Technology Licensing and Environmental Policy Instruments: Price Control versus Quantity Control

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Abstract

This paper analyzes the welfare implication of an abatement technology licensing under the Pigouvian taxation and emission trading schemes. We demonstrate that a firm with a better abatement technology optimally sells a per unit royalty license to a competitor under both schemes, but it offers a higher royalty rate under the latter, which, unless the technology is perfectly transferrable, strictly outperforms the former in terms of social surplus and incentives for technology investment by inducing more (less) production by the licensor (licensee). These are reversals of the welfare implications suggested by the literature that adopts a partial equilibrium approach omitting either the market for the advanced technology or final goods.

Keywords: Emission Trading, Pigouvian Taxation, Technology Licensing

JEL Classification: H23, Q55, Q58

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1 Introduction

Economists and policy makers aware of the aggravated threat of climate change are devoting enormous effort to getting the global economy on the track of sustainable growth. Recognizing technological progress, especially with regard to emission abatement and other environment-friendly technologies, to be a necessary condition for sustainable growth, they are endeavoring to design public policies that provide right incentives for investment and diffusion of such technology. Motivated by these actions, the present analysis of the interaction between environmental policy instruments and technology licensing assesses, in terms of technology investment and diffusion through patent licensing, the Pigouvian taxation and emission trading schemes.

Seminal work by Baumol (1972) showing a "Pigouvian tax" to effectively internalize negative externalities from pollution has led academic researchers and practitioners to a consensus that emission pricing has the potential to achieve emission reduction at lower cost than other instruments, such as mandated technologies and performance standards. Yet debate persists as to which form of emission pricing, Pigouvian taxation or cap-and-trade, better achieves ex ante and ex post social efficiency.[1] Studies can be found that favor Pigouvian taxation or emission trading schemes, and Goulder and Schein (2013) conclude from a survey of the literature that both schemes induce equivalent allocations without government failure[2] and provide equivalent incentives to invest in abatement technology. The literature analyzing technology investment has paid little attention, however, to the market for advanced abatement technologies, the use of which firms can license to competitors. Technology transfer through licensing appears to be popular, and is expected to generate stronger incentives for ex ante technology investment. The present paper, in contrast to previous literature, by taking into account the market for advanced abatement technologies, demonstrates social surplus to be greater and the innovating firm to accrue more profit under the emission trading than under the Pigouvian taxation scheme.

Consider the standard duopoly model in which two firms produce homogenous goods and compete à la Cournot fashion. Under Pigouvian taxation, each firm emits carbon dioxide in an amount dependent on its production level and abatement technology and pays tax at a predetermined rate, which remains unchanged (price control) even after an innovating firm licenses its advanced technology to a competing firm. Under the emission trading scheme, in contrast, when two firms engage in technology transfer via a per unit royalty contract, the equilibrium permit price after licensing declines with the royalty rate given that the number of permits is fixed (quantity control), because the licensee's permit demand and output decline together with the royalty rate.

[1]Seminal work by Weitzman (1974) that sorts policy instruments according to price and quantity control underlies evaluations of numerous policy instruments on the basis of social welfare.

[2]Keohane (2009) describes the rising, despite the absence of strong support from economic theorists, popularity of emission trading schemes in the following manner.

> Economists were once frustrated that their prescriptions were not followed by legislators - to use Hahn's (1989) memorable analogy, they worried that the patient was not following the doctor's order. But now that the patient is dutifully taking her medicine, recovering beautifully, and asking for a refill, the doctor wants to abandon the treatment and try an alternative therapy.

Sim and Lin (2016), in a two-country model with international trade and transboundary pollution, similarly demonstrate emission trading to outperform Pigouvian taxation.

It enables the licensor (the licensee) to charge (accept) a higher royalty rate, which in turns allows the firm with the advanced technology to take a larger market share and the government to implement a more stricter environmental regulation under the emission trading scheme. Based on this observation, this paper demonstrates that (*i*) a firm with advanced technology prefers a per unit royalty contract to two-part tariff and fixed fee contracts regardless which scheme the government implements and (*ii*) it charges a higher royalty rate and garners greater market share under the emission trading scheme, and (*iii*) that social surplus is larger under the emission trading than under the Pigouvian taxation scheme.

The prevalence of technology spillover through patent licensing notwithstanding, the interaction between technology licensing and the environmental policy instruments has not received enough attention. Early studies like those of Magat (1978) and Downing and White (1986) assume advanced technology to be used exclusively by innovating firms, later studies, including those of Requate and Unold (2003) and D'Amato and Dijkstra (2015), acknowledge adoption of new technology by introducing a fixed installation cost. Some recent studies focused on so-called "R&D externality," such as those of Parry (1995), Fischer, Parry, and Pizer (2003), and Fischer and Newell (2008), assume that advanced technology can be acquired without paying the innovating firm such that the latter benefits little from technology diffusion. Another string of literature such as Parry (1995) and Biglaiser and Horowitz (1995) takes technology licensing into account, but their analyses were confined to the emission taxation case. Similarly, Chang, Hu, and Tzeng (2009), and Miyaoka (2014) study the effect of abatement technology licensing in a Cournot duopoly under emission tax, without providing a detailed analysis of the case under the emission trading scheme. Milliman and Prince (1989), and Fischer, Parry, and Pizer (2003) consider technology license market in their analyses under a range of instruments, but none of these papers consider product market competition, favoring the Pigouvian taxation over the emission trading scheme.[3]

Technology innovation is discouraged in the absence of legal protection, yielding a sub-optimal outcome, discussion of which hardly captures the reality in which trading of advanced technology is protected and encouraged by laws. Following Kamien and Tauman (1984, 1986) and Wang (1998), we incorporate patent licensing into the simple framework of environmental economics. Seminal works by Kamien and Tauman (1984, 1986) show an outside patent holder to accrue more profit from fixed-fee than from royalty licensing, regardless of industry size and/or magnitude of innovation. Wang (1998) shows an inside patent holding firm selling a license to a competitor to prefer royalty to fixed-fee licensing. We demonstrate that combining Wang (1998) with the environment economics literature results in the reversed welfare implication. Licensing in the abatement technology market reduces aggregate permit demand in the emission permit market, which can be further exploited by the licensor through a higher royalty rate under the emission trading (quantity control) than under the Pigouvian taxation (price control) scheme.

The paper proceeds as follows. In Section 2, we develop the model. Policy instru-

[3] Parry (1995) cautiously suggests possible factors which make emission trading scheme less efficient than an emission tax. Milliman and Prince (1989) and Jung, Krutilla, and Boyd (1996) favor auctioned emission permits over an emission tax, but rank free marketable permits lower than an emission tax. Krysiak (2008) points out that firms can be encouraged to adopt socially desirable types of technology by quantity-based, but not by price control, instruments.

ments are discussed in Sections 3 and 4, illustrative examples provided in Section 5. Section 6 concludes.

2 The Model

2.1 Primitives

Consider a duopoly market in which two firms, denoted by $i \in \{A, B\}$, produce and sell homogenous products à la Cournot competition.[4] The inverse demand for final goods is given by $P : \mathbb{R}_+ \to \mathbb{R}_{++}$ such that $P(Q)$ is non-negative, strictly decreasing, (at least) twice differentiable, and $P''(Q)Q + P'(Q) < 0$.[5] For simplicity, we drop each firm's marginal cost. Firm $i \in \{A, B\}$, producing q_i units of output, emits $\delta_i q_i$ units of pollutants. Parameter δ_i can be interpreted as carbon dioxide (CO_2) intensity. It being assumed that each firm initially adopts its own emission abatement technology, $\delta_A = \underline{\delta} < \overline{\delta} = \delta_B$ without loss of generality. Firm A can license its advanced abatement technology to firm B.[6] Firm A offers its competitor (r, f) a license contract, where $r \in \mathbb{R}_+$ represents per unit royalty and $f \in \mathbb{R}_+$ a fixed fee. Note that the pure royalty (fixed fee) license consists of $r > 0$ and $f = 0$ ($r = 0$ and $f > 0$). We initially allow firm A to offer a two-part tariff contract with $r \geq 0$ and $f \geq 0$. Firm B purchases a license from firm A in order to use the technology to lower its carbon dioxide intensity by $\varepsilon \leq \overline{\delta} - \underline{\delta}$. Parameter ε captures the degree of transferability of the abatement technology; if firm B purchases the license, $\delta_B = \overline{\delta} - \varepsilon \geq \underline{\delta} = \delta_A$, otherwise, $\delta_B = \overline{\delta}$. The government announces its environmental policy in advance. If it implements the Pigouvian taxation scheme, it specifies $t \in \mathbb{R}_+$, the tax rate per unit of pollutants. If it implements the emission trading scheme, it specifies $n \in \mathbb{R}_+$, the number of tradable permits to be issued. The basic time horizon of the game is as follows.

- The government announces either t or n.
- Firm A offers to license its advanced abatement technology to firm B. Firm B decides whether or not to accept.
- Both firms pay the emission tax (or purchase the tradable permits) and sell their products à la Cournot fashion.

In particular, following Hong and Sim (2017), we assume that the emission trading scheme implemented via the Walrasian auction mechanism, when the government announces n in stage 1. All firms are asked to submit their permit demand schedules at every $p_i \in \mathbb{R}_{++}$ in advance, and the government chooses n such that $\delta q_A + \delta q_B - n = 0$. The Walrasian mechanism is often used in case of IPO in the stock market as well as in the actual permit markets in order to estimate "demand curves" for new stocks and permits. Under the Walrasian auction mechanism, each firm is a "price-taker" in

[4] Katsoulacos and Xepapadeas (1995) analyze the Cournot oligopoly outcomes with and without free entry under emission taxes.

[5] We borrow this assumption from Choi (1995) and Sim and Lin (2016), which is the sufficient condition for the second order condition to be globally satisfied. In other words, even when this condition is violated, the second order sufficient condition is satisfied and the equilibrium can be well-defined. This condition does not bind for any other purposes.

[6] Seminal work by Kamien and Tauman (1986) spawned an extensive literature on modes of patent licensing. Wang (1998) studies patent licensing by an inside innovator that sells its technology to competitors.

the permit market, which prevents additional efficiency loss from delegating emission pricing authority to the market mechanism.[7]

2.2 Under Pigouvian Taxation

Suppose that the government imposes the Pigouvian taxation scheme to maximize total surplus at the beginning of the game. The firms sign up for the licensing contract and begin producing. We solve for the sub game perfect equilibrium backward, as follows.

At stage 3, taking the other firm's choice as given, firm A chooses q_A such that

$$q_A^{BR}(q_B|t,r,\delta_B) = \underset{q_A}{\text{argmax}}\ [P(q_A+q_B) - t\underline{\delta}]q_A + rq_B + f, \tag{1}$$

and firm B chooses q_B such that

$$q_B^{BR}(q_A|t,r,\delta_B) = \underset{q_B}{\text{argmax}}\ [P(q_A+q_B) - r - t\delta_B]q_B - f. \tag{2}$$

Superscript BR stands for "best response." Note that fixed fee, f, does not affect either firm's production. The first order conditions are given by

$$0 = P'(q_A+q_B)q_A + P(q_A+q_B) - t\underline{\delta}, \quad \text{and} \tag{3}$$
$$0 = P'(q_A+q_B)q_B + P(q_A+q_B) - r - t\delta_B, \tag{4}$$

where $q_A = q_A^{BR}(q_B|t,r,\delta_B)$ and $q_B = q_B^{BR}(q_A|t,r,\delta_B)$. Denote by $q_i(t,r,\delta_B)$ the equilibrium choice of firm $i \in \{A,B\}$ at stage 3. If firm B purchases the license, we denote by $q_i(t,r)$ each $i \in \{A,B\}$.[8] Without mutual agreement on the licensing contract, $(r,f,\delta_B) = (0,0,\overline{\delta})$. The mutual best responses imply that for each $i,j \in \{A,B\}$ and $j \neq i$,

$$q_i(t,r,\delta_B) = q_i^{BR}(q_j^{BR}(q_i(t,r,\delta_B)|t,r,\delta_B)|t,r,\delta_B). \tag{5}$$

We get each firm's profit, $\pi_A(t,r,f,\delta_B)$ and $\pi_B(t,r,f,\delta_B)$, by plugging (5) into the objective functions of (1) and (2), respectively. Lemma 1 tells us that as per unit royalty rises, aggregate output and output produced by firm B decline.

Lemma 1 *Suppose that firm B purchases the license from firm A under the Pigouvian taxation scheme. Given $t \in \mathbb{R}_+$, both $q_B(t,r)$ and $q_A(t,r)+q_B(t,r)$ are strictly decreasing in r, whereas $q_A(t,r)$ is strictly increasing in r.*

At stage 2, firm A, taking $t \in \mathbb{R}_+$ as given, offers $(r,f) \in \mathbb{R}_+^2$ to maximize

$$[P(q_A(t,r,\delta_B)+q_B(t,r,\delta_B)) - t\underline{\delta}]q_A(t,r,\delta_B) + rq_B(t,r,\delta_B) + f, \tag{6}$$

subject to $r \geq 0$, $f \geq 0$, and $\pi_B(t,r,f,\overline{\delta}-\varepsilon) \geq \pi_B(t,0,0,\overline{\delta})$. The last participation constraint can be rewritten as $f \leq \pi_B(t,r,0,\overline{\delta}-\varepsilon) - \pi_B(t,0,0,\overline{\delta})$, which should be binding. Unlike Chang, Hu, and Tzeng (2009), we rule out the case of so-called "drastic

[7] When the permit allowances are determined via the Walrasian auctioned mechanism, ex post permit trade occurs only due to an idiosyncratic shock to each firm.

[8] Noting as well the tax rate $t \in \mathbb{R}_+$ and permit price $p \in \mathbb{R}_+$, we use $q_i(p,r,\delta_B)$ and $q_i(p,r)$ under the emission trading scheme without notational abuse.

technology" in which the superior technology firm can be a monopolist in the final goods market by using the technology exclusively and knocking-out its competitors. Although the licensor can prevent potential competitors' entry by exclusively holding or trading the technology in other patent licensing markets, the innovating firm in our case can hardly enforce its existing competitor to exit from the market by exclusively holding the abatement technology. Typically, the amount of saving from a new abatement technology is not large enough for an existing firm to give up its business.[9] Denote by superscript P the outcome under the Pigouvian taxation scheme. Rewriting (6) yields $f^P = 0$ and

$$r^P = \underset{r}{\operatorname{argmax}} \ [P(q_A + q_B) - t\underline{\delta}]q_A + [P(q_A + q_B) - t(\overline{\delta} - \varepsilon)]q_B - \pi_B(t, 0, 0, \overline{\delta}), \quad (7)$$

where $q_i = q_i(t, r)$ for each $i \in \{A, B\}$.

Lemma 2 *Under Pigouvian taxation, firm A optimally offers the royalty license contract with $r^P = t\varepsilon$ and $f^P = 0$.*

Lemma 2, which characterizes the equilibrium license contract offered by firm A under Pigouvian taxation, shows that "no license contract" and "a fixed fee license contract" cannot be optimal. It implies that an optimal license contract should make $q_B(t, t\varepsilon, \overline{\delta} - \varepsilon) = q_B(t, 0, \overline{\delta})$, and, hence, $q_A(t, t\varepsilon, \overline{\delta} - \varepsilon) = q_A(t, 0, \overline{\delta})$. The equilibrium outcome under the Pigouvian taxation scheme is consistent with Wang (1998), who argues that the inside innovator strictly prefers per unit royalty to fixed fee licensing. Lemma 2 provides a generalized proof of the main argument in Wang (1998) by showing that even when the inside innovator can offer a two-part tariff contract, it optimally chooses the per unit royalty contract to maximize its controlling power over the rival's marginal cost and, hence, production.

Net consumer surplus after subtracting environmental damages (CS) is given by

$$CS(q_A, q_B) = \int_0^{q_A+q_B} [P(q') - P(q_A + q_B)]dq' - \delta_A q_A - \delta_B q_B, \quad (8)$$

and the sum of producer surplus and government revenue by

$$PS(q_A, q_B) = (q_A + q_B)P(q_A + q_B), \quad (9)$$

where $q_i = q_i(t, t\varepsilon)$ on the equilibrium path. At stage 1, the government chooses $t \in \mathbb{R}_+$ to maximize

$$\int_0^{q_A+q_B} [P(q') - P(q_A + q_B)]dq' + P(q_A + q_B)(q_A + q_B) - \underline{\delta} q_A - \delta_B q_B. \quad (10)$$

By invoking Leibniz' rule, we obtain

$$\frac{d}{dq_i} \int_0^{q_A+q_B} [P(q') - P(q_A + q_B)]dq' = -P'(q_A + q_B)(q_A + q_B) > 0. \quad (11)$$

The first order condition implies that

$$P(q_A + q_B)\Big[\frac{dq_A}{dt} + \frac{dq_B}{dt}\Big] = \underline{\delta}\frac{dq_A}{dt} + \delta_B \frac{dq_B}{dt}, \quad (12)$$

[9] To focus on the structural differences between two policy instruments, we also simplify the bargaining process by assuming that firm A makes a take-it-or-leave-it offer under each environmental policy.

where

$$\frac{dq_i}{dt} = \frac{\partial q_i(t,r)}{\partial t} + \frac{\partial q_i(t,r)}{\partial r}\varepsilon \text{ for each } i \in \{A, B\}. \tag{13}$$

Lemma 3 *Suppose that the government implements the Pigouvian taxation scheme. Then, both $q_B(t, t\varepsilon)$ and $q_A(t, t\varepsilon) + q_B(t, t\varepsilon)$ are strictly decreasing in $t \in \mathbb{R}_+$.*

Lemma 3 implies that $P(q_A+q_B) \geq \underline{\delta}$ in the market equilibrium under the Pigouvian taxation scheme. Divide both sides of (12) by the square bracket on the left-hand side. When $\overline{\delta} - \varepsilon > \underline{\delta}$, the value of the right-hand side is larger than $\underline{\delta}$, whether or not $q_A(t, t\varepsilon)$ is decreasing in t. When $\overline{\delta} - \varepsilon = \underline{\delta}$, $P(q_A + q_B) = \underline{\delta}$. This result will be reviewed again in the efficiency analysis.

Eventually, the government imposes $t^P \in \mathbb{R}_+$ such that it solves (12). Firm A, after observing t^P, offers its optimal royalty contract with $r^P = t^P\varepsilon$ and $f^P = 0$. Then, each firm $i \in \{A, B\}$ produces $q_i^P = q_i(t^P, t^P\varepsilon)$ so that (q_A^P, q_B^P) jointly solve equations (3) and (4). For later use, denote by n^P the total pollutants under the Pigouvian taxation scheme together with the per unit royalty licensing, that is,

$$n^P = \underline{\delta} q_A(t^P, t^P\varepsilon) + (\overline{\delta} - \varepsilon) q_B(t^P, t^P\varepsilon). \tag{14}$$

2.3 Under Emission Trading

Suppose that the government implements the emission trading scheme and announces the number of tradable permits, $n \in \mathbb{R}_+$, at the beginning of the game.[10] The permit price, $p \in \mathbb{R}_+$, is determined by the permit market clearing condition, pre production, given by

$$\underline{\delta} q_A(p, r, \delta_B) + \delta_B q_B(p, r, \delta_B) = n. \tag{15}$$

As mentioned before, when the government implements the emission trading scheme via the Walrasian auction mechanism which ask each firm to submit its permit demand at every price prior to determining total allowances, each firm leaves as a price-taker as in the taxation case. Replacing $t \in \mathbb{R}_+$ in (1)-(4) with permit price, $p \in \mathbb{R}_+$, yields the equilibrium output by each firm, given (p, r, f, δ_B). The first order conditions imply that

$$0 = P'(q_A + q_B)q_A + P(q_A + q_B) - p\underline{\delta}, \text{ and} \tag{16}$$
$$0 = P'(q_A + q_B)q_B + P(q_A + q_B) - r - p\delta_B, \tag{17}$$

where the permit price can be denoted by a function of (n, r, δ_B), that is, $p = p(n, r, \delta_B)$. Note that whereas tax rate in (3) and (4) is fixed under Pigouvian taxation, permit price in (16) and (17) is affected by per unit royalty. That permit price under the emission trading scheme, $p(n, r, \delta_B)$, (Pigouvian taxation scheme, t) is affected by (independent of) r creates a critical difference between the two regimes.

[10] Following Hong and Sim (2017), this paper assumes the government to sell n number of permits through the Walrasian auction mechanism, a simplified version of the cap-and-trade scheme with free allowances, although the Walrasian mechanism results in "no permit trade" ex post. All results in the paper except firm profit remain unchanged under the free allowances scheme.

Suppose that firm A and B agree on royalty licensing. Summing (16) and (17) reveals total output $[q_A(p,r)+q_B(p,r)]$ and $q_B(p,r)$ to decline with p, causing "movement along the permit demand."[11]

Lemma 4 *Suppose that the government issues n-unit of tradable permits and both firms agree to technology licensing.*

(i) The equilibrium permit price $p(n,r,\delta_B)$ *is strictly decreasing in* r.

(ii) The marginal cost of firm B, $[r+p(n,r,\overline{\delta}-\varepsilon)(\overline{\delta}-\varepsilon)]$, *is strictly increasing in* r.

The first statement in Lemma 4 implies that increasing r adversely affects permit demand by firm B, lowering the equilibrium permit price. The second statement implies that despite the low permit price, firm B still incurs a higher marginal cost as r increases. Apparently, firm B cannot but decrease production, which dampens its permit demand and lowers the permit price. In turns, the low permit price due to a high royalty rate enables firm B to accept the high royalty rate. The two statements in Lemma 4, together with Lemma 5, imply that, unlike the Pigouvian taxation scheme, the emission trading scheme gives firm A an additional incentive and ability to raise the per unit royalty rate, that is, "to lower permit price."

Lemma 5 *If firm* B *purchases a license from firm* A *under the emission trading scheme, both* $[q_A(p(n,r,\overline{\delta}-\varepsilon),r)+q_B(p(n,r,\overline{\delta}-\varepsilon),r)]$ *and* $q_B(p(n,r,\overline{\delta}-\varepsilon),r)$ *are strictly decreasing in* r, *whereas* $q_A(p(n,r,\overline{\delta}-\varepsilon))$ *strictly increasing in* r.

Lemma 5 is the analogy under emission trading of Lemma 1 under Pigouvian taxation. Lemma 4 and 5 jointly imply that firm A, by increasing r, induces firm B to purchase fewer permits and produce less. Firm A produces more, but firm B produces less as r rises.

Knowing these results, firm A offers (r,f) to maximize

$$[P(q_A(p,r,\delta_B)+q_B(p,r,\delta_B))-p\underline{\delta}]q_A(p,r,\delta_B)+rq_B(p,r,\delta_B)+f, \tag{18}$$

subject to $p=p(n,r,\overline{\delta}-\varepsilon)$, $r\geq 0$, $f\geq 0$, and $\pi_B(p,r,f,\overline{\delta}-\varepsilon)\geq \pi_B(p,0,0,\overline{\delta})$. As before, neither "no license" nor "a fixed fee license" can be optimal. Given n, firm A chooses $r\in\mathbb{R}_+$ to maximize

$$[P(q_A+q_B)-p\underline{\delta}]q_A+[P(q_A+q_B)-p(\overline{\delta}-\varepsilon)]q_B-\pi_B(p(n,0,\overline{\delta}),0,0,\overline{\delta}), \tag{19}$$

and $f\in\mathbb{R}_+$ to solve for

$$\pi_B(p,r,0,\overline{\delta}-\varepsilon)-\pi_B(p(n,0,\overline{\delta}),0,0,\overline{\delta})=0, \tag{20}$$

where $p=p(n,r,\overline{\delta}-\varepsilon)$ and $q_i=q_i(p,r)$ for each $i\in\{A,B\}$. The left-hand side of (20) necessitates solving for $p(n,0,\overline{\delta})$ as well, but $p(n,0,\overline{\delta})$ is not affected by r. Denote by superscript E the outcome of this game, and define the function of $r^E:\mathbb{R}_+\to\mathbb{R}_+$ such that, given n, $r^E(n)$ makes firm B indifferent whether or not it purchases a license.

[11] We obtain this result by the same reasoning applied in Lemma 1. Note that the left-hand side of (15) can be rewritten as $\underline{\delta}q_A(p,r,\delta_B)+\delta_B q_B(p,r,\delta_B)=\underline{\delta}(q_A(p,r,\delta_B)+q_B(p,r,\delta_B))+(\delta_B-\underline{\delta})q_B(p,r,\delta_B)$.

Lemma 6 *If the government implements the emission trading scheme, firm A offers the license contract, which solves*

$$\pi_B(p(n, r^E(n), \overline{\delta} - \varepsilon), r^E(n), 0, \overline{\delta} - \varepsilon) = \pi_B(p(n, 0, \overline{\delta}), 0, 0, \overline{\delta}) \text{ and } f^E = 0. \tag{21}$$

The left-hand side of (21) can be expressed as a decreasing function, whereas the right-hand side is independent, of r. Given n, the equilibrium royalty rate, $r^E(n)$, can be uniquely determined by equation (21).

At stage 1, the government chooses $n \in \mathbb{R}_+$ to maximize

$$\int_0^{q_A+q_B} [P(q') - P(q_A + q_B)]dq' + P(q_A + q_B)(q_A + q_B) - \underline{\delta} q_A - \delta_B q_B, \tag{22}$$

where $q_i = q_i(p(n, r^E(n), \delta_B), r^E(n))$ for each $i \in \{A, B\}$. Alternatively, because the per unit royalty is optimal for firm A, we use the short notations $p = p(n, r^E(n))$ and $q_i = q_i(p(n, r^E(n)), r^E(n))$ for each $i \in \{A, B\}$ when it is innocuous to do so. The first order condition implies that

$$P(q_A + q_B)\Big[\frac{dq_A}{dn} + \frac{dq_B}{dn}\Big] = \underline{\delta}\frac{dq_A}{dn} + \delta_B \frac{dq_B}{dn}, \tag{23}$$

where $r = r^E(n)$ and

$$\frac{dq_i(p,r)}{dn} = \frac{\partial q_i(p,r)}{\partial p}\Big[\frac{\partial p(n,r)}{\partial n} + \frac{\partial p(n,r)}{\partial r}\frac{\partial r}{\partial n}\Big] + \frac{\partial q_i(p,r)}{\partial r}\frac{\partial r}{\partial n}, \tag{24}$$

for each $i \in \{A, B\}$. Eventually, under the emission trading scheme the government issues n^E-number of tradable permits such that it maximizes (22). Firm A offers its optimal royalty contract with $r^E = r^E(n^E)$ and $f^E = 0$ so as to solve for (21), and each firm $i \in \{A, B\}$ produces $q_i^E(p^E(n^E, r^E, \overline{\delta} - \varepsilon), r^E)$ so that $q_A^E(p^E(n^E, r^E, \overline{\delta} - \varepsilon), r^E)$ and $q_B^E(p^E(n^E, r^E, \overline{\delta} - \varepsilon), r^E)$ jointly solve for (16) and (17).

3 Efficiency Analysis

As an efficiency benchmark, consider the problem of the social planner who sets the technology standards and directly orders the efficient pair of (q_A^*, q_B^*) to maximize the total surplus described in (10).[12] The planner induces (q_A^*, q_B^*) such that

$$P(q_A^* + q_B^*) = \underline{\delta} \text{ and } q_B^* = 0. \tag{25}$$

The solution for the planner's problem is uniquely determined as well, as the second order condition is globally satisfied.[13] Apparently, this allocation is difficult to obtain through the market equilibrium, which cannot prevent firm B from producing.

[12] The planner's outcome cannot be obtained only by tightening emission standards because the remaining firm will maximize its profit rather than the social surplus.

[13] When $\varepsilon = \overline{\delta} - \underline{\delta}$, the efficient allocation cannot be uniquely determined. The allocation of (q_A, q_B) satisfying $P(q_A^* + q_B^*) = \underline{\delta}$ can be the solution.

Lemma 7 *When $\varepsilon < \overline{\delta} - \underline{\delta}$, the market equilibrium under Pigouvian taxation produces less, but emits more pollutants per unit of output, compared to the planner's problem. When $\varepsilon = \overline{\delta} - \underline{\delta}$, the Pigouvian taxation scheme achieves the efficient allocation of the planner's problem.*

Lemma 7 reveals the sources of inefficiency associated with Pigouvian taxation. Consider the case in which $\underline{\delta} < \overline{\delta} - \varepsilon$. The market equilibrium with the (somewhat tight) regulation produces less than the planner's solution (regulation inefficiency) because a common tax rate is applied to both firms. The Pigouvian taxation scheme cannot prohibit production by firm B (allocation inefficiency), which causes more pollution conditional on the same output level. When $\underline{\delta} = \overline{\delta} - \varepsilon$, both production and allocation inefficiencies are resolved so that the Pigouvian taxation scheme achieves the planner's outcome.

To compare the Pigouvian taxation and emission trading schemes, consider the case in which the government issues n^P number of tradable permits under the emission trading scheme, where n^P is the amount of the equilibrium pollutants under the Pigouvian taxation scheme, as defined in (14). Given n^P and $r^E(n^P)$, firm B demands fewer permits after purchasing a license from firm A and can reduce carbon dioxide intensity by ε per unit. Then, $p(n^P, 0, \overline{\delta}) > p(n^P, r^E(n^P), \overline{\delta} - \varepsilon)$.

Lemma 8 *Suppose that the government issues n^P number of tradable permits.*

(i) Firm A charges a higher royalty rate than $r^P = t^P \varepsilon$.

(ii) Firm A produces more, firm B less, relative to the case under Pigouvian taxation.

If the government implements the emission trading scheme and allocates n^P units of tradable permits through the Walrasian auction mechanism, Lemma 8 tells us that firm A will charge a higher per unit royalty, produce more, and induce the licensee to produce less relative to the case under Pigouvian taxation. Note that in both cases total pollutants are controlled at n^P units, resulting in higher aggregate output given the same level of allowances. Provided that n^P is not the optimal solution implemented by the government, the emission trading scheme can achieve a more efficient outcome, which possibility is proved by the following proposition.

Proposition 1 *With technology licensing,*

$$TS(t^P, r^P) < TS(p(n^P, r^E(n^P), \overline{\delta} - \varepsilon), r^E(n^P)) \leq TS(p(n^E, r^E, \overline{\delta} - \varepsilon), r^E). \tag{26}$$

It being straightforward to prove Proposition 1, we skip the proof. Proposition 1 shows total surplus to be strictly larger under the emission trading than under the Pigouvian taxation scheme whether n^E is larger or smaller than n^P because the innovating firm with better technology is accorded a larger market share under the former than under the latter scheme. Later, section 5 presents illustrative examples in which emission trading has a stronger regulatory effect than Pigouvian taxation ($n^P > n^E$), but total output and surplus are strictly greater under the former than under the latter.

4 Dynamic Extension

In this section, we extend the timeline to examine both ex-ante and ex-post social efficiency regarding technology investment and spillover. First, consider the symmetric case with $\overline{\delta}_A = \overline{\delta}_B = \overline{\delta}$ before an innovative technology arrives. Lemma 9 summarizes the equivalence of emission trading and Pigouvian taxation without technology innovation, which is consistent with previous literature. Note that the result of Lemma 9 holds even when the ex-ante abatement technology is heterogeneous, i.e., $\overline{\delta}_A \neq \overline{\delta}_B$, as long as $\varepsilon \in [0, \overline{\delta}_B - \underline{\delta}]$ so that $\delta_B = \overline{\delta}_B - \varepsilon \geq \underline{\delta} = \delta_A$.

Lemma 9 *Without technology innovation, the emission trading scheme implements the equivalent equilibrium outcome as the Pigouvian taxation scheme. In particular, both schemes result in the same level of pollution and the same profit for both firms.*

Now, let us allow technology licensing. The commitment issue regarding each environmental regulation arises, as in Requate and Unold (2003) and D'Amato and Dijkstra (2015) show. We first consider the case in which the government ex-ante commits a particular tax rate under Pigouvian taxation or the number of tradable permits under emission trading. More specifically, the government announces tax rate t or number of permits n before the innovation takes place.

Proposition 2 *Suppose that the government commits its environmental policy before technology innovation takes place. An innovating firm expects a higher profit under the emission trading scheme than the Pigouvian taxation scheme. It implies that the former provides stronger incentives for ex ante technology investment.*

If the government does not commit its environmental policy, or declares the regulation instrument after the advanced abatement technology is realized, we get the result of Proposition 3. Proposition 3 provides the sufficient condition that firms make more investment on technology innovation under the emission trading scheme than the other. It shows that ex-post profit of innovating firm is also larger under the emission trading scheme if both the emission amount and the emission price are lower under the emission trading scheme than the other. When the government is expected to adjust the strength of its environmental regulation depending on technology innovation and licensing, each firm gets stronger incentives for technology investment ex ante under emission trading than under Pigouvian taxation.

Proposition 3 *Suppose that the government can adjust its tax rate or number of tradable permits after a new abatement technology arrives. If $n^E < n^P$ but $p(n^E, r^E, \overline{\delta} - \varepsilon) < t^P$, the innovating firm expects a higher profit under the emission trading scheme than the Pigouvian taxation scheme.*

5 Illustrative Examples

Let us assume $P(q_A + q_B) = a/(b + q_A + q_B)$, where $(a, b, \underline{\delta}, \overline{\delta}) = (15, 1, 2, 3)$. We vary the transferability parameter, ε, plotted on the horizontal axes of all figures in this

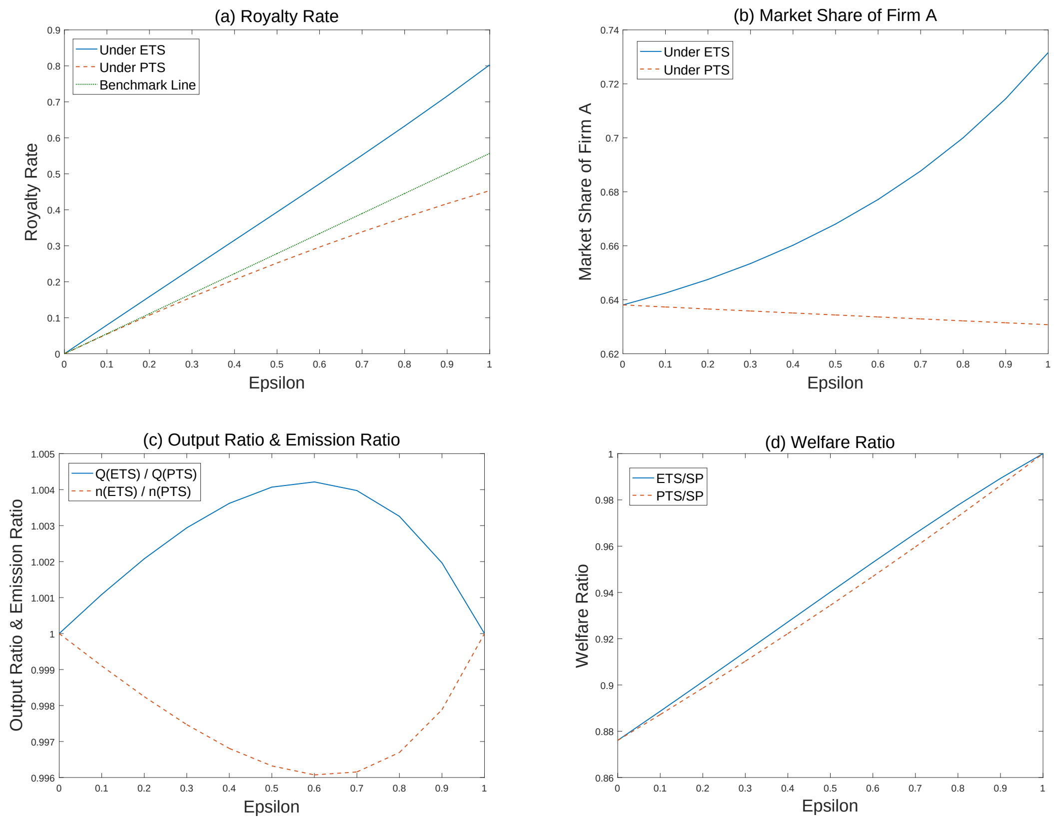

Figure 1: **Equilibrium outcomes**

This figure plots the equilibrium outcomes of (a) royalty, (b) market share of firm A, (c) total output (Q) and aggregate emission amount (n), and (d) welfare ratio under the emission trading and Pigouvian taxation schemes with the first-benchmark case with respect to the scale of technology transferability (ε) on the horizontal axis. Note that $\epsilon = 1$ indicates the technology to be fully transferable. ETS, PTS, and SP stand for emission trading scheme, Pigouvian taxation scheme, and the first-best benchmark case under the social planner, respectively.

section, from zero to one ($= \overline{\delta} - \underline{\delta}$).

Figure 1 presents (a) the royalty rate, (b) firm A's market share, (c) output and pollution ratios, and (d) the welfare ratio. Panel (a) shows the relationship between transferability of a new abatement technology and royalty rate. The solid and dotted lines represent the loci of per unit royalty along ε under the emission trading and Pigouvian taxation schemes respectively, whereas the dashed line in the middle of those two curves represents an imaginary benchmark case in which the tax rate is fixed at the initial level with $\varepsilon = 0$. The royalty rate is larger and grows faster with ε under emission trading than under Pigouvian taxation. Interestingly, as ε increases, the government reduces the tax rate under Pigouvian taxation, which makes the dotted line ($= t^P\varepsilon$) go below the benchmark line. In contrast, under the emission trading scheme firm B's profit gap between "free licensing" and "no licensing" cases expands, as new technology becomes more transferable, enabling firm A to extract more surplus from the licensing contract with the high royalty rate. It makes the solid line go above the benchmark line and be accelerated with ε.

Panel (b) depicts the relationship between ε and firm A's market share. The solid line represents firm A's market share under emission trading, the dotted line under Pigouvian taxation. Trivially, the social planner may allow only firm A to produce, thereby making its market share one. The market based approach, the emission trading scheme, predicts a higher market share for firm A, albeit not as high as in the planner's problem. It is because under this scheme firm A charges a higher royalty rate which lowers the equilibrium permit price by raising firm B's marginal cost and mitigating its permit demand. Firm A consequently produces more, firm B less. Firm A's market share declines with ε under Pigouvian taxation, but runs in the opposite direction under emission trading. It is consistent with Panel (a) in which the solid (dotted) line go above (below) the benchmark line.

Panel (c) reveals an interesting contrast in that the level of aggregate output is larger, but the level of target allowances smaller, under the emission trading than under the Pigouvian taxation scheme. The output ratio is depicted by the solid line and the allowance ratio by the dotted line. The market, although more strictly regulated with less allowances (regulation inefficiency), sees greater production under emission trading than under Pigouvian taxation because under the former the better technology of firm A is more effectively exploited (allocation efficiency). As mentioned above, based on higher royalty rates, the emission trading scheme induces firm B to reduce, and firm A to expand, production relative to the Pigouvian taxation scheme.

Panel (d) describes the relationship between ε and welfare ratios. Setting social welfare of the efficiency benchmark as a denominator, we compare the welfare outcomes under each policy instrument. The solid line shows social welfare of the market equilibrium with emission trading on a nominator, while the dotted line represents social welfare associated with Pigouvian taxation on a nominator. The solid line is higher than the dotted line except at both end points. It is natural from panel (c) because the emission trading scheme generates larger production and less pollution than the Pigouvian taxation scheme. Under both schemes, technology licensing has a positive effect on social surplus so that as ε increases, social welfare under both schemes converges to the planner's outcome.

Panel (a) in Figure 2 reveals a negative correlation between emission prices under each policy and ε. Both permit price under the emission trading scheme and tax rate under the Pigouvian taxation decreases as ε rises, but permit price drops faster than tax rate does as new technology becomes more transferable. The difference in speed comes from the considerable gap in royalty rate between those different policy instruments shown in panel (a) in Figure 1. Higher royalty rate raises firm B's marginal cost and mitigates its permit demand, further reducing permit price under the emission trading scheme. Panel (b) shows a positive correlation between firm A's profit and ε, which is obvious from Figure 1. An increase in ε results in a higher royalty rate and market share for firm A. In the market equilibrium under the emission trading scheme, firm A realizes additional profit from lower permit prices and higher royalty rates relative to the equilibrium under the Pigouvian taxation scheme, which implies that emission trading is superior to Pigouvian taxation in terms of inducing technology innovation.

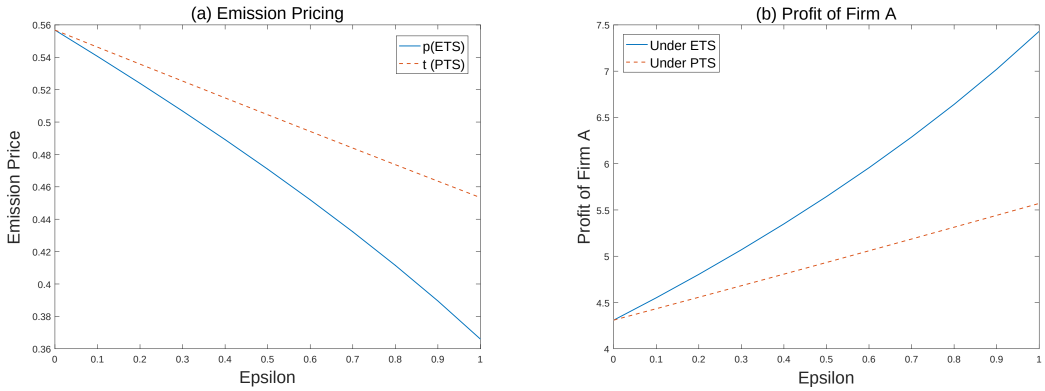

Figure 2: **Efficiency Analysis**

This figure plots on the vertical axis the (a) emission prices under emission trading scheme (p) and under the Pigouvian taxation (t), and (b) profit of firm A with respect to the scale of technology transferability (ε).

6 Conclusion

Ex post technology licensing, despite its considerable importance, has received little attention by environmental economists and policy makers relative to ex ante technology investment. Technology licensing, not only improves ex post efficiency by transferring better technologies, but also reduces ex ante inefficiency by encouraging technology investment. Motivated by the prevalence of technology licensing, this paper examines how consequent technology licensing affects and is affected by such environmental policy instruments as emission trading and Pigouvian taxation. We find an increase in the royalty rate under emission trading to lower the equilibrium permit price by mitigating permit demand by the licensee, which incentives the patent holder to further raise the royalty rate. Because a higher royalty rate increases (decreases) the market share of the licensor (licensee), licensors with a better abatement technology produce more, and licensees less, under the emission trading than under the Pigouvian taxation scheme. Unless the technology is perfectly general and transferrable, aggregate output and social surplus improve more under the emission trading than under the Pigouvian taxation scheme.

This paper, being consistent with Wang (1998), analyzes the inside-innovator case in which a firm operating with a better abatement technology sells the superior technology to a competitor. Alternatively, a university, government-sponsored research institute, or third party may develop and sell an environment-friendly technology. Given that, in general, an outside innovator may prefer a licensing contract other than the per unit royalty contract, as shown in Kamien and Tauman (1984, 1986), the analysis regarding an outside innovator requires a cautious approach. The innovator's choice of licensing contract, *i.e.*, the royalty license, fixed fee license, or two-part tariff contract, is affected by the environmental policy instrument, and also affects the strength of regulation. We leave it to future research to determine whether this exclusion has led us to overvalue the dominance of the emission trading over the Pigouvian taxation scheme.

Appendices

A Mathematical Appendix

Proof of Lemma 1 Summing up equations (3) and (4) and reordering yields

$$P'(q_A+q_B)(q_A+q_B)+2P(q_A+q_B)=t(\underline{\delta}+\overline{\delta}-\varepsilon)+r. \tag{A1}$$

Since $P''(q_A+q_B)(q_A+q_B)+3P'(q_A+q_B)<0$, an increase in $r\in\mathbb{R}_+$ strictly lowers (q_A+q_B).

Suppose to the contrary that q_B is non-decreasing in r. Since (q_A+q_B) decreases in r, q_A should strictly decrease in r. Subtracting (4) from (3) and reordering implies that

$$-P'(q_A+q_B)(q_A-q_B)=r+t(\overline{\delta}-\varepsilon-\underline{\delta})\geq 0. \tag{A2}$$

Equation (A2) dictates $q_A>q_B$ for any $r\in\mathbb{R}_+$, because $P'(\cdot)<0$. It also implies that as r increases, $|P'(q_A+q_B)|$ should increase, because (q_A-q_B) strictly decreases with r. Then, the first order conditions in (3) and (4) jointly imply that when r increases, $|P'(q_A+q_B)q_A|$ should increase as much as $|P'(q_A+q_B)q_B-r|$. However, since q_A is decreasing in r but q_B is non-decreasing, $|P'(q_A+q_B)q_A|$ cannot rise as much as $|P'(q_A+q_B)q_B-r|$, which is contradiction. Therefore, q_B should be strictly decreasing in r. Differentiating (3) with respect to r yields

$$\begin{aligned}0&=P''(q_A+q_B)q_A(\frac{\partial q_A}{\partial r}+\frac{\partial q_B}{\partial r})+P'(q_A+q_B)(2\frac{\partial q_A}{\partial r}+\frac{\partial q_B}{\partial r}) \qquad \text{(A3)}\\ \Leftrightarrow -(P''(q_A+q_B)q_A+P'(q_A+q_B))\frac{\partial q_B}{\partial r}&=(P''(q_A+q_B)q_A+2P'(q_A+q_B))\frac{\partial q_A}{\partial r}.\end{aligned}$$

Note that $P''(Q)Q+P'(Q)<0$ implies both $P''(q_A+q_B)q_A+P'(q_A+q_B)$ and $P''(q_A+q_B)q_A+2P'(q_A+q_B)$ are negative. Since $\frac{\partial q_B}{\partial r}<0$, $\frac{\partial q_A}{\partial r}>0$. $\square$

Proof of Lemma 2 First, consider the case in which firm A uses the abatement technology exclusively without licensing. Compare firm A's profits with and without technology licensing. In particular, consider the license contract with $r=t\varepsilon$ and $f=0$, which makes firm B maintain the same output level, that is $q_B(t,0,\overline{\delta})=q_B(t,t\varepsilon,\overline{\delta}-\varepsilon)$. Equation (3) implies that $q_A(t,0,\overline{\delta})=q_A(t,t\varepsilon,\overline{\delta}-\varepsilon)$ as well. Since firm A gets additional profit from selling the license $t\varepsilon q_B(t,t\varepsilon,\overline{\delta}-\varepsilon)$, 'no license' cannot be an optimal strategy for firm A.

Now, check the optimality of the license contract with $r=t\varepsilon$ and $f=0$. Denote by $\hat{\pi}_A(t,r,\overline{\delta}-\varepsilon)$ the objective function in (7), which is given $\hat{\pi}_A=[P(q_A+q_B)-t\underline{\delta}]q_A+rq_B+f$, *where* $f=[P(q_A+q_B)-r-t\delta_B]q_B-\overline{\pi}^N$. Taking derivative of $\hat{\pi}_A(t,r,\overline{\delta}-\varepsilon)$ with respect to r and combining it with (3) and (4) yields

$$\begin{aligned}\frac{\partial\hat{\pi}_A}{\partial r}&=P'(q_A+q_B)q_A(\frac{\partial q_A}{\partial r}+\frac{\partial q_B}{\partial r})+[P(q_A+q_B)-t\underline{\delta}]\frac{\partial q_A}{\partial r}\\ &\quad+P'(q_A+q_B)q_B(\frac{\partial q_A}{\partial r}+\frac{\partial q_B}{\partial r})+[P(q_A+q_B)-t\delta_B]\frac{\partial q_B}{\partial r} \qquad \text{(A4)}\\ &=P'(q_A+q_B)q_B\frac{\partial q_A}{\partial r}-[P(q_A+q_B)-r-t\underline{\delta}]\frac{\partial q_B}{\partial r}.\end{aligned}$$

Lemma 1 implies that $0 < (\partial q_A)/(\partial r) < -(\partial q_B)/(\partial r)$. Thus,

$$\begin{aligned}\frac{\partial \hat{\pi}_A}{\partial r} &= P'(q_A+q_B)q_B\frac{\partial q_A}{\partial r} + [P(q_A+q_B) - r - t\underline{\delta}]\Big(-\frac{\partial q_B}{\partial r}\Big) \\ &> P'(q_A+q_B)q_B\frac{\partial q_A}{\partial r} + [P(q_A+q_B) - r - t\underline{\delta}]\frac{\partial q_A}{\partial r} \\ &\geq [P'(q_A+q_B)q_B + P(q_A+q_B) - r - t(\overline{\delta}-\varepsilon)]\frac{\partial q_A}{\partial r} = 0.\end{aligned} \tag{A5}$$

The last equality follows from (4). Therefore, firm A's profit increases in per unit royalty. Firm A will charge $r = t\varepsilon$ and $f = 0$ to make firm B indifferent whether it purchases the license or not. If it charges $r > t\varepsilon$, the fixed fee should be negative. $\square$

Proof of Lemma 3 Plugging $r(t) = t\varepsilon$ into (A1) yields

$$P'(q_A+q_B)(q_A+q_B) + 2P(q_A+q_B) = t(\underline{\delta}+\overline{\delta}). \tag{A6}$$

Since $P''(q_A+q_B)(q_A+q_B) + 3P'(q_A+q_B) < 0$, an increase in t lowers (q_A+q_B). Suppose to the contrary that $q_B(t, r(t))$ is non-decreasing in t. Then, $q_A(t, r(t))$ should be strictly decreasing in t. Subtracting (4) from (3), we obtain that

$$P'(q_A+q_B)q_A - t\underline{\delta} = P'(q_A+q_B)q_B - t\overline{\delta} < 0. \tag{A7}$$

In equation (A7), as t increases, $|P'(q_A+q_B)q_B - t\overline{\delta}|$ grows faster than $|P'(q_A+q_B)q_A - t\underline{\delta}|$. It's contradiction. Therefore, $q_B(t, r(t))$ should be strictly decreasing in t. $\square$

Proof of Lemma 4 (i) Suppose to the contrary that $p(n, r, \overline{\delta}-\varepsilon)$ (or shortly $p(n, r)$) is non-decreasing in $r \in \mathbb{R}_+$. Summing up (16) and (17) yields

$$P'(q_A+q_B)(q_A+q_B) + 2P(q_A+q_B) = r + p(n, r, \overline{\delta}-\varepsilon)(\underline{\delta}+\overline{\delta}-\varepsilon). \tag{A8}$$

As r increases, $q_A(p(n,r), r, \delta_B) + q_B(p(n,r), r, \delta_B)$ should decrease, by the same reasoning as in Lemma 1. Then, rewriting (15) yields

$$\underline{\delta}(q_A(p(n,r), r, \delta_B) + q_B(p(n,r), r, \delta_B)) + (\delta_B - \underline{\delta})q_B(p(n,r), r, \delta_B) = n, \tag{A9}$$

which implies that $q_B(p(n,r), r, \delta_B)$ should increase in r but $q_A(p(n,r), r, \delta_B)$ should decrease. Connecting (16) and (17) implies that

$$-P'(q_A+q_B)(q_A-q_B) = r + p(n, r, \overline{\delta}-\varepsilon)(\overline{\delta}-\underline{\delta}-\varepsilon) > 0. \tag{A10}$$

Again, equation (A10) dictates that $q_A > q_B$ and $|P'(q_A+q_B)|$ should increase, as r increases. Then, the first order conditions in (16) and (17) jointly imply that when r increases, $|P'(q_A+q_B)q_A - p\underline{\delta}|$ should increase as much as $|P'(q_A+q_B)q_B - r - p(\overline{\delta}-\varepsilon)|$. However, since q_A is decreasing in r but q_B is increasing, $|P'(q_A+q_B)q_A - p\underline{\delta}|$ cannot rise as much as $|P'(q_A+q_B)q_B - r - p(\overline{\delta}-\varepsilon)|$. It's contradiction. Therefore, $p(n, r, \overline{\delta}-\varepsilon)$ should decline with r, as long as firm B accepts the license contract.
(ii) First, suppose to the contrary that the right hand side of (A8) $[r + p(n, r, \overline{\delta}-\varepsilon)(\overline{\delta}+\underline{\delta}-\varepsilon)]$ is nonincreasing in r. This dictates that (q_A+q_B) should increase. Then, equation (A10) tells us that $q_A > q_B$ and q_B should increase by the same reasoning

as before. However, if both q_B and $q_A + q_B$ increase, the market clearing condition in (A9) is violated. It's contradiction. Since $p(n, r, \overline{\delta} - \varepsilon)$ is strictly decreasing in r, it is obvious that once $[r + p(n, r, \overline{\delta} - \varepsilon)(\overline{\delta} + \underline{\delta} - \varepsilon)]$ increases in r, $[r + p(n, r, \overline{\delta} - \varepsilon)(\overline{\delta} - \varepsilon)]$ should also increase in r. $\square$

Proof of Lemma 5 We have already proved in the proof of Lemma 4 that the right hand side of (A8) rises with r so that $(q_A + q_B)$ falls with r. The second part of Lemma 4 clearly dictates that q_B should be strictly decreasing in r. To show that q_A strictly increases in r, differentiating (16) with respect to r yields

$$0 = P''(q_A + q_B)q_A(\frac{\partial q_A}{\partial r} + \frac{\partial q_B}{\partial r}) + P'(q_A + q_B)(2\frac{\partial q_A}{\partial r} + \frac{\partial q_B}{\partial r}) - \frac{\partial p}{\partial r}\underline{\delta} \qquad \text{(A11)}$$

$$\Leftrightarrow -(P''(q_A + q_B)q_A + P'(q_A + q_B))\frac{\partial q_B}{\partial r} = (P''(q_A + q_B)q_A + 2P'(q_A + q_B))\frac{\partial q_A}{\partial r} - \frac{\partial p}{\partial r}\underline{\delta}$$

By the same logic used in Proof of Lemma 1 with $\frac{\partial p}{\partial r} < 0$ from Lemma 4, $\frac{\partial q_A}{\partial r} > 0$. $\square$

Proof of Lemma 6 First, consider the case in which firm A uses the abatement technology exclusively. Compare firm A's profits with and without technology licensing. In particular, consider the license contract with $r = t\varepsilon$ and $f = 0$, which makes firm B maintain the same output level, that is $q_B(t, 0, \overline{\delta}) = q_B(t, t\varepsilon, \overline{\delta} - \varepsilon)$. Equation (3) implies that $q_A(t, 0, \overline{\delta}) = q_A(t, t\varepsilon, \overline{\delta} - \varepsilon)$ as well. Since firm A gets additional profit from selling the license $t\varepsilon q_B(t, t\varepsilon, \overline{\delta} - \varepsilon)$, 'no license' cannot be an optimal strategy for firm A.

Now, consider optimality of the license contract characterized in (21). Denote by $\hat{\pi}_A(p(n, r, \overline{\delta} - \varepsilon), r, \overline{\delta} - \varepsilon)$ the objective function in (19). Taking derivative of $\hat{\pi}_A(p(n, r, \overline{\delta} - \varepsilon), r, \overline{\delta} - \varepsilon)$ with respect to r and combining it with (16) and (17) yields

$$\begin{aligned}
\frac{\partial \hat{\pi}_A}{\partial r} &= P('(q_A + q_B)(\frac{\partial q_A}{\partial r} + \frac{\partial q_B}{\partial r}) - \underline{\delta}\frac{\partial p}{\partial r})q_A + [P(q_A + q_B) - p\underline{\delta}]\frac{\partial q_A}{\partial r} \\
&\quad + P'(q_A + q_B)\frac{\partial q_A}{\partial r} + (\frac{\partial q_B}{\partial r} - \delta_B\frac{\partial p}{\partial r})q_B + [P(q_A + q_B) - p\delta_B]\frac{\partial q_B}{\partial r} \qquad \text{(A12)} \\
&= P'(q_A + q_B)q_B\frac{\partial q_A}{\partial r} - [P(q_A + q_B) - r - p\underline{\delta}]\frac{\partial q_B}{\partial r} - (\underline{\delta}q_A + \delta_B q_B)\frac{\partial p}{\partial r},
\end{aligned}$$

where $p = p(n, r, \overline{\delta} - \varepsilon)$. Since $0 < (\partial q_A)/(\partial r) < -(\partial q_B)/(\partial r)$ from Lemma 5 and $\underline{\delta} \leq \overline{\delta} - \varepsilon$,

$$\begin{aligned}
\frac{\partial \hat{\pi}_A}{\partial r} &= P'(q_A + q_B)q_B\frac{\partial q_A}{\partial r} + [P(q_A + q_B) - r - p\underline{\delta}]\Big(-\frac{\partial q_B}{\partial r}\Big) - (\underline{\delta}q_A + \delta_B q_B)\frac{\partial p}{\partial r} \\
&> P'(q_A + q_B)q_B\frac{\partial q_A}{\partial r} + [P(q_A + q_B) - r - p\underline{\delta}]\frac{\partial q_A}{\partial r} - (\underline{\delta}q_A + \delta_B q_B)\frac{\partial p}{\partial r} \\
&\geq [P'(q_A + q_B)q_B + P(q_A + q_B) - r - p(\overline{\delta} - \varepsilon)]\frac{\partial q_A}{\partial r} - (\underline{\delta}q_A + \delta_B q_B)\frac{\partial p}{\partial r} \qquad \text{(A13)} \\
&= -(\underline{\delta}q_A + \delta_B q_B)\frac{\partial p}{\partial r} > 0.
\end{aligned}$$

The last equality follows from (17). Therefore, firm A's profit increases in per unit royalty. $\square$

Proof of Lemma 7 First, consider the case with $\varepsilon = \overline{\delta} - \underline{\delta}$. Since

$$P(q_A^P + q_B^P) = \underline{\delta} = P(q_A^* + q_B^*), \tag{A14}$$

the aggregate output levels are same in both planner's problem and the market equilibrium outcome under Pigouvian taxation. In addition, all firms in both problems use the same abatement technology, $\delta_A = \underline{\delta} = \overline{\delta} - \varepsilon = \delta_B$ so that the amount of pollutants are same as well. From equation (10), we conclude that when $\varepsilon = \overline{\delta} - \underline{\delta}$, the Pigouvian taxation scheme achieves the efficient allocation of the planner's problem.

Second, consider the case with $\varepsilon < \overline{\delta} - \underline{\delta}$. Lemma 3 says that $d(q_A + q_B)/dt < 0$ and $dq_B/dt < 0$. Then, equation (12) implies that, whether (dq_A/dt) is negative or not, $P(q_A^P + q_B^P) > \underline{\delta}$, which implies that $q_A^P + q_B^P < q_A^* + q_B^*$ and $\underline{\delta}_A q_A^P + (\overline{\delta}_B - \varepsilon) q_B^P > \underline{\delta} q_A^*$. $\square$

Proof of Lemma 8 (i) Suppose that firm A offers $\hat{r} = r^P = t^P \varepsilon$ under the emission trading scheme and firm B accepts it. Then, (t^P, r^P) through (q_A^P, q_B^P, n^P) satisfying (3), (4), and (14). Once n^P is fixed by the government, conditions (14) and (15) are equivalent. Let $\hat{p} = p(n^P, r^P, \overline{\delta} - \varepsilon)$. If $\hat{p}$ is lower (higher) than t^P, equations (3), (4), (16), and (17) imply that $(q_A(\hat{p}, \hat{r}), q_B(\hat{p}, \hat{r}))$ are more (less) than (q_A^P, q_B^P). The former cannot satisfy with (15). Thus, $\hat{p} = p(n^P, r^P, \overline{\delta} - \varepsilon) = t^P$. We also obtain $q_A(\hat{p}, \hat{r}) = q_A^P$ and $q_B(\hat{p}, \hat{r}) = q_B^P$ so that $\pi_B(\hat{p}, \hat{r}, 0, \overline{\delta} - \varepsilon) = \pi_B(t^P, t^P \varepsilon, 0, \overline{\delta} - \varepsilon)$.

Now, consider the case that firm B rejects the license contract. Under the Pigouvian taxation scheme, t^P remains unchanged. Under the emission trading scheme, the permit price is determined at $p(n^P, 0, \overline{\delta})$, which is greater than $\hat{p} = t^P$. It implies that $\pi_B(p(n^P, 0, \overline{\delta}), 0, 0, \overline{\delta}) < \pi_B(t^P, 0, 0, \overline{\delta})$. Then,

$$\pi_B(\hat{p}, \hat{r}, 0, \overline{\delta} - \varepsilon) - \pi_B(p(n^P, 0, \overline{\delta}), 0, 0, \overline{\delta}) > \pi_B(t^P, t^P \varepsilon, 0, \overline{\delta} - \varepsilon) - \pi_B(t^P, 0, 0, \overline{\delta}) = 0, \tag{A15}$$

which implies that firm A can get more profit by imposing a higher royalty rate than $\hat{r} = t^P \varepsilon$ under the emission trading scheme with n^P.

(ii) From the result of (i), we obtain that

$$q_B^P(t^P, r^P) = q_B^E(p^E(n^P, r^P, \overline{\delta} - \varepsilon), r^P) > q_B^E(p^E(n^P, r^E(n^P), \overline{\delta} - \varepsilon), r^E(n^P)). \tag{A16}$$

From (14), we also get $q_A^P(t^P, r^P(t^P)) < q_A^E(p^E(n^P, r^E(n^P), \overline{\delta} - \varepsilon), r^E(n^P))$. $\square$

Proof of Lemma 9 Under Pigouvian taxation, the strategy profile of $(t_0^P, q_{A0}^P, q_{B0}^P)$ maximizes total surplus and each firm's profit, respectively. Note that this is a unique equilibrium outcome, as the second order sufficient conditions are globally satisfied.

Each firm's profit maximization problem under the Pigouvian taxation scheme is equivalent to the problem under the emission trading scheme, because the latter is obtained by replacing t in the former with p. Then, as long as $t_0^P = p(n_0^E, \overline{\delta} - \varepsilon)$, we obtain that $(q_{A0}^P, q_{B0}^P) = (q_{A0}^E, q_{B0}^E)$. In other words, let n_0^P be the total pollution level under the socially optimal taxation policy with $t = t_0^P$. The government can achieve the same allocation under the emission trading scheme by choosing $n_0^E = n_0^P$. The equilibrium outcome under the Pigouvian taxation scheme can be implemented under the emission trading scheme.

Now, suppose that there exists another strategy profile $(n_0^{E'}, q_{A0}^{E'}, q_{B0}^{E'})$ under the emission trading scheme. It should be an equilibrium strategy profile under the Pigouvian taxation scheme as well, because the government can directly choose $t = p(n_0^{E'})$

without the market clearing condition. It violates the uniqueness of the solution under the Pigouvian case. Therefore, $(t_0^P, q_{A0}^P, q_{B0}^P)$ and $(n_0^E, q_{A0}^E, q_{B0}^E)$ should uniquely implement an equivalent outcome under each scheme. Trivially, the total pollution level is same ($n_0^P = n_0^E$), and the profit of firm A are same as well. $\square$

Proof of Proposition 2 Suppose that the government maintains its original environment policy. That is, $t = t_0^P$ if it implements the Pigouvian taxation scheme, $n = n_0^E = n_0^P$ if it adopts the emission trading scheme. Then, the ex post price adjustment in the permit market dictates that $p(n_0^E, r^P, \overline{\delta} - \varepsilon) < t_0^P$, which implies that $r^P = t_0^P \varepsilon$ is a feasible option for firm A under the emission trading scheme. Moreover, by the same reasoning in the proof of Lemma 8, firm A's optimal choice of $r^E(n_0^E, \overline{\delta} - \varepsilon)$ under the emission trading scheme is strictly greater than $r^P(t_0^P, \overline{\delta} - \varepsilon)$. Given $r^E(n_0^E, \overline{\delta}-\varepsilon) > r^P(t_0^P, \overline{\delta}-\varepsilon)$, firm A gets more profit after technology innovation and licensing under the emission trading scheme than the Pigouvian taxation scheme. Since it gets the same profit ex ante regardless of the policy instrument (as shown in the previous proof), firm A expects a higher benefit from technology innovation under the emission trading scheme. $\square$

Proof of Proposition 3 Suppose that firm A offers r^P under the emission trading scheme. Note that $n^E < n^P$, which implies that $p(n^E, r^P, \overline{\delta}-\varepsilon) > p(n^P, r^P, \overline{\delta}-\varepsilon) = t^P$. Since $p(n^E, r^E, \overline{\delta} - \varepsilon) < t^P$, there exists $\hat{r} \in (r^P, r^E)$ such that $\hat{r}$ solve $p(n^E, \hat{r}, \overline{\delta} - \varepsilon) = t^P$. Of course, the license offer with $r = \hat{r}$ and $f = 0$ under the Pigouvian taxation scheme is hardly accepted by firm B. But, if it is accepted,

$$\pi_A^P(t^P, \hat{r}, 0, \overline{\delta} - \varepsilon) > \pi_A^P(t^P, r^P, 0, \overline{\delta} - \varepsilon), \tag{A17}$$

because $\hat{r} > r^P$ and $(\partial \pi_A^P)/(\partial r) > 0$ from the proof of Lemma 2. On the other hand, $\hat{r}(< r^E)$ is feasible under the emission trading scheme, which implies that

$$\pi_A^E(p(n^E, \hat{r}, \overline{\delta} - \varepsilon), \hat{r}, 0, \overline{\delta} - \varepsilon) \leq \pi_A^E(p(n^E, r^E, \overline{\delta} - \varepsilon), r^E, 0, \overline{\delta} - \varepsilon), \tag{A18}$$

by the optimality of r^E. Connecting (A17) with (A18) yields

$$\begin{aligned} & \pi_A^P(t^P, r^P, 0, \overline{\delta} - \varepsilon) < \pi_A^P(t^P, \hat{r}, 0, \overline{\delta} - \varepsilon) \\ = \; & \pi_A^E(p(n^E, \hat{r}, \overline{\delta} - \varepsilon), \hat{r}, 0, \overline{\delta} - \varepsilon) \leq \pi_A^E(p(n^E, r^E, \overline{\delta} - \varepsilon), r^E, 0, \overline{\delta} - \varepsilon), \end{aligned} \tag{A19}$$

where the equality in the middle comes from the definition of $\hat{r}$. $\square$

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