n - m_1 - m_2]q_0^T + m_1 q_1^T + m_2 q_2^T]$ into Equations (7), (8), and (42), and solving for $q_0^T(m_1, m_2)$, $q_1^T(m_1, m_2)$, and $q_2^T(m_1, m_2)$ yields[11]:

$$q_0^T(m_1, m_2) = \frac{a - \zeta_0^T - m_1[\zeta_0^T - \zeta_1^T]m_2[\zeta_0^T - \zeta_2^T]}{b[n+1]}, \tag{43}$$

$$q_1^T(m_1, m_2) = q_0^T(m_1, m_2) + \frac{[\zeta_0^T - \zeta_1^T]}{b}, \tag{44}$$

$$q_2^T(m_1, m_2) = q_1^T(m_1, m_2) + \frac{[\zeta_1^T - \zeta_2^T]}{b}, \tag{45}$$

where $q_2^T(m_1, m_2) > q_1^T(m_1, m_2) > q_0^T(m_1, m_2)$. This is to say, continuous technological upgrading allows firms to increase their output. Substituting the profit-maximizing levels of production in the maximization problem for adopters and nonadopters yields profits,

$$\pi_s^T(m_1, m_2) = b\left[q_s^T(m_1, m_2)\right]^2, \quad \forall\, s = 0, 1, 2. \tag{46}$$

By analogy, for the exogenously refunded tax, the FOC determining the optimal choice of output of adopters of G_2 corresponds to:

$$P(Q) + P'(Q)q^j = \zeta_2^T - \sigma\bar{\varepsilon}, \quad \forall\, 1 \leq j \leq m_2. \tag{47}$$

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

The equilibrium output corresponding to the case with two technologies are

$$q_s^X(m_1, m_2) = q_s^T(m_1, m_2) + \frac{\sigma \bar{\varepsilon}^X(m_1, m_2)}{b\,[n+1]}, \quad \forall\, s = 0, 1, 2. \tag{48}$$

and profits,

$$\pi_s^X(m_1, m_2) = b\left[q_s^X(m_1, m_2)\right]^2 = b\left[q_s^T(m_1, m_2) + \frac{\sigma \bar{\varepsilon}^X(m_1, m_2)}{b\,[n+1]}\right]^2, \quad \forall\, s = 0, 1, 2, \tag{49}$$

where $\bar{\varepsilon}^X(m_1, m_2)$ is the emission intensity with m_1 adopters of G_1 and m_2 adopters of G_2.

Let us now analyze the incentives for continuous technological upgrading under emission taxes versus exogenous refunding for all three groups of firms separately.

Laggards

Let us first analyze the difference in the increase in profit rate from adoption of G_2 with and without refunding for the *laggards* which at time t_2 still produce with G_0. The difference in the profit rate increase from adoption of G_2 under the exogenous refunded tax compared to the emission tax can be represented as:

$$\begin{aligned}\Delta\pi_{02,j}^X - \Delta\pi_{02,j}^T = {} & [\pi_2^X(k^X, j) - \pi_2^T(k^T, j)] \\ & - [\pi_0^X(k^X, j-1) - \pi_0^T(k^T, j-1)],\end{aligned} \tag{50}$$

for $1 \leq j \leq n - k^X$.

Note that the sign of Equation (50) is ambiguous. On the one hand, the profits from adoption are always larger under refunded emission taxes than under nonrefunded taxes (and hence, both the first and the second term in brackets on the RHS of Equation (50) are positive). On the other hand, if more firms have already adopted G_1 under refunded taxes, the average emission intensity $\bar{\varepsilon}^X(k^X, m_2)$ is lower than $\bar{\varepsilon}^X(k^T, m_2)$; this implies a lower implicit output subsidy and that the second term in brackets on the RHS of Equation (50) can be larger than the first. Substituting the expressions for profits in Equations (46) and (49), Equation (50) can after some simplifications be represented as[12]:

$$\Delta\pi^X_{02,j} - \Delta\pi^T_{02,j} = 2\frac{n[\zeta^T_0 - \zeta^T_2]}{b[n+1]^2}[\sigma\bar{\varepsilon}^X(k^X, j) - [k^X - k^T][\zeta^T_0 - \zeta^T_1]], \quad (51)$$

where $0 \leq [k^X - k^T] < n$. Hence, it is clear that $\Delta\pi^X_{02,j} - \Delta\pi^T_{02,j} > 0$ if $k^X = k^T$, and that analogous to the result with two technologies, laggards would adopt G_2 earlier under the refunded tax than under a nonrefunded tax. Hence, we can state the following proposition

Proposition 4. *The exogenously refunded tax provides larger incentives than a nonrefunded emission tax for continuous technological upgrading of firms that are dirtier than average provided the initial composition of dirty and clean firms is the same under both policies.*

However, (50) can be negative when $k^X > k^T$. In particular, let us assume that $k^X - k^T = n - 1$, and hence, $\bar{\varepsilon}^X(k^X, j) \simeq \varepsilon_1$. Substituting this expression into Equation (51) we can show that $\Delta\pi^X_{02,j} - \Delta\pi^T_{02,j} < 0$ implying that the laggards would adopt earlier under an emission tax than under the refunded tax.[13]

Hence, whether or not refunding provides incentives for laggards to "catch up" depends critically on the stock of firms that have adopted G_1 under both policies when G_2 arrives. From Equation (51) we can see that if $k^X - k^T > [\sigma\bar{\varepsilon}^X(k^X, j)]/[\zeta^T_0 - \zeta^T_1]$ there will be no "catching up."

Intermediates

Let us now examine the difference in profits for the *intermediates*, which only exist if the number of firms which would have adopted G_1 by t_2 is lower under the emission tax than under the exogenous refunding, that is, $k^T < k^X$. The jth adopter, for which $j \in [n - k^X + 1, n - k^T]$, would switch from G_0 under an emission tax, and from G_1 under a refunded tax. Therefore, the difference between adoption incentives between exogenous refunding compared to the emission tax can be

[12] Recall that under exogenous refunding $\bar{\varepsilon}^X(k^X, j) = \bar{\varepsilon}^X(k^X, j-1)$.

[13] Note that $\zeta^T_0 > \zeta^T_1 > \sigma\bar{\varepsilon}^X$ to ensure that the costs of production are positive. Moreover, $\bar{\varepsilon}^X(k^X, j) \simeq \varepsilon_1$. Hence, $\zeta^T_0 - \zeta^T_1 > 0 > \sigma\varepsilon_1 - \zeta^T_1$. Finally, $\sigma\varepsilon_1 < [n-1][\zeta^T_0 - \zeta^T_1]$ since $\zeta^T_0 + [\sigma\varepsilon_1 - \zeta^T_1] < n[\zeta^T_0 - \zeta^T_1]$ when $[n-1]\zeta^T_0 - n\zeta^T_1 > 0$.

represented as:

$$\Delta\pi^X_{12,j} - \Delta\pi^T_{02,j} = [\pi^X_2(n-j,j) - \pi^X_1(n-j+1,j-1)] \\ - [\pi^T_2(k^T,j) - \pi^T_0(k^T,j-1)]. \tag{52}$$

Like in the previous case, note that the sign of Equation (52) is ambiguous. Since the stock of firms that has adopted the new technology is different under each policy, it is difficult to determine the sign of the terms in brackets on the RHS of Equation (52). Therefore, as in the case of the laggards, the intermediates would adopt either earlier or later under exogenous refunding compared to a nonrefunded emission tax. However, it is possible to show that $\Delta\pi^X_{12,j} - \Delta\pi^T_{02,j} < \Delta\pi^X_{02,j} - \Delta\pi^T_{02,j}$ (see Appendix D). This is to say, the difference between adoption incentives between exogenous refunding compared to the emission tax is lower for intermediates than for laggards. Moreover, it is clear that if laggards adopt earlier under nonrefunded emission taxes, the intermediates will do so too.

Early Adopters

Finally, let us analyze the incentives to adopt G_2 under the emission tax and the refunded tax for those firms that would have adopted G_1 by t_2 under both policies, that is, the *early adopters*. When the first of the firms with G_1 invests in G_2, there is no longer any firm using G_0. This means that there are again only two production technologies in the market and that results are comparable to the ones in the "Exogenous Refunded Tax" section. The difference in profit rate increase is given by:

$$\Delta\pi^X_{12,j} - \Delta\pi^T_{12,j} = [\pi^X_2(n-j,j) - \pi^T_2(n-j,j)] \\ - [\pi^X_1(n-j+1,j-1) - \pi^T_1(n-j+1,j-1)], \tag{53}$$

for $n - k^T + 1 \leq j \leq n$.

Substituting the expressions for profits in Equations (46) and (49) and after some simplifications, Equation (53) can be represented as[14]:

$$\Delta\pi^X_{12,j} - \Delta\pi^T_{12,j} = \frac{2n[\zeta^T_1 - \zeta^T_2]}{b[n+1]^2}\sigma\bar{\varepsilon}^X(n-j,j) > 0. \tag{54}$$

[14]Recall that under exogenous refunding $\bar{\varepsilon}^X(n-j,j) = \bar{\varepsilon}^X(n-j+1,j-1)$.

Hence, analogous to the case with two technologies, early adopters invests earlier under the refunded tax than under a standard emission tax. This is to say, compared to an emission tax, exogenous refunding provides larger incentives for continuous technological upgrading for early adopters.

This finding can be summarized in the following proposition.

Proposition 5. *An exogenously refunded tax provides larger incentives than a nonrefunded emission tax for continuous technological upgrading for firms that are cleaner than average and have adopted emissions reducing technologies in the past.*

In sum, our results indicate that the incentives for continuous technological upgrading under refunding 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*) and for the *intermediates* (those firms that would have already adopted cleaner technologies under the refunded tax but would not have adopted under an emission tax). 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.

Conclusions

This paper studies technological diffusion under refunded emission taxes. The main conclusion is that refunding speeds up diffusion in an imperfectly competitive industry relative to a nonrefunded emission tax if firms do not strategically influence the size of the refund. In such a setting, adoption provides firms with a competitive advantage as it allows them to increase output, market share and total profits. In contrast, if firms do influence the size of the refund (because they realize that the adoption of a technology that reduces emissions also reduces the magnitude of the refund that is returned to firms), diffusion can be either faster or slower than under a nonrefunded emission tax. The more concentrated the industry is the more likely it is that refunding will distort adoption incentives so that diffusion is slower than under a nonrefunded tax. In any case, the difference between refunded and nonrefunded taxes becomes smaller as the number of firms increases and the equilibrium comes closer to the outcome under perfect competition. It also becomes smaller as new technologies appear. In particular, we have shown that it is unclear whether the "catching up" effect of refunded taxes — understood as an increased incentive for firms dirtier than average to adopt new technologies — is larger than the one under nonrefunded emission taxes. This is because refunding induces faster diffusion of existing technologies than nonrefunded taxes, which leads to a lower average emission intensity and thus to a lower refund and lower profit gains from adopting technologies that reduce emissions even further.

Though a welfare analysis is beyond the scope of this paper, it is straighforward to see that the policies will lead to different levels of welfare because of the different patterns of adoption. Faster diffusion of the cost-reducing technology not only raises consumer surplus and lowers environmental damages in present value terms for the whole diffusion period but also raises total investment costs. Which effect dominates is an empirical question which will also depend on the magnitude of the discount rate as well as on the steepness of the environmental damage function. Welfare effects will also be different under the policies because, even with the same number of adopters at a certain point in time, equilibrium output and aggregate emissions differ. The empirical evaluation of the welfare effects of refunding is left as an area for further research. Additional aspects to consider are the effects of learning on investment costs and the existence of externalities preventing R&D activities which generate further innovation.

Finally, our analysis focuses on the incentives for 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.* (2015) for a study of the incentives provided by that type of scheme.

As discussed in the introductory section, refunding makes emission taxes more politically feasible while in the absence of refunding it might not be possible to implement a tax at all. The fact that the rate of technology adoption is influenced by refunding is potentially good news for a regulator, who has political constraints on the level of the tax to be imposed on an imperfectly — but not too concentrated — competitive industry and wants to promote faster uptake of existing abatement technologies as a way to speed up the pace of emission reductions. Nevertheless, our results also indicate that refunding is not a panacea, and it might lead to unintended effects if, in the search for maximizing their refund, firms delay adoption of environmentally friendly technologies and there is a relative shift in production toward unclean firms. In particular, our paper has shown that the effects of refunding on technology diffusion critically depends on the regulated industry's prior technological composition and its market structure.

Appendix A. Demonstration of Nash Equilibrium

For the demonstration of the existence of a Nash equilibrium under assumptions (1i), (1ii), (2i), (2ii), and (2iii), we refer to Reinganum (1981). For the existence of a Nash equilibrium under our specific assumptions in this paper, however, we also need to demonstrate that assumption (1ii) holds under the different policies.

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 $\rho = 1/[b[n+1]^2]$. Then,

$$\pi_1(m_1 - 1) = \rho[a - [n - m_1 + 2]\zeta_1^T + [n - m_1 + 1]\zeta_0^T]^2, \quad \text{(A1)}$$

$$\pi_0(m_1 - 2) = \rho[a + [m_1 - 2]\zeta_1^T - [m_1 - 1]\zeta_0^T]^2, \quad \text{(A2)}$$

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

$$\begin{aligned}\Delta\pi_{m_1-1}^T &= n^2\rho[\zeta_1^T + \zeta_0^T][\zeta_1^T + \zeta_0^T] \\ &\quad - 2n\rho[\zeta_1^T + \zeta_0^T][a + [m_1 - 2]\zeta_1^T + [m_1 - 1]\zeta_0^T]. \quad \text{(A3)}\end{aligned}$$

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

$$\begin{aligned}\Delta\pi_{m_1}^T &= n^2\rho[\zeta_1^T + \zeta_0^T][\zeta_1^T + \zeta_0^T] \\ &\quad - 2n\rho[\zeta_1^T + \zeta_0^T][a + [m_1 - 1]\zeta_1^T + m_1\zeta_0^T]. \quad \text{(A4)}\end{aligned}$$

and hence:

$$\Delta\pi_{m_1-1}^T - \Delta\pi_{m_1}^T = 2n\rho[\zeta_1^T + \zeta_0^T]^2 > 0 \quad \forall\, m_1 \geq 2. \quad \text{(A5)}$$

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

Exogenous Refunded Tax

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

$$\begin{aligned}\Delta\pi^X_{m_1-1} - \Delta\pi^X_{m_1} &= \Delta\pi^T_{m_1-1} - \Delta\pi^T_{m_1} \\ &\quad + \frac{2\sigma\overline{\varepsilon}^X(m_1)}{b[n+1]}[q^T_1(m_1-1) - q^T_0(m_1-2)] \\ &\quad - \frac{2\sigma\overline{\varepsilon}^X(m_1)}{b[n+1]}[q^T_1(m_1) - q^T_0(m_1-1)]. \qquad \text{(A6)}\end{aligned}$$

Since $q^T_1(m_1) - q^T_0(m_1 - 1) = [n[\zeta^T_1 - \zeta^T_0]]/[b[n+1]]$, Equation (A6) simplifies to:

$$\Delta\pi^X_{m_1-1} - \Delta\pi^X_{m_1} = 2n\rho[\zeta^T_1 + \zeta^T_0]^2 > 0 \quad \forall\, m_1 \geq 2. \qquad \text{(A7)}$$

Endogenous Refunded Tax

$$\begin{aligned}&\Delta\pi^D_{m_1-1} - \Delta\pi^D_{m_1} \\ &\quad = b\left[1 - \frac{\sigma}{bQ^D(m_1-1)}\left[\varepsilon_1 - \overline{\varepsilon}^D(m_1-1)\right]\right][q^D_1(m_1-1)]^2 \\ &\qquad - b\left[1 - \frac{\sigma}{bQ^D(m_1-2)}\left[\varepsilon_0 - \overline{\varepsilon}^D(m_1-2)\right]\right]\left[q^D_0(m_1-2)\right]^2 \\ &\qquad - b\left[1 - \frac{\sigma}{bQ^D(m_1)}\left[\varepsilon_1 - \overline{\varepsilon}^D(m_1)\right]\right]\left[q^D_1(m_1)\right]^2 \\ &\qquad + b\left[1 - \frac{\sigma}{bQ^D(m_1-1)}\left[\varepsilon_0 - \overline{\varepsilon}^D(m_1-1)\right]\right][q^D_0(m_1-1)]^2. \qquad \text{(A8)}\end{aligned}$$

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

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

$$
\begin{aligned}
&- b\left[1 + \frac{\sigma\delta[n - m_1]s_0^D(m_1)}{bQ^D(m_1)}\right][q_1^D(m_1)]^2 \\
&+ b\left[1 - \frac{\sigma\delta[m_1 - 1]s_1^D(m_1 - 1)}{bQ^D(m_1 - 1)}\right][q_0^D(m_1 - 1)]^2.
\end{aligned} \tag{A9}
$$

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

$$
\begin{aligned}
& b[[q_1^D(m_1 - 1)]^2 - [q_1^D(m_1)]^2] \\
&\quad + \sigma\delta[n - m_1]s_0^D(m_1 - 1)s_1^D(m_1 - 1)q_1^D(m_1 - 1) \\
&\quad - \sigma\delta[n - m_1]s_0^D(m_1)s_1^D(m_1)q_1^D(m_1) \\
&\quad + \sigma\delta s_0^D(m_1 - 1)s_1^D(m_1 - 1)q_1^D(m_1 - 1) \\
&> b[[q_0^D(m_1 - 2)]^2 - [q_0^D(m_1 - 1)]^2] \\
&\quad + \sigma\delta[m_1 - 1]s_0^D(m_1 - 1)s_1^D(m_1 - 1)q_0^D(m_1 - 1) \\
&\quad - \sigma\delta[m_1 - 1]s_0^D(m_1 - 2)s_1^D(m_1 - 2)q_0^D(m_1 - 2) \\
&\quad + \sigma\delta s_0^D(m_1 - 2)s_1^D(m_1 - 2)q_0^D(m_1 - 2).
\end{aligned} \tag{A10}
$$

We have that

$$
s_0^D(m_1 - 1)s_1^D(m_1 - 1)q_j^D(m_1 - 1) \simeq s_0^D(m_1)s_1^D(m_1)q_j^D(m_1), \tag{A11}
$$

$\forall\, m_1 \neq 1, n$ & $j \in \{0, 1\}$[15] and thus this expression simplifies to:

$$
\begin{aligned}
& b[[q_1^D(m_1 - 1)]^2 - [q_0^D(m_1 - 2)]^2] \\
&\quad + \sigma\delta s_0^D(m_1 - 1)s_1^D(m_1 - 1)q_1^D(m_1 - 1) \\
&> b[[q_1^D(m_1)]^2 - [q_0^D(m_1 - 1)]^2] \\
&\quad + \sigma\delta s_0^D(m_1 - 2)s_1^D(m_1 - 2)q_0^D(m_1 - 2).
\end{aligned} \tag{A12}
$$

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

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

Appendix B. Comparison of Endogenous and Exogenous Refunding

Rewriting the equilibrium conditions (27) for the m_1 adopters as

$$a - bQ^D(m_1) - bq_1^D(m_1) = c_1 + \sigma[\varepsilon_1 - \overline{\varepsilon}^D(m_1)]\left[1 - \frac{q_1^D(m_1)}{Q^D}\right], \quad \text{(B1)}$$

and (28) for the $n - m_1$ adopters as

$$a - bQ^D(m_1) - bq_0^D(m_1) = c_0 + \sigma[\varepsilon_0 - \overline{\varepsilon}^D(m_1)]\left[1 - \frac{q_0^D(m_1)}{Q^D}\right], \quad \text{(B2)}$$

we can sum over all n conditions to get

$$\begin{aligned} &m_1[a - bQ^D(m_1) - bq_1^D(m_1)] + [n - m_1][a - bQ^D(m_1) - bq_0^D(m_1)] \\ &= m_1\left[c_1 + \sigma[\varepsilon_1 - \overline{\varepsilon}^D(m_1)]\left[1 - \frac{q_1^D(m_1)}{Q^D}\right]\right] \\ &\quad + [n - m_1]\left[c_0 + \sigma[\varepsilon_0 - \overline{\varepsilon}^D(m_1)]\left[1 - \frac{q_0^D(m_1)}{Q^D}\right]\right]. \end{aligned} \quad \text{(B3)}$$

This simplifies to

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

yielding

$$Q^D(m_1) = \frac{na - m_1\zeta_1^T - [n - m_1]\zeta_0^T + n\sigma\overline{\varepsilon}^D(m_1)}{b[n+1]}. \quad \text{(B4)}$$

Similarly, using the n equilibrium conditions in (17) and (18), we get

$$Q^X(m_1) = \frac{na - m_1\zeta_1^T - [n - m_1]\zeta_0^T + n\sigma\overline{\varepsilon}^X(m_1)}{b[n+1]}. \quad \text{(B5)}$$

Hence,

$$Q^D(m_1) - Q^X(m_1) = \frac{n\sigma[\overline{\varepsilon}^D(m_1) - \overline{\varepsilon}^X(m_1)]}{b[n+1]}, \quad \text{(B6)}$$

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

$$a - bQ^k - bq_j^k = \psi_j^k, \tag{B7}$$

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

$$q_j^k = \frac{a - \psi_j^k}{b} - Q^k, \tag{B8}$$

with

$$\psi_j^T = \zeta_j^T, \tag{B9}$$

$$\psi_j^X = c_j + \sigma[\varepsilon_j - \overline{\varepsilon}^X], \tag{B10}$$

$$\psi_j^D = c_j + \sigma[\varepsilon_j - \overline{\varepsilon}^D]\left[1 - \frac{q_j^D}{Q^D}\right]. \tag{B11}$$

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

$$\begin{aligned} q_1^X - q_1^D &= \frac{\psi_1^D - \psi_1^X}{b} + Q^D - Q^X \\ &= \frac{c_1 + \sigma[\varepsilon_1 - \overline{\varepsilon}^D][1 - \frac{q_1^D}{Q^D}] - [c_1 + \sigma[\varepsilon_1 - \overline{\varepsilon}^X]]}{b} \\ &\quad + \frac{n\sigma}{b[n+1]}[\overline{\varepsilon}^D - \overline{\varepsilon}^X] \\ &= \frac{\sigma}{b}\left[\frac{[\overline{\varepsilon}^D - \varepsilon_1]q_1^D}{Q^D} - \frac{[\overline{\varepsilon}^D - \overline{\varepsilon}^X]}{[n+1]}\right]. \end{aligned} \tag{B12}$$

Moreover, since $q_1^D(i)/Q^D(i) \geq 1/n$, it holds that:

$$\begin{aligned} q_1^X - q_1^D &\geq \frac{\sigma}{b}\left[\frac{[\overline{\varepsilon}^D - \varepsilon_1]}{n} - \frac{[\overline{\varepsilon}^D - \overline{\varepsilon}^X]}{n+1}\right] \\ &= \frac{\sigma}{b}\left[\frac{[\overline{\varepsilon}^D - \varepsilon_1] + n[\overline{\varepsilon}^X - \varepsilon_1]}{n[n+1]}\right] > 0 \quad \forall\, i \geq 1. \end{aligned} \tag{B13}$$

Furthermore, for non-adopters, we can write

$$
\begin{aligned}
q_0^X - q_0^D &= \frac{\psi_0^D - \psi_0^X}{b} + Q^D - Q^X \\
&= \frac{\left[c_0 + \sigma[\varepsilon_0 - \bar{\varepsilon}^D]\left[1 - \frac{q_0^D}{Q^D}\right]\right] - [c_0 + \sigma[\varepsilon_0 - \bar{\varepsilon}^X]]}{b} \\
&\quad + \frac{n\sigma}{b[n+1]}[\bar{\varepsilon}^D - \bar{\varepsilon}^X] \\
&= \frac{\sigma}{b}\left[\frac{[\bar{\varepsilon}^X - \bar{\varepsilon}^D]}{n+1} - \frac{[\varepsilon_0 - \bar{\varepsilon}^D]q_0^D}{Q^D}\right], \qquad \text{(B14)}
\end{aligned}
$$

which implies that a sufficient but not necessary condition for $q_0^X < q_0^D$ is $\bar{\varepsilon}^D > \bar{\varepsilon}^X$.

Let us now compare adoption profits under exogenous versus endogeneous profits in Equation (33):

$$
\begin{aligned}
\Delta\pi_i^X - \Delta\pi_i^D &= b[[q_1^X(i)]^2 - [q_1^D(i)]^2] \\
&\quad + b[[q_0^D(i-1)]^2 - [q_0^X(i-1)]^2] \\
&\quad - \sigma\left[\frac{[\varepsilon_0 - \bar{\varepsilon}^D(i-1)]}{Q^D(i-1)}[q_0^D(i-1)]^2\right] \\
&\quad - \sigma\left[\frac{[\bar{\varepsilon}^D(i) - \varepsilon_1]}{Q^D(i)}[q_1^D(i)]^2\right]. \qquad \text{(B15)}
\end{aligned}
$$

Substituting (B13) and (B14) in (33) yields

$$
\begin{aligned}
\Delta\pi_i^X - \Delta\pi_i^D &= \sigma\left[\frac{\left[\bar{\varepsilon}^D(i) - \varepsilon_1\right] q_1^X(i) q_1^D(i)}{Q^D(i)}\right] \\
&\quad - \sigma\left[\frac{\left[\bar{\varepsilon}^D(i) - \bar{\varepsilon}^X(i)\right]\left[q_1^X(i) + q_1^D(i)\right]}{n+1}\right] \\
&\quad + \sigma\left[\frac{\left[\varepsilon_0 - \bar{\varepsilon}^D(i-1)\right] q_0^D(i-1) q_0^X(i-1)}{Q^D(i-1)}\right] \\
&\quad + \sigma\left[\frac{\left[\bar{\varepsilon}^D(i-1) - \bar{\varepsilon}^X(i-1)\right]\left[q_0^D(i-1) + q_0^X(i-1)\right]}{n+1}\right]. \qquad \text{(B16)}
\end{aligned}
$$

The sign of Equation (33) cannot be easily determined since output levels and emission intensities are endogenous. Nevertheless, to be able to say something about the relative magnitude of the output and refund effect, we follow the approach in Fisher (2011) and compare adoption incentives between exogenous refunding for an equivalent average emission intensity. That is, we compare adoption profits under exogenous versus endogenous refunding for the firms which are the first and last to adopt.

When $i = 1$, Equation (33) simplifies to:

$$\begin{aligned}\Delta\pi_1^X - \Delta\pi_1^D &= \sigma\left[\frac{[\overline{\varepsilon}^D(1) - \varepsilon_1]q_1^X(1)q_1^D(1)}{Q^D(1)}\right]\\ &\quad - \sigma\left[\frac{[\overline{\varepsilon}^D(1) - \overline{\varepsilon}^X(1)][q_1^X(1) + q_1^D(1)]}{n+1}\right].\end{aligned} \tag{B17}$$

Since $q_1^D(1)/Q^D(1) > 1/n$, we have that:

$$\begin{aligned}\Delta\pi_1^X - \Delta\pi_1^D &> \sigma\left[\frac{[\overline{\varepsilon}^D(1) - \varepsilon_1]q_1^X(1)}{n}\right]\\ &\quad - \sigma\left[\frac{[\overline{\varepsilon}^D(1) - \overline{\varepsilon}^X(1)][q_1^X(1) + q_1^D(1)]}{n+1}\right],\\ \Delta\pi_1^X - \Delta\pi_1^D &> \frac{\sigma}{n+1}\left[\frac{1}{n}\left[\overline{\varepsilon}^D(1) - \varepsilon_1\right]q_1^X(1)\right]\\ &\quad + \frac{\sigma}{n+1}\left[\overline{\varepsilon}^X(1) - \varepsilon_1\right]q_1^X(1)\\ &\quad + \frac{\sigma}{n+1}\left[\overline{\varepsilon}^X(1) - \overline{\varepsilon}^D(1)\right]q_1^D(1) > 0.\end{aligned} \tag{B18}$$

Note that $[\overline{\varepsilon}^X(1) - \varepsilon_1]q_1^X(1) > [\overline{\varepsilon}^X(1) - \overline{\varepsilon}^D(1)]q_1^D(1)$ since $q_1^X(1) > q_1^D(1)$ and $|\overline{\varepsilon}^X(1) - \varepsilon_1| > |\overline{\varepsilon}^X(1) - \overline{\varepsilon}^D(1)|$.

When $i = n$,

$$\begin{aligned}\Delta\pi_n^X - \Delta\pi_n^D &= \sigma\left[\frac{[\varepsilon_0 - \overline{\varepsilon}^D(n-1)]q_0^D(n-1)q_0^X(n-1)}{Q^D(n-1)}\right]\\ &\quad + \sigma\left[\frac{[\overline{\varepsilon}^D(n-1) - \overline{\varepsilon}^X(n-1)][q_0^D(n-1) + q_0^X(n-1)]}{n+1}\right].\end{aligned} \tag{B19}$$

The sign of $\Delta\pi_n^X - \Delta\pi_n^D$ is determined by the difference $[\bar{\varepsilon}^D - \bar{\varepsilon}^X]$. Moreover, $\bar{\varepsilon}^D > \bar{\varepsilon}^X$ if

$$\frac{m\varepsilon_1 q_1^D + [n-m]\varepsilon_0 q_0^D}{mq_1^D + [n-m]q_0^D} > \frac{m\varepsilon_1 q_1^X + [n-m]\varepsilon_0 q_0^X}{mq_1^X + [n-m]q_0^X}.$$

Cross multipying, reducing terms and so on this expression simplifies to:

$$q_1^X q_0^D > q_1^D q_0^X.$$

Since $q_1^X(n-1) > q_1^D(n-1)$ and $q_0^D(n-1) > q_0^X(n-1)$, it follows that $\bar{\varepsilon}^D(n-1) > \bar{\varepsilon}^X(n-1)$ and that:

$$\Delta\pi_n^X - \Delta\pi_n^D > 0.$$

What about other emission intensities? We go back to formula (B16).

We know that $q_1^X(i) > q_0^X(i-1)$, and $q_1^D(i) > q_0^D(i-1)$. Hence, $q_1^X(i) + q_1^D(i) > q_0^D(i-1) + q_0^X(i-1)$. This is to say, $\Delta\pi_i^X - \Delta\pi_i^D > 0$ when $\bar{\varepsilon}^X(i) > \bar{\varepsilon}^D(i)$.

To find the sign of $[\Delta\pi_i^X - \Delta\pi_i^D]$ when $\bar{\varepsilon}^D(i) > \bar{\varepsilon}^X(i)$, we can use that

$$\begin{aligned}\Delta\pi_i^X - \Delta\pi_i^D > \sigma q_1^X(i)&\left[\frac{[\bar{\varepsilon}^D(i) - \varepsilon_1]}{n[n+1]} + \frac{[\bar{\varepsilon}^X(i) - \varepsilon_1]}{n+1}\right]\\ &-\sigma\left[\frac{[\bar{\varepsilon}^D(i) - \bar{\varepsilon}^X(i)]q_1^D(i)}{n+1}\right]\\ &+\sigma\left[\frac{[\varepsilon_0 - \bar{\varepsilon}^D(i-1)]q_0^D(i-1)q_0^X(i-1)}{Q^D(i-1)}\right]\\ &+\sigma\left[\frac{[\bar{\varepsilon}^D(i-1) - \bar{\varepsilon}^X(i-1)][q_0^D(i-1) + q_0^X(i-1)]}{n+1}\right],\end{aligned} \tag{B20}$$

which should be positive (unless $q_1^D(i)$ is very large).

Appendix C. Comparison of an Endogenous Refunded Tax and a Non-refunded Emission Tax

From Appendix B, we know that the difference in adopters' output between exogenous and endogenous refunding is given by:

$$q_1^X - q_1^D = \frac{\sigma}{b}\left[\frac{[\bar{\varepsilon}^D - \varepsilon_1]q_1^D}{Q^D} - \frac{\bar{\varepsilon}^D - \bar{\varepsilon}^X}{n+1}\right], \tag{C1}$$

and since

$$q_1^X = q_1^T + \frac{\sigma\bar{\varepsilon}^X}{b[n+1]}.$$

It holds that

$$q_1^T - q_1^D = \frac{\sigma}{b}\left[\frac{[\bar{\varepsilon}^D - \varepsilon_1]q_1^D}{Q^D} - \frac{\bar{\varepsilon}^D}{n+1}\right] < 0 \quad \forall\,\bar{\varepsilon}^D < \varepsilon_1\frac{1}{1-\frac{Q^D}{q_1^D[n+1]}}. \tag{C2}$$

Moreover,

$$q_0^T - q_0^D = -\frac{\sigma}{b}\left[\frac{[\varepsilon_0 - \bar{\varepsilon}^D]q_0^D}{Q^D} + \frac{\bar{\varepsilon}^D}{n+1}\right] < 0. \tag{C3}$$

Finally, it is possible to show that:

$$q_1^T(i) - q_0^T(i-1) > q_1^D(i) - q_0^D(i-1),$$

or:

$$q_0^D(i-1) - q_0^T(i-1) > q_1^D(i) - q_1^T(i).$$

After substituting in the expressions in (C2) and (C3), this condition reduces to:

$$\frac{\bar{\varepsilon}^D(i-1) - \bar{\varepsilon}^D(i)}{n+1} > -\left[\frac{\left[\varepsilon_0 - \bar{\varepsilon}^D(i-1)\right]q_0^D(i-1)}{Q^D(i-1)} + \frac{\left[\bar{\varepsilon}^D(i) - \varepsilon_1\right]q_1^D(i)}{Q^D(i)}\right], \tag{C4}$$

which holds since $\bar{\varepsilon}^D(i-1) - \bar{\varepsilon}^D(i) > 0$.

Let us now compare adoption profits under nonrefunded taxes versus endogeneous refunding

$$\begin{aligned}\Delta\pi_i^T - \Delta\pi_i^D &= b[[q_1^T(i)]^2 - [q_1^D(i)]^2] \\ &\quad + b[[q_0^D(i-1)]^2 - [q_0^T(i-1)]^2] \\ &\quad - \sigma\left[\frac{[\varepsilon_0 - \overline{\varepsilon}^D(i-1)]}{Q^D(i-1)}[q_0^D(i-1)]^2\right] \\ &\quad - \sigma\left[\frac{[\overline{\varepsilon}^D(i) - \varepsilon_1]}{Q^D(i)}[q_1^D(i)]^2\right]. \end{aligned} \tag{C5}$$

Substituting Equations (C2) and (C3) into (C5) yields:

$$\begin{aligned}\Delta\pi_i^T - \Delta\pi_i^D &= \sigma\left[\frac{\left[\overline{\varepsilon}^D(i) - \varepsilon_1\right] q_1^T(i) q_1^D(i)}{Q^D(i)}\right] \\ &\quad - \sigma\left[\frac{\overline{\varepsilon}^D(i)\left[q_1^T(i) + q_1^D(i)\right]}{n+1}\right] \\ &\quad + \sigma\left[\frac{\left[\varepsilon_0 - \overline{\varepsilon}^D(i-1)\right] q_0^T(i-1) q_0^D(i-1)}{Q^D(i-1)}\right] \\ &\quad + \sigma\left[\frac{\overline{\varepsilon}^D(i-1)\left[q_0^T(i-1) + q_0^D(i-1)\right]}{n+1}\right]. \end{aligned} \tag{C6}$$

When $i = 1$, Equation (C5) simplifies to:

$$\begin{aligned}\Delta\pi_1^T - \Delta\pi_1^D &= \sigma\left[\frac{\left[\overline{\varepsilon}^D(1) - \varepsilon_1\right] q_1^T(1) q_1^D(1)}{Q^D(1)}\right] \\ &\quad - \sigma\left[\frac{\overline{\varepsilon}^D(1)\left[q_1^T(1) + q_1^D(1)\right]}{n+1}\right] \\ &\quad + \sigma\left[\frac{\varepsilon_0\left[q_0^T(0) + q_0^D(0)\right]}{n+1}\right] \end{aligned} \tag{C7}$$

Further, since $q_1^D(i)\,[n+1] > Q^D(i)$, we have that:

$$\Delta\pi_1^T - \Delta\pi_1^D > \frac{\sigma}{n+1}\left[\varepsilon_0\left[q_0^T(0) + q_0^D(0)\right] - \varepsilon_1 q_1^T(1) - \overline{\varepsilon}^D(1) q_1^D(1)\right].$$

Let $A = \frac{\sigma}{n+1}[\varepsilon_0[q_0^T(0) + q_0^D(0)] - \varepsilon_1 q_1^T(1) - \overline{\varepsilon}^D(1)q_1^D(1)]$. It holds that:

$$\Delta\pi_1^T - \Delta\pi_1^D > A,$$
$$A > \frac{\sigma}{n+1}[\varepsilon_0[q_0^T(0) + q_0^D(0)] - \overline{\varepsilon}^D(1)[q_1^T(1) + q_1^D(1)]]. \tag{C8}$$

Thus, a sufficient condition for $\Delta\pi_1^T - \Delta\pi_1^D > 0$ is:

$$\varepsilon_0[q_0^T(0) + q_0^D(0)] > \overline{\varepsilon}^D(1)[q_1^T(1) + q_1^D(1)].$$

When $i = n$, Equation (C5) simplifies to:

$$\begin{aligned}\Delta\pi_n^T - \Delta\pi_n^D &= \frac{\sigma}{[n+1]}[\overline{\varepsilon}^D(n-1)[q_0^T(n-1) + q_0^D(n-1)]] \\ &\quad - \frac{\sigma}{[n+1]}[\overline{\varepsilon}^D(n)[q_1^T(n) + q_1^D(n)]] \\ &\quad + \sigma\left[\frac{[\varepsilon_0 - \overline{\varepsilon}^D(n-1)]q_0^T(n-1)q_0^D(n-1)}{Q^D(n-1)}\right].\end{aligned} \tag{C9}$$

Note that a sufficient condition for $\Delta\pi_n^T - \Delta\pi_n^D > 0$ is:

$$\frac{\overline{\varepsilon}^D(n-1)\left[q_0^T(n-1) + q_0^D(n-1)\right]}{q_1^T(n) + q_1^D(n)} \geq \overline{\varepsilon}^D(n).$$

Appendix D. Incentives for Continuous Technological Upgrading Intermediates

The difference between adoption incentives between exogenous refunded tax compared to the emission tax can be represented as:

$$\begin{aligned}\Delta\pi_{12,j}^X - \Delta\pi_{02,j}^T &= [\pi_2^X(n-j,j) - \pi_1^X(n-j+1,j-1)] \\ &\quad - [\pi_2^T(k^T,j) - \pi_0^T(k^T,j-1)].\end{aligned}$$

Let us evaluate Equation (52) when $j = n - k^X + 1$

$$\begin{aligned}\Delta\pi_{12,j}^X - \Delta\pi_{02,j}^T &= [\pi_2^X(k^X-1,j) - \pi_1^X(k^X,j-1)] \\ &\quad - [\pi_2^T(k^T,j) - \pi_0^T(k^T,j-1)].\end{aligned} \tag{D1}$$

Since the increase in profit rates from adoption of G_2 is higher for a firm which produces with G_0 than for a firm which has already adopted G_1 it holds that

$$\pi_2^X(k^X, j) - \pi_0^X(k^X, j-1) > \pi_2^X(k^X - 1, j) - \pi_1^X(k^X, j-1). \quad \text{(D2)}$$

Hence,

$$\begin{aligned}\Delta\pi_{12,j}^X - \Delta\pi_{02,j}^T < {} & [\pi_2^X(k^X, j) - \pi_0^X(k^X, j-1)] \\ & - [\pi_2^T(k^T, j) - \pi_0^T(k^T, j-1)]. \end{aligned} \quad \text{(D3)}$$

Or:

$$\Delta\pi_{12,j}^X - \Delta\pi_{02,j}^T < \Delta\pi_{02,j}^X - \Delta\pi_{02,j}^T. \quad \text{(D4)}$$

The same condition is obtained if we evaluate Equation (52) when $j = n - k^T$.

Appendix E. Numerical Illustrations

This section presents simulations on the diffusion patterns under a standard emission tax as well as exogenous and endogenous refunding. 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

$$p_1(t) = K_1 e^{-[\theta + r]t} + \upsilon t, \quad \text{(E1)}$$

where $\theta > 0$ captures drivers such as learning and technological progress which lead to decreasing investment costs over time until, in line with assumption 2(ii), the efficient scale of adjustment is reached and adoption costs starts to increase. We assume $\theta = 3\%$, $r = 6\%$ and $K_1 = 20$ and for the remaining parameters $a = 10$, $b = 1$, $\varepsilon_0 = 1$, $\varepsilon_1 = 0.5$, $c_0 = c_1 = 1$, $\sigma = 1$, and $\upsilon = 0.0001$.

Figures A1 and A2 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

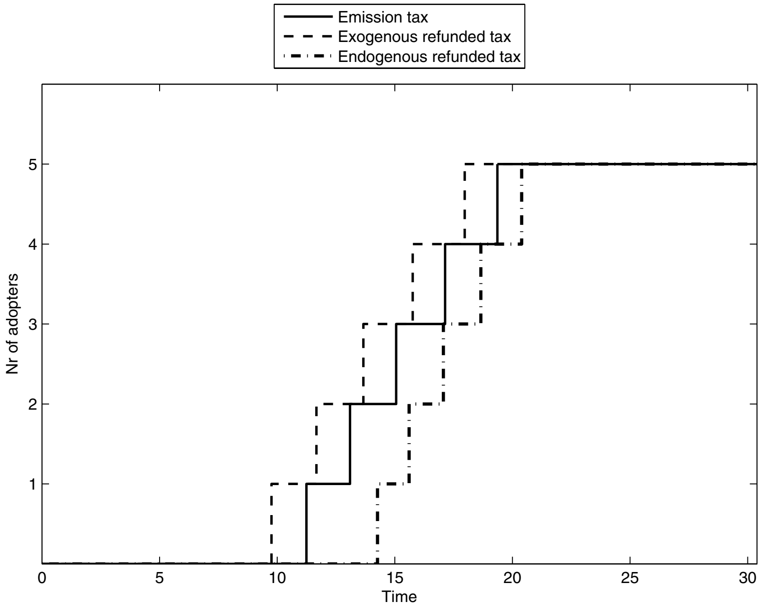

Figure A1: Diffusion with five firms in the industry.

than the non-refunded emission tax, just as discussed in the section "Adoption Incentives under a Refunded Tax". However, with endogenous refunding, the firms would adopt later than under exogenous refunding, as well as later than they would under a nonrefunded emission tax. Figure A3 illustrates the contribution from the "output" and "refunding" effects to the difference between endogenous and exogenous refunding. As discussed in the section "Endogenous Refunded Tax", the output effect dominates the refunding effect.

With $n = 15$ firms in Figure A2, 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

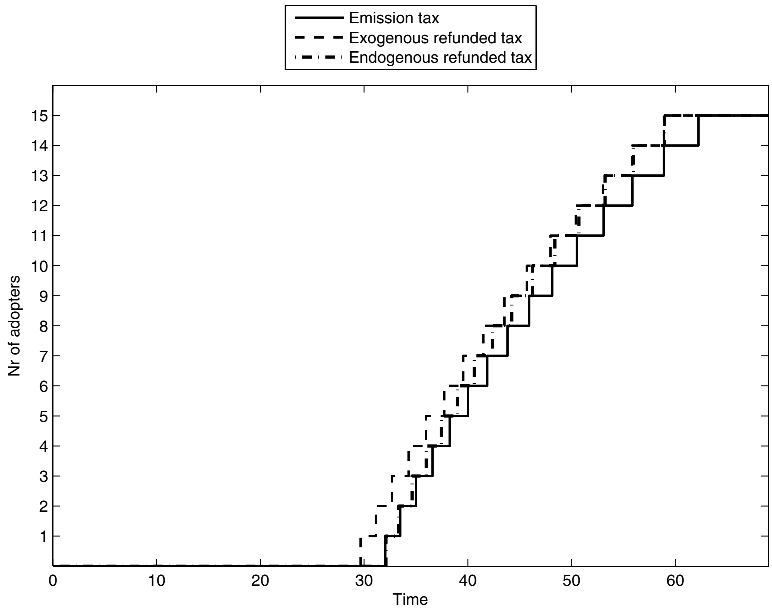

Figure A2: Diffusion with 15 firms in the industry.

increases, the diffusion pattern under a refunded tax also approaches the pattern under a standard emission tax.

In Figure A4, 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 A2. Figure A4 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.

Note that when it comes to output, our simulations indicate that nonadopters do produce slightly more and adopters slightly less with endogenous refunding compared to the case with exogenous refunding

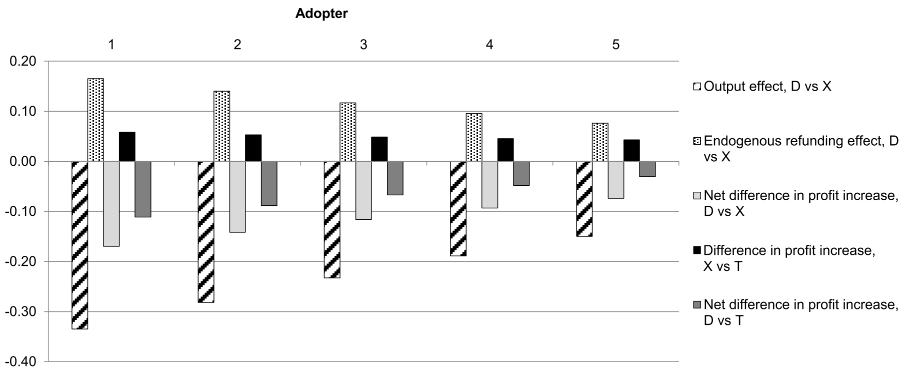

Figure A3: Output and endogenous refunding effects explaining net differences in profit increase from adoption with five firms in the industry. T refers to emission tax, X to exogenous refunded tax, and D to endogenous refunded tax.

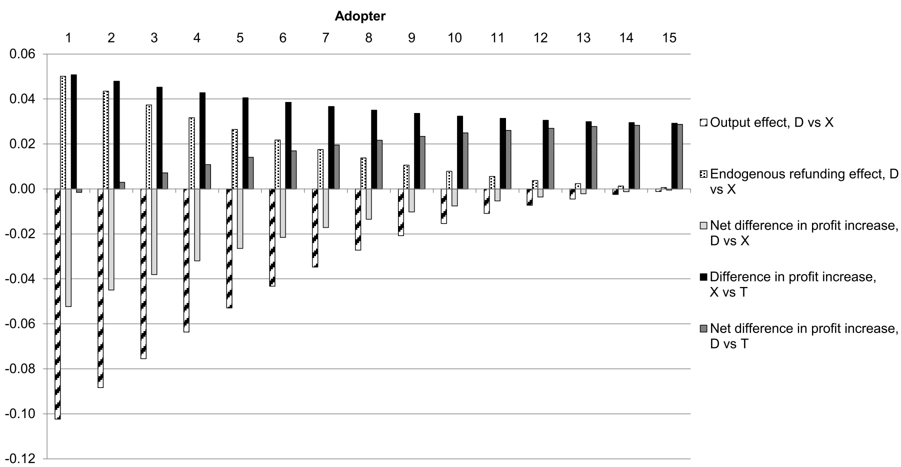

Figure A4: Output and endogenous refunding effects explaining net differences in profit increase from adoption with 15 firms in the industry. T refers to emission tax, X to exogenous refunded tax, and D to endogenous refunded tax.

in line with Fischer (2011) and as discussed in the section "Endogenous Refunded Tax". However, at the aggregate level, output does not differ significantly between the two refunding situations.

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References

Acemoglu, D., P. Aghion, L. Bursztyn, and D. Hemous (2012), "The Environment and Directed Technical Change", *The American Economic Review*, 102(1), 131–66.

Aidt, T. S. (2010), "Green Taxes: Refunding Rules and Lobbying", *Journal of Environmental Economics and Management*, 60(1), 31–43.

Bonilla, J., J. Coria, K. Mohlin, and T. Sterner (2015), "Refunded Emission Payments and Diffusion of NO_x Abatement Technologies in Sweden", *Ecological Economics*, 116, 132–45.

Cato, S. (2010), "Emission Taxes and Optimal Refunding Schemes with Endogenous Market Structure", *Environmental and Resource Economics*, 46(3), 275–80.

Coria, J. (2009), "Taxes, Permits, and the Diffusion of A New Technology", *Resource and Energy Economics*, 31(4), 249–71.

d'Haultfoeuille, X., P. Givord, and X. Boutin (2014), "The Environmental Effect of Green Taxation: The Case of the French Bonus/Malus", *The Economic Journal*, 124(578), F444–F480.

Fischer, C. (2011), "Market Power and Output-Based Refunding of Environmental Policy Revenues", *Resource and Energy Economics*, 33(1), 212–30.

Fredriksson, P. G. and T. Sterner (2005), "The Political Economy of Refunded Emissions Payment Programs", *Economics Letters*, 87(1), 113–9.

Gersbach, H. (2002), "How to Get Firms to Invest: A Simple Solution to the Hold-up Problem in Regulation", *Review of Economic Design*, 7(1), 45–56.

Gersbach, H. and T. Requate (2004), "Emission Taxes and Optimal Refunding Schemes", *Journal of Public Economics*, 88(3-4), 713–25.

Hagem, C., M. Hoel, B. Holtsmark, and T. Sterner (2015), "Refunding Emissions Payments", RFF Discussion Paper 15-05.

Kerr, S. and R. G. Newell (2003), "Policy-Induced Technology Adoption: Evidence from the U.S. Lead Phasedown", *The Journal of Industrial Economics*, 51(3), 317–43.

Montero, J.-P. (2008), "A Simple Auction Mechanism for the Optimal Allocation of the Commons", *The American Economic Review*, 98(1), 496–518.

Reinganum, J. F. (1981), "Market Structure and the Diffusion of New Technology", *The Bell Journal of Economics*, 12(2), 618–24.

Sterner, T. and L. Höglund-Isaksson (2006), "Refunded emission payments theory, distribution of costs, and Swedish experience of NO_x abatement", *Ecological Economics*, 57(1), 93–106.

Sterner, T. and B. Turnheim (2009), "Innovation and Diffusion of Environmental Technology: Industrial NO_x Abatement in Sweden Under Refunded Emission Payments", *Ecological Economics*, 68(12), 2996–3006.

van Soest, D. P. (2005), "The Impact of Environmental Policy Instruments on the Timing of Adoption of Energy-saving Technologies", *Resource and Energy Economics*, 27(3), 235–47.