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# The Effects of Emission Taxes on Pollution through the Diffusion of Clean Technology: The Presence of Green Consumers

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# The Effects of Emission Taxes on Pollution through the Diffusion of Clean Technology: The Presence of Green Consumers*

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**Abstract**

We analyze how the implementation of an emission tax influences aggregate pollution through the diffusion of a new, less polluting technology. Our focus is on how the consumption behavior of green consumers changes the relationship between policy stringency and the equilibrium state of technology diffusion or the ranking of the states of technology diffusion (i.e., full, partial, and no diffusion) in terms of aggregate pollution. We find that emission taxes should not be too high for an "efficient full-diffusion equilibrium" to emerge, in which the full diffusion of the new technology occurs in equilibrium and attains the lowest level of aggregate pollution. If the emission tax is high, aggregate pollution may be lowest in the no diffusion scenario. In addition, the presence of green consumers narrows the range of emission taxes and degree of the new technology that leads to the efficient full-diffusion equilibrium and widens the range of parameters for which aggregate pollution is lowest in the no diffusion case.

*Keywords*: technology diffusion; emission taxes; green consumers

*JEL classification*: Q55; Q58; H23; L13

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# 1 Introduction

Conventional wisdom in environmental economics suggests that environmental policy is required to reduce pollution. However, while a monotonic relationship between policy stringency and aggregate pollution holds under a static framework, this fact may not be true in a dynamic one in which environmental policy affects the incentives to develop and/or adopt a less polluting technology. Indeed, recent studies have shown that the relationship between policy stringency and the rate of technology adoption is actually non-monotonic (Perino and Requate, 2012; Bréchet and Meunier, 2014).

Moreover, a growing stream of research has suggested that the presence of environmentally aware agents should be taken into account when optimal environmental policy is designed (e.g., Bansal, 2008; Bansal and Gangopadhyay, 2003; Brécard, 2011; Doni and Ricchiuti, 2013). Environmentally conscious consumers, or *green consumers*, are willing to pay a price premium to purchase less polluting and environmentally friendly goods. In addition, given that such consumers have an incentive to contribute voluntarily to reduce aggregate pollution, optimal environmental policy should reflect their preferences and behaviors. However, little investigation has thus far explored how the presence of green consumers affects the relationship between policy stringency and the adoption of the new technology.

Based on the foregoing, we examine the effects of emission taxes on aggregate pollution when the diffusion of a new, less polluting technology is taken into account. In particular, our interest lies in how the presence of green consumers changes the relationship between policy stringency and the equilibrium state of technology diffusion or the ranking of the states of technology diffusion (i.e., full, partial, and no diffusion) in terms of aggregate pollution. To our best knowledge, no study has examined the policy implications of an imperfectly competitive, polluting output market, market power in the upstream research and development (R&D) sector, and the presence of green consumers simultaneously.

To explore the effects of emission taxes under a framework that captures all these elements, we extend and modify the model of a duopolistic product market with environmentally conscious consumers developed by Gil-Moltó and Varvarigos (2013). In their model, two manufacturing firms produce a homogeneous good, with pollution generated from the production. Further, the government exogenously imposes emission taxes and consumers are environmentally conscious in the sense that an increase in aggregate pollution reduces demand for the good. Each firm can also reduce its emission rate by developing a new technology at a fixed cost. In order to extend their model, we include the imperfectly competitive upstream R&D sector. To simplify the analysis, however, we assume that the upstream R&D sector is monopolistic.[1] We then analyze the diffusion of this new technology in the model of a three-stage game. In stage 1, the R&D firm that has developed a new, cleaner technology sets its price level. In stage 2, two downstream manufacturing firms simultaneously decide whether to adopt the new technology. In the final stage, the two downstream firms compete in the product market in a Cournot fashion. We then show that the partial diffusion of the new technology can naturally emerge in equilibrium. Whereas Gil-Moltó and Varvarigos (2013) assume in an ad hoc manner that positive spillovers associated with the adoption of a cleaner technology by other firms reduce the fixed cost of technology adoption, we do not need such an assumption. Moreover, in contrast to Gil-Moltó and Varvarigos (2013), we investigate how emission taxes influence aggregate pollution through the diffusion of an advanced technology.

Most previous studies of green consumers employ the framework of a vertically differentiated duopoly with heterogeneous consumers (Bansal, 2008; Bansal and Gangopadhyay, 2003; Brécard, 2011; Doni and Ricchiuti, 2013). Under such a framework, even though consumption goods are physically homogeneous, consumers perceive them to be differentiated by their environmental performance (possibly in the production stage). In addition, because consumers make different marginal valuations of the environmental attributes of these goods, those with higher (lower) environmental consciousness purchase a good with higher (lower) environmental quality. We depart from the majority of the literature by modeling the behavior of green consumers according to the framework developed by Gil-Moltó and Varvarigos (2013).

[1] Perino (2010) and Requate (2005) also assume the presence of a monopolistic R&D sector. Since our focus is on the diffusion of a new, cleaner technology and we do not explicitly model the R&D stage, our framework can be interpreted as a static one in which one firm has already won the R&D race.

Under their framework, the degree to which consumers are environmentally friendly is measured as the aggregate consumption of homogeneous goods. Specifically, green consumers change their individual levels of demand for such goods depending on the environmental performance of the industry as a whole. Hence, if firms in the industry are more polluting, consumers reduce their demand for all the goods produced by this sector. For instance, consumers know that their electricity consumption contributes to emissions of greenhouse gases such as $CO_2$. The emission rate varies by the mode of electric power generation (thermal, hydro, nuclear, solar, etc.). Since electric power companies release detailed information on their technologies and total outputs, consumers can therefore calculate the extent to which their electricity consumption decisions lead to greenhouse gas emissions. In addition, electricity itself is typically a homogeneous product whose quality—from a consumer's perspective—is little related to its emission rate. Coal-fired thermal power plants, for example, can reduce their $CO_2$ emissions by installing technologically advanced electric power equipment. Consumers are known to be willing to pay a premium for green electricity (e.g., Roe et al., 2001; Longo et al., 2008). In the same vein, Kotchen and Moore (2008) theoretically show an equivalent relationship between willingness to pay a price premium for green electricity and voluntary restraint (i.e., a decrease in demand) for conventional electricity. In addition, by using billing data for both participants and non-participants in a green electricity program in the United States during 2003–2008, Jacobsen et al. (2012) find that households with higher electricity consumption are more likely to participate in the green electricity program, which implies that they care about the actual level of emissions. They also find that participating households that enroll at the minimum level of the green electricity program increase electricity consumption by 2.5 percent after their enrollment.

We find a number of interesting results in this paper. We first show that the new technology is adopted by the two downstream firms or by only one firm in equilibrium if an emission tax is lower or higher than a particular level and that the presence of green consumers lowers this threshold. Second, we show that an increase in the degree of technological advancement allows the upstream R&D firm to charge a higher price in both the partial and the full diffusion scenarios, whereas such a rise narrows the range of emission taxes in the latter. Third, we show that consumer surplus monotonically increases with the average level of the clean technology in the industry, which contrasts with the non-monotonic relationship between aggregate pollution and technology level or emission taxes. Fourth, we demonstrate that there exists a range of emission taxes for which the full diffusion of the new technology is the equilibrium but that aggregate pollution is lower under partial diffusion. Finally, we characterize the range of emission taxes and the new technology for which the equilibrium states of technology diffusion are ranked by aggregate pollution in order to show how the range of parameters differs in the presence and absence of green consumers. Without green consumers, full diffusion occurs in equilibrium and yields the lowest level of aggregate pollution for any level of the new technology if an emission tax is set below a particular level. If the emission tax is higher than this threshold, however, full diffusion may not be obtained in equilibrium and the lowest level of aggregate pollution is attained in either the partial or the no diffusion scenarios. On the contrary, the presence of green consumers narrows the range of parameters for which full diffusion is obtained in equilibrium and the lowest level of aggregate pollution is achieved. The presence of green consumers also widens the range of parameters for which aggregate pollution is lowest when no firm adopts the new technology.

A number of studies have examined the relationship between environmental policy and the development and diffusion of a cleaner technology (Requate and Unold, 2001, 2003; Requate, 2005; Perino and Requate, 2012; Bréchet and Meunier, 2014). Requate and Unold (2001, 2003) and Requate (2005) examine the linkage between environmental policy and incentives to adopt a new technology or to invest in R&D in a competitive market, finding a monotonic relationship between policy stringency and the rate of technology diffusion or R&D investment. Unlike Requate (2005), however, we analyze the interplay between imperfect competition in the output market and the incentive to adopt an advanced technology, showing that strategic interactions between polluting firms in the output market crucially affect their incentive to adopt a new technology and hence the degree of technology diffusion. In particular, when polluting firms compete in such an imperfectly competitive output market, only a proportion of firms may adopt the advanced technology in equilibrium even if they are *ex ante* identical and the sector is regulated by the implementation of emission taxes. This result contrasts with those in the case of a competitive market (Requate and Unold, 2001; Requate, 2005), in which heterogeneity among firms is needed for the partial diffusion of the new technology induced by tax policy. In addition, market power in the upstream R&D sector plays a major role in determining the degree of technology diffusion. A monopolistic R&D firm may charge a price that leads to the partial diffusion of an advanced technology if it can earn higher profits by doing so.[2] More recent studies such as Perino and Requate (2012) and Bréchet and Meunier (2014) also derive a non-monotonic relationship between policy stringency and technology adoption. Perino and Requate (2012) employ an abatement function cost approach with exogenous markets and show that crossing the marginal abatement cost curves for old and new technologies leads to an inverted U-shaped technology adoption rate. Bréchet and Meunier (2014) explicitly model a competitive output market and show that the share of adopting firms is non-monotonic with the stringency of environmental policy. We extend this stream of studies by examining how the presence of green consumers affects the relationship between stringency of emission taxes and the rate of technology diffusion. Our study also differs from Perino and Requate (2012) and Bréchet and Meunier (2014) in assuming the imperfectly-competitive upstream and downstream industries.

The contribution of the current paper differs from those of previous works in three main respects. First, we find a range of emission tax rates for which the equilibrium state indicates the full diffusion of the new technology but where total emissions are lower under the partial diffusion scenario. Second, our results indicate that emission taxes should not be too high for the full diffusion of the new technology to reach equilibrium and attain the lowest level of aggregate pollution, which we call the "efficient full-diffusion equilibrium." An intermediate level of emission taxes means that aggregate pollution can be reduced by changing the state of technology diffusion from full to partial. Moreover, for a combination of high emission taxes and a small degree of technological advancement, aggregate pollution is lowest at the status quo and highest under the full diffusion scenario. This result thus extends the finding by Bréchet and Meunier (2014). Third and most importantly, we find that the presence of green consumers

[2] Perino (2010) derives a similar result in the case of a competitive downstream industry.

narrows the range of emission taxes and degree of the new technology that leads to the efficient full-diffusion equilibrium and widens the range of these parameters for which aggregate pollution increases with the level of technology diffusion.

The remainder of the paper is organized as follows. In Section 2, we present the model setup. In Section 3, we obtain the equilibrium of the model. In Section 4, we explain how emission taxes and the new technology affect aggregate pollution and consumer surplus. In Section 5, we conclude.

## 2 The model

Consider a market in which two firms produce a homogeneous good, with pollution generated from the production. Consumers may be "green" in the sense that the market demand for this good is affected by the amount of total emissions. The degree of consumers' "greenness" is measured by the degree to which market demand for this good is affected by total emissions. The greener the consumers, the more market demand for the good decreases as emissions from its production increase.

Market demand for the good, $d(P, E)$, is assumed to be given by

$$d(P, E) = a - \gamma E - P, \tag{1}$$

where $a > 0$ is a parameter, $P$ is the price of the good, $E$ is total emissions, and $\gamma \geq 0$, the sensitivity of consumption to pollution, measures how market demand responds to a change in total emissions. Eq. (1) indicates that when $\gamma > 0$, market demand for the good decreases as $E$ increases. The larger $\gamma$, the greater is the negative effect of $E$ on demand.

Let $q_j$ be the quantity of the output of firm $j$ and $\mu_j$ the emissions from one unit of firm $j$'s production. Then, total emissions, $E$, are given by

$$E = \sum_{j=1}^{2} \mu_j q_j. \tag{2}$$

From the market clearing condition, it holds that

$$d(P, E) = \sum_{j=1}^{2} q_j. \tag{3}$$

The demand component is decreasing in price $P$ and level of pollution $E$. Hence, we substitute Eqs. (2) and (3) into (1) and arrange the terms to yield the inverse demand function:

$$P = a - \sum_{j=1}^{2}(1+\gamma\mu_j)q_j. \tag{4}$$

Next, let $c > 0$ be the constant marginal cost of production faced by both firms and $\tau \geq 0$ the charges for every unit of emissions.[3] Firm $j$'s variable profits are then given by

$$v_j = \left[a - \sum_{j=1}^{2}(1+\gamma\mu_j)q_j\right] q_j - (c+\tau\mu_j)q_j, \tag{5}$$

where $(c+\tau\mu_j)q_j$ represents firm $j$'s variable costs.

The two firms initially use the old, dirty technology for which $\mu_j = 1$. However, there is an R&D sector in which many R&D firms engage in developing a new, cleaner technology and one succeeds, making $\mu_j = g \in (0,1)$. This R&D firm sells the new technology to the manufacturing firms at price $\Psi$. Each manufacturing firm decides whether to buy and install the new, cleaner technology. Because we analyze the market after the invention of this new technology, the successful R&D firm acts as a monopolist.

We consider the following three-stage game. In stage 1, the R&D firm chooses the price of the cleaner technology. In stage 2, the two manufacturing firms simultaneously decide whether to buy and install the new technology. In stage 3, the two firms compete in a Cournot fashion. We use the subgame perfect Nash equilibrium as the solution concept and hence solve the model backward, as usual.

# 3 The diffusion of the clean technology

## 3.1 The third stage: Output choices of the manufacturing sector

The analysis of the third stage is basically the same as that in Gil-Moltó and Varvarigos (2013), although they only focus on the interior solution. Since the cost of adopting the new technology is sunk in the

[3] Although the government imposes the emission tax $\tau$, we treat it as a parameter and thus analyzing how $\tau$ is chosen is outside the scope of this study.

third stage, the two firms compete on quantity to maximize their variable profits $v_j$. The first-order condition for firm $j$ is then given by

$$\frac{\partial v_j}{\partial q_j} = [a - \sum_{j=1}^{2}(1+\gamma)q_j] - q_j(1+\gamma\mu_j) - c - \tau\mu_j = 0. \tag{6}$$

The second-order condition is satisfied:

$$\frac{\partial^2 \pi_j}{\partial q_j^2} = -2(1+\gamma\mu_j) < 0.$$

By solving (6), we obtain the best response for firm $j$:

$$q_j^* = \frac{[a - c - \tau\mu_j - q_{-j}(1+\gamma\mu_{-j})]}{2(1+\gamma\mu_j)}. \tag{7}$$

Then, by solving the system of best response functions for $j = \{1, 2\}$, we obtain the equilibrium levels of output as

$$q_1^* = \frac{a - c - \tau(2\mu_1 - \mu_2)}{3(1+\gamma\mu_1)}, \quad q_2^* = \frac{a - c - \tau(2\mu_2 - \mu_1)}{3(1+\gamma\mu_2)}.$$

For simplicity, we assume the original emission rate for producing one unit of the good is 1. After adopting the new, cleaner technology, the emission rate may reduce to $g$, with $g \in (0, 1)$. Depending on the choices of technology by the two firms, there are four possible cases for the quantity of firm $j$'s output, $q_j^{\mu_j,\mu_{-j}}$, as follows:

$$q_j^{1,1} = \frac{a - c - \tau}{3(1+\gamma)}, \tag{8}$$

$$q_j^{g,1} = \frac{a - c - (2g-1)\tau}{3(1+g\gamma)}, \tag{9}$$

$$q_j^{1,g} = \frac{a - c - (2-g)\tau}{3(1+\gamma)}, \tag{10}$$

$$q_j^{g,g} = \frac{a - c - g\tau}{3(1+g\gamma)}, \tag{11}$$

where $q_j^{1,1}$ represents the level of output when firms $j$ and $-j$ both use the old technology, $q_j^{g,1}$ output when firm $j$ adopts the clean technology and reduces the emission rate from 1 to $g$, while firm $-j$ does not, and so on. We assume $\tau < (a - c)$ to ensure a positive output when both firms use the old technology (Eq. (8)). When $\tau > (a - c)/(2 - g)$ holds, Eq. (10) implies that $q_j^{1,g}$ becomes negative.

Thus, for $\tau \geq (a-c)/(2-g)$, the firm that does not adopt the clean technology stops producing the good and thus the market structure changes from an oligopoly to a monopoly. Therefore, Eq. (10) should be rewritten as

$$q_j^{1,g} = \begin{cases} \frac{a-c-(2-g)\tau}{3(1+\gamma)} & \text{if } 0 \leq \tau < \frac{a-c}{2-g}, \\ \\ 0 & \text{if } \frac{a-c}{2-g} \leq \tau < a-c, \end{cases} \tag{12}$$

and hence Eq. (9) is given by

$$q_j^{g,1} = \begin{cases} \frac{a-c-(2g-1)\tau}{3(1+g\gamma)} & \text{if } 0 \leq \tau < \frac{a-c}{2-g}, \\ \\ \frac{a-c-\tau g}{2(1+g\gamma)} & \text{if } \frac{a-c}{2-g} \leq \tau < a-c. \end{cases} \tag{13}$$

Substituting Eqs. (8), (12), (13), and (11) into (5) yields the variable profits in each scenario:

$$v^{1,1} = \frac{(a-c-\tau)^2}{9(1+\gamma)}, \tag{14}$$

$$v^{g,1} = \begin{cases} \frac{(a-c-(2g-1)\tau)^2}{9(1+g\gamma)} & \text{if } 0 \leq \tau < \frac{a-c}{2-g}, \\ \\ \frac{(a-c-g\tau)^2}{4(1+g\gamma)} & \text{if } \frac{a-c}{2-g} \leq \tau < a-c, \end{cases} \tag{15}$$

$$v^{1,g} = \begin{cases} \frac{[a-c-(2-g)\tau]^2}{9(1+\gamma)} & \text{if } 0 \leq \tau < \frac{a-c}{2-g}, \\ \\ 0 & \text{if } \frac{a-c}{2-g} \leq \tau < a-c, \end{cases} \tag{16}$$

$$v^{g,g} = \frac{(a-c-g\tau)^2}{9(1+g\gamma)}. \tag{17}$$

### 3.2 The second stage: Technology choices of the manufacturing firms

We next analyze the manufacturing firms' decisions on technology adoption in the second stage. Here, each firm has two choices: adopt (A) or not adopt (N) the clean technology. Thus, the Nash equilibrium in the second stage can be analyzed by looking at the normal form game given in Table 1. Recall that $\Psi$ is the price of the clean technology charged by the R&D firm.

To analyze the Nash equilibria in stage 2, it is useful to define the benefits of and losses from adopting the clean technology. Let $\omega$ be the change in variable profits from adopting the clean technology, which

|  |  | Firm 2 |  |
|---|---|---|---|
|  |  | A | N |
| Firm 1 | A | $v^{g,g}-\Psi,\ v^{g,g}-\Psi$ | $v^{g,1}-\Psi,\ v^{1,g}$ |
|  | N | $v^{1,g},\ v^{g,1}-\Psi$ | $v^{1,1},\ v^{1,1}$ |

Table 1: The normal form game of technology adoption

we call "adoption benefits." In particular, we define the following:

$$\omega_1 \equiv v_j^{g,1} - v_j^{1,1} = \begin{cases} \frac{[a-c-\tau(2g-1)]^2}{9(1+\gamma g)} - \frac{(a-c-\tau)^2}{9(1+\gamma)} & \text{if } 0 \le \tau < \frac{a-c}{2-g} \\ \frac{(a-c-\tau g)^2}{4(1+\gamma g)} - \frac{(a-c-\tau)^2}{9(1+\gamma)} & \text{if } \frac{a-c}{2-g} \le \tau < a-c, \end{cases} \tag{18}$$

$$\omega_{-1} \equiv v_j^{1,g} - v_j^{1,1} = \begin{cases} -\frac{(a-c-\tau)^2}{9(1+\gamma)} + \frac{[a-c-\tau(2-g)]^2}{9(1+\gamma)} & \text{if } 0 \le \tau < \frac{a-c}{2-g} \\ -\frac{(a-c-\tau)^2}{9(1+\gamma)} & \text{if } \frac{a-c}{2-g} \le \tau < a-c, \end{cases} \tag{19}$$

$$\omega_2 \equiv v_j^{g,g} - v_j^{1,g} = \begin{cases} \frac{(a-c-\tau g)^2}{9(1+\gamma g)} - \frac{[a-c-\tau(2-g)]^2}{9(1+\gamma)} & \text{if } 0 \le \tau < \frac{a-c}{2-g} \\ \frac{(a-c-\tau g)^2}{9(1+\gamma g)} & \text{if } \frac{a-c}{2-g} \le \tau < a-c, \end{cases} \tag{20}$$

where $\omega_1$ denotes the adoption benefits when the rival producer still uses the dirty technology or when only one producer adopts the clean technology. Likewise, $\omega_2$ denotes the adoption benefits of the producers when their rival producer implements the clean technology as well. $\omega_{-1}$ indicates the adoption benefits when only the rival firm purchases the new technology. Since $\omega_{-1}$ is negative, this represents the loss from the rival firm's unilateral technology adoption, which implies that even if all the adoption benefits are seized by the R&D firm, producers still tend to buy the new technology, if possible, to avoid the possible loss generated by their competitor's implementation of it. We then obtain the following lemma:

**Lemma 1.** *For $\tau > 0$, the adoption benefit is larger when only one firm adopts the new technology. That is, $\omega_2 < \omega_1$.*

*Proof.* See the Appendix. □

When $\tau = 0$, it holds that

$$\omega_2 = \omega_1 = \frac{(a-c)^2\gamma(1-g)}{9(1+\gamma)(1+\gamma g)} \equiv \omega_0. \tag{21}$$

That is, the adoption benefit for a firm is the same regardless of whether the rival firm adopts the clean technology.

From the above results, we obtain the following proposition:

**Proposition 1.** *The Nash equilibria in the second stage are (i) (N, N) if $\Psi > \omega_1$, (ii) (N, N), (N, A), and (A, N) if $\Psi = \omega_1$, (iii) (N, A) and (A, N) if $\omega_2 < \Psi < \omega_1$, (iv) (A, A), (N, A), and (A, N) if $\Psi = \omega_2$, and (v) (A, A) if $0 < \Psi < \omega_2$.*

Proposition 1 shows that the degree of technology diffusion depends on the price of the clean technology charged by the R&D firm. At least one manufacturing firm adopts the clean technology if $\Psi$ is no higher than $\omega_1$. If $\Psi \leq \omega_2$, then the full diffusion of the new technology occurs.

Note that in case (iii) in Proposition 1, there are two equilibria. However, since the two manufacturing firms are ex ante identical, the outcomes in these two equilibria are actually the same; only the identity of the firm changes. If we assume that firms choose A or N sequentially, then the Nash equilibrium is unique even in case (ii).

## 3.3 The first stage: Pricing the technology

In stage 1, the R&D firm chooses the price of the clean technology to maximize its revenue. The revenue of the R&D firm is given by

$$\max_{\Psi} \Pi = N \times \Psi,$$

where $N$ denotes the number of manufacturing firms that adopt the clean technology and $\Psi$ the price set by the R&D firm.

Actually, there are only two possible choices for $\Psi$: $\Psi = \omega_1$ and $\Psi = \omega_2$. As shown in Proposition 1, both $\Psi = \omega_1$ and $\Psi = \omega_2$ result in multiple outcomes. However, if the R&D firm charges a price just below $\omega_1$ or $\omega_2$ by a small $\varepsilon > 0$, then the equilibrium is either (iii) or (v) in Proposition 1 and hence the outcome becomes unique in either case. We assume this is the case and indicate the prices by $\Psi = \omega_1$ and $\Psi = \omega_2$ for simplicity. Then, we define

$$\Omega \equiv 2\omega_2 - \omega_1,$$

which measures the difference in the R&D firm's revenue between the two choices of $\Psi$. The following proposition is thus obtained.

**Proposition 2.** *(i) If $\gamma = 0$, $\Omega \geq 0$ holds for all $\tau \in (0, \frac{a-c}{2-g})$.*

*(ii) If $\gamma > 0$, there exists $\tau^* \in (0, \frac{a-c}{2-g})$ such that*

$$\Omega \begin{cases} \geq 0 & for\ \tau \leq \tau^*, \\ < 0 & for\ \tau > \tau^*. \end{cases}$$

*(iii) When $\tau \in (\frac{a-c}{2-g}, a-c)$, $\Omega < 0$ holds for $\gamma \geq 0$.*

*Proof.* See the Appendix. □

The relationship between $\Omega$ and the state of the clean technology diffusion is as follows: (1) if $\Omega < 0$, the R&D firm chooses $\Psi = \omega_1$ so that only one manufacturing firm adopts the clean technology in equilibrium, leading to an equilibrium of partial diffusion and (2) if $\Omega > 0$, the R&D firm chooses $\Psi = \omega_2$ so that both manufacturing firms adopt the clean technology, and thus the full diffusion of the clean technology is the equilibria. In addition, $\tau^*$ is the upper limit of tax rate for full diffusion. In other words, full diffusion can be accomplished if and only if $\tau^* \geq \tau$.

When consumers are not green (i.e., $\gamma = 0$), since $\tau^* = (a-c)/(2-g)$ holds, the R&D firm always sets $\Psi = \omega_2$ and hence full diffusion is the only possible outcome for all rates of the emission tax that allow the duopoly market structure.

By contrast, when consumers are green (i.e., $\gamma > 0$), the partial diffusion of the clean technology becomes a possible outcome in a duopoly. Low emission taxes $\tau$ can encourage the R&D firm to sell its technology to more buyers, as the diffusion benefits would be positive. Moreover, an increase in $\tau$ facilitates the diffusion of the clean technology at lower levels of $\tau$ but impedes the diffusion of the clean technology at higher levels of $\tau$.

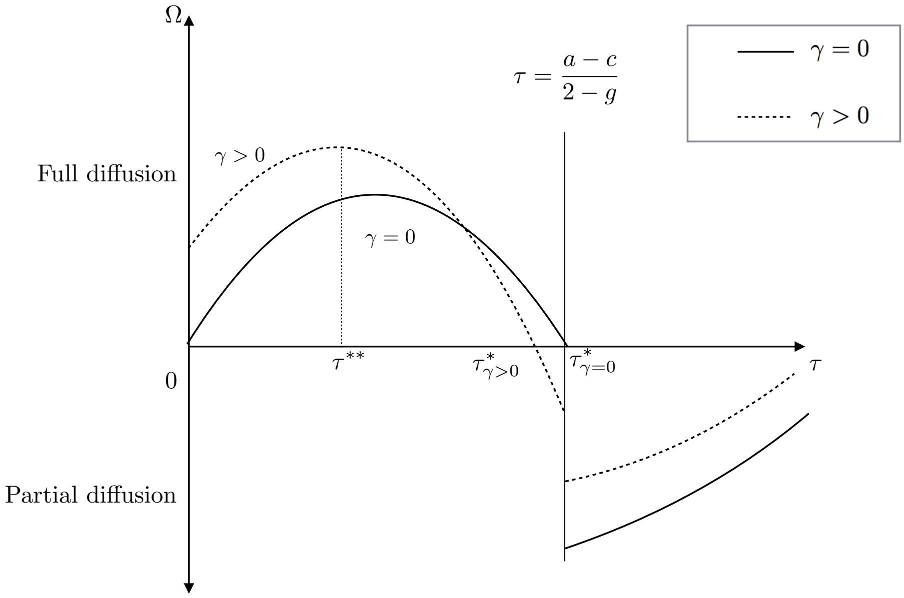


Figure 1: Emission taxes, green consumers' behavior, and technology diffusion

As shown in Figure 1, the upper limit of emission tax rate that allows the full diffusion of the clean technology lowers as consumers become greener. Thus, when consumers are green, an increase in the emission tax may change the state of technology adoption from full to partial diffusion.

### 3.4 Clean technology level and technology diffusion

We next examine how a change in the level of the clean technology affects the price charged by the R&D firm and the threshold level of the emission tax for full diffusion. We obtain the following proposition.

**Proposition 3.** *A cleaner technology (i.e., a lower $g$) allows the R&D firm to charge a higher price in both the partial and the full diffusion scenarios. However, a cleaner technology narrows the range of $\tau$ for the full diffusion of the new technology.*

*Proof.* See the Appendix. □

The implication of Proposition 3 can be illustrated by comparing two levels of technologies. We use the subscript $C$ to denote a clean technology and $D$ a dirty technology. Thus, we have $g_C < g_D$. Full diffusion will be accomplished when the tax rate is lower than $\tau_C^*$. Partial diffusion, namely when only one manufacturer adopts the clean technology, is the equilibrium if the emission tax is higher than $\tau_D^*$, where $\tau_C^* < \tau_D^*$. There exists a range of $\tau \in (\tau_C^*, \tau_D^*)$ in which the technology of $g_C$ is only partially diffused, whereas that of $g_D$ is fully diffused.

# 4 The effects of the clean technology on consumer surplus and total emissions

## 4.1 Diffusion of clean technologies and consumers

We first examine how the diffusion of clean technologies affects consumer surplus. Let $k = \mu_1 + \mu_2$ and $l = \mu_1\mu_2$, where $0 < k \leq 2$ and $0 < l \leq 1$. Then, $k/2$ can be seen as the average level of the clean technology in this industry. A low value of $k$ means a high average technology level. From Eq. (4), consumer surplus is given by

$$CS = \frac{[2(a-c) - \tau k][(a-c)(2+\gamma k) - (6\gamma l + k - \gamma k^2)\tau]}{18(1+\gamma k + \gamma^2 l)}. \tag{22}$$

It is easy to show that consumer surplus is decreasing in $\tau$. Moreover, with regard to how the average level of the clean technology affects consumer surplus, the following proposition is obtained:

**Proposition 4.** *Consumer surplus monotonically increases at the average clean technology level of the industry for* $\tau \in (0, \frac{a-c}{2-g})$.

*Proof.* Partially differentiating Eq. (22) with respect to $k$ yields

$$\begin{aligned} J(\tau) = \frac{\partial CS}{\partial k} = & \frac{2(a-c)^2\gamma\left(l\gamma^2 - 1\right) + (a-c)\tau\left[\gamma^2\left(k^2 + 8l\right) + 2kl\gamma^3 + 2k\gamma - 4\right]}{18(r(k+l\gamma)+1)^2} \\ & + \frac{\tau^2\left\{\gamma l[k\gamma(2-3k\gamma)+6] - 2k(k\gamma(k\gamma+1)-1) + 6\gamma^3 l^2\right\}}{18(r(k+l\gamma)+1)^2}. \end{aligned} \tag{23}$$

Note that in the above equation, every coefficient of $l$ is positive, and we have $l \leq k^2/4$. Thus, by substituting $l = k^2/4$ into Eq. (23), $f(\tau)$ is maximized. Thus, we have

$$J(\tau) < -\frac{[2(a-c) - k\tau][2(a-c)\gamma + \tau(k\gamma + 4)]}{9(k\gamma + 2)^2} < 0. \tag{24}$$

The function of consumer surplus $CS$ is monotonically decreasing in $k$. □

Proposition 4 implies that $CS_N < CS_P < CS_F$, for $k_F < k_P < k_N$, where the subscripts N, P, and F indicate the cases of no adoption, partial diffusion, and full diffusion, respectively.

We next consider the case in which $\tau > (a-c)/(2-g)$ holds, where the firm that adopts the new technology produces the good as a monopolist. In this case, the average technology level in the industry is $g$, which is the same as that when the clean technology is fully diffused, while the value of $k$ is $g$ and $2g$, respectively.

Let $\widehat{CS}_P$ represent consumer surplus when one firm owns the technology level of $g$, while another stops producing. Given Eq. (4) and Eq. (13), $\widehat{CS}_P$ is given by

$$\widehat{CS}_P = \frac{(a-c-g\tau)^2}{8(1+g\gamma)},$$

which is decreasing in both the emission tax rate $\tau$ and the technology level $g$. Thus, even when the market structure becomes a monopoly, a lower emission tax and a cleaner technology increase consumer surplus.

## 4.2 Diffusion of clean technologies and the environment

In this subsection, we analyze how the diffusion of the clean technology affects total emissions. Let $E_N$ be total emissions when no firm adopts the clean technology, $E_P$ total emissions when only one firm adopts, and $E_F$ total emissions when both manufacturing firms adopt. By substituting Eqs. (8)–(13)

into (2), total emissions in each case are given by

$$E_N = \frac{2[(a-c)-\tau]}{3(\gamma+1)},$$

$$E_P = \begin{cases} \frac{(a-c)-(2-g)\tau}{3(\gamma+1)} + \frac{g[(a-c)-(2g-1)\tau]}{3(g\gamma+1)} & \text{if } 0 < \tau \leq \frac{a-c}{2-g}, \\ \frac{g(a-c-g\tau)}{2(g\gamma+1)} & \text{if } \frac{a-c}{2-g} < \tau < a-c, \end{cases} \tag{25}$$

$$E_F = \frac{2g[(a-c)-g\tau]}{3(g\gamma+1)}.$$

Since full diffusion will never occur if $\tau > (a-c)/(2-g)$, we first discuss the range of $0 < \tau < (a-c)/(2-g)$ in which $E_F$ exists. The expressions of total emissions $E_N$, $E_P$, and $E_F$ are strictly decreasing functions of $\gamma$, which implies that green consumers can help reduce pollution at each state of technology diffusion.

Next, we consider the relations among $E_N$, $E_P$, and $E_F$. The following proposition shows that a greater diffusion of the clean technology may not necessarily reduce total emissions.

**Proposition 5.** *(i) There exists $\tau_1 > 0$, $\tau_2 > 0$, and $\tau_3 > 0$ such that*

$$\begin{cases} E_F - E_P < 0 \text{ if } \tau < \tau_1, \\ E_F - E_N < 0 \text{ if } \tau < \tau_2, \\ E_P - E_N < 0 \text{ if } \tau < \tau_3. \end{cases} \tag{26}$$

*Furthermore, we have $\tau_1 < \tau_2 < \tau_3$ for $\forall g < 1$ and $\forall \gamma$.*

*(ii) $0 < \tau_1 < \tau^*$ holds for $\tau \in (0, \frac{a-c}{2-g})$*

*Proof.* $(i)$ According to Eqs. (25) and (26),

$$\begin{aligned} E_P - E_N &= -\frac{(1-g)[(a-c)-g(2+\gamma)\tau]}{3(\gamma+1)(g\gamma+1)}, \\ E_F - E_P &= -\frac{(1-g)[(a-c)-\tau(g\gamma+2)]}{3(\gamma+1)(g\gamma+1)}, \\ E_F - E_N &= -\frac{2(1-g)[(a-c)-(1+g+g\gamma)\tau]}{3(1+\gamma)(1+g\gamma)}. \end{aligned} \tag{27}$$

Solving each of $E_F - E_p = 0$, $E_F - E_N = 0$, and $E_P - E_N = 0$ yields, respectively:

$$\tau_1 = \frac{a-c}{2+g\gamma}, \;\; \tau_2 = \frac{a-c}{1+g+g\gamma}, \;\; \tau_3 = \frac{a-c}{2g+g\gamma}. \tag{28}$$

From Eq. (27), at $g = 1$, we have $\tau_1 = \tau_2 = \tau_3 = (a - c)/(2 + \gamma)$. For $g < 1$, we have $2 + g\gamma = 1 + 1 + g\gamma > 1 + g + g\gamma$, which means that the denominator of $\tau_1$ is larger than that of $\tau_2$. Thus, $\tau_1 < \tau_2$ holds. Similarly, because $1 + g + g\gamma > g + g + g\gamma > 2g + g\gamma$, $\tau_2 < \tau_3$.

*(ii)* From Eq. (27), we find that $E_F - E_P$ is a linear decreasing function of $\tau$, and we thus have $E_F - E_P|_{\tau=\tau^*} > 0$ and $E_F - E_P|_{\tau=0} < 0$. Hence, $\tau_1$ must exist in $(0, \tau^*)$. $\square$

The first part of Proposition 5 shows the relationship between total emissions at different states of technology diffusion and levels of the emission tax. First, for $\tau < \tau_1$, $E_F < E_P < E_N$. Under the same emission tax rate, the full diffusion of the clean technology leads to the lowest total emissions, while no adoption causes the highest total emissions. The outcome of partial diffusion lies somewhere between the two. Next, for $\tau_1 < \tau < \tau_2$, $E_P < E_F < E_N$ holds, which means that the full diffusion of the clean technology generates higher total emissions than partial diffusion does. Moreover, $E_P < E_N < E_F$ holds if the tax rate is $\tau_2 < \tau < \tau_3$. In this case, the full diffusion of the clean technology actually increases total emissions compared with the case of both firms using the old technology. Finally, if $\tau > \tau_3$, $E_N < E_P < E_F$ holds. Thus, in this case, even the partial diffusion of the clean technology generates higher total emissions than does no technology adoption. Although the adoption of the clean technology reduces the emission rate for producing one unit of the good, a reduction in the marginal cost due to the lower emission rate causes the output of the adopted firm(s) to expand. Consequently, total emissions may increase by the diffusion of the clean technology.

In fact, the existence of $\tau_2$ and $\tau_3$ may be ambiguous, but $\tau_1$ must exist in the available range of $\tau$. Therefore, the second part of Proposition 5 reveals the relationship between the state of technology diffusion and environmental consequences under a duopoly market structure. We have already demonstrated in Proposition 2 that the full diffusion of the clean technology occurs if and only if $\tau \leq \tau^*$. As the emission tax rate rises above $\tau^*$, the equilibrium outcome changes to partial diffusion. However, the full diffusion of the clean technology does not necessarily lead to lower total emissions, as shown in Proposition 5. Moreover, Proposition 5 shows that there exists a range of emission taxes $\tau \in [\tau_1, \tau^*)$ for which total emissions are lower under partial diffusion, whereas the equilibrium outcome is full diffusion. This situation is depicted in Figure 2.

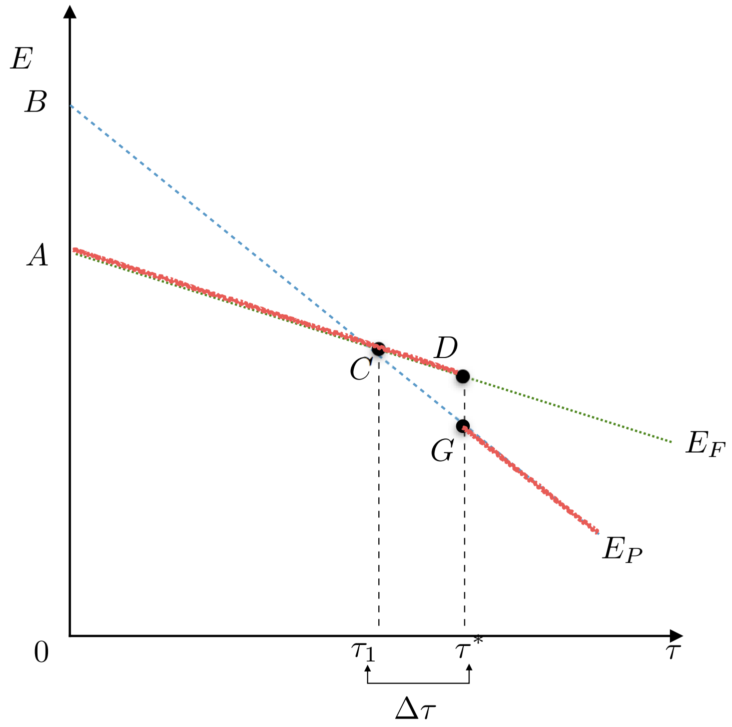


Figure 2: Environmental effects, emission taxes, and technology level

Figure 2 shows how total emissions change by altering the level of emission taxes. In this figure, the $E_P$ line indicates total emissions under partial diffusion and the $E_F$ line total emissions under full diffusion. The change in total emissions in equilibrium is presented as the line ACD. However, lower emissions are attained by the kinked line ACG. Thus, for $\tau \in [\tau_1, \tau^*)$, total emissions could reduce by changing full diffusion to partial diffusion. We term this case the "inefficient full-diffusion equilibrium."

The relationships among the emission tax rate and technological level and the ranking of total emissions at different states of technology diffusion are depicted in Figures 3 and 4.

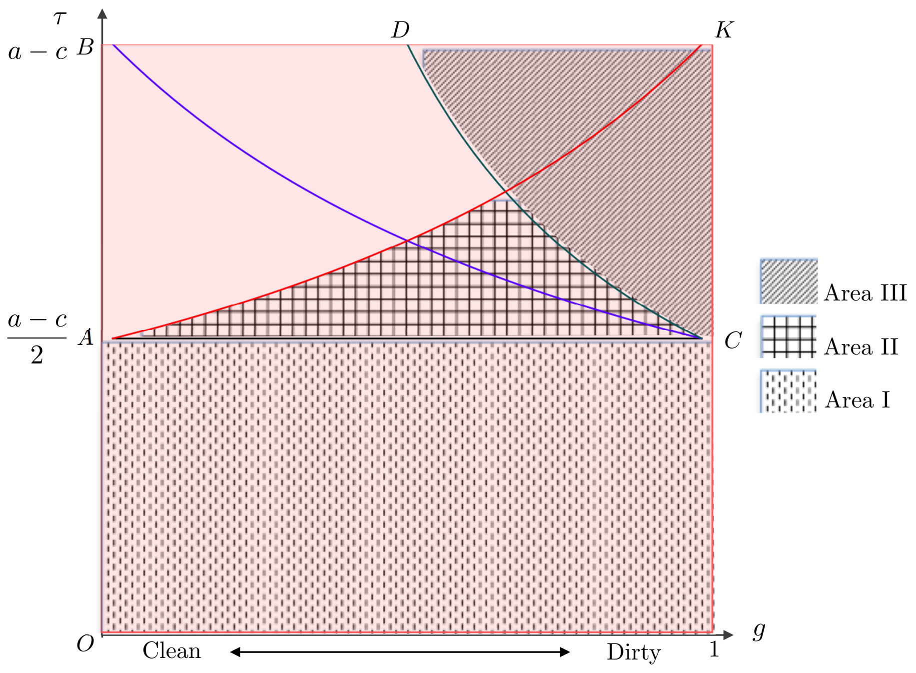


Figure 3: Clean technologies and policy design: without green consumers

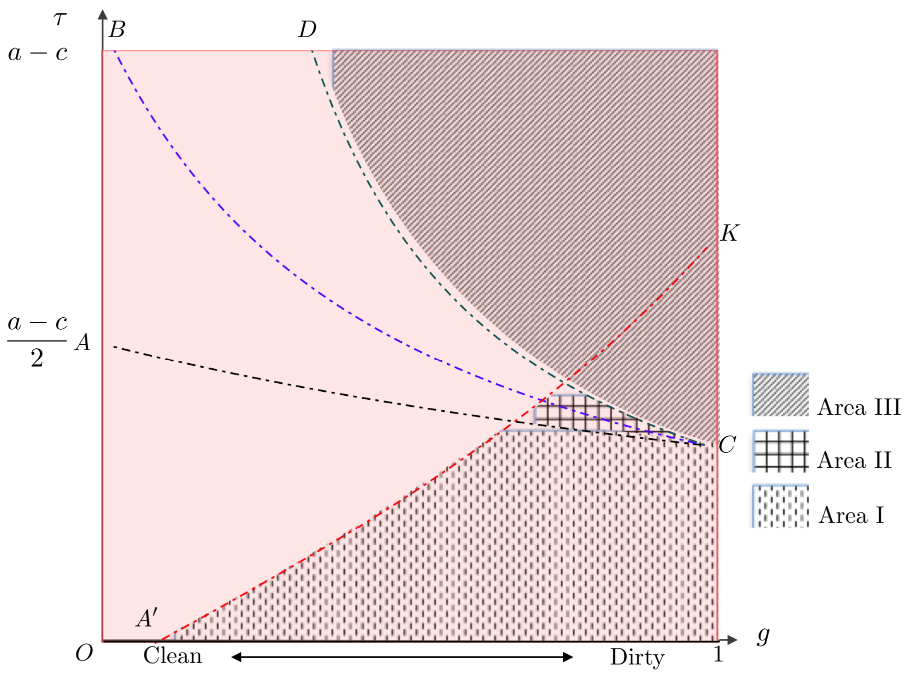


Figure 4: Clean technologies and policy design: with green consumers

In both these figures, the lines $\tau = \tau^*$, $\tau = \tau_1$, $\tau = \tau_2$, and $\tau = \tau_3$ are depicted as AK (A'K), AC, BC, and DC, respectively. Figure 3 illustrates the environmental outcomes under certain clean technologies and emission taxes when $\gamma = 0$. Area I represents the combination of technology level and emission tax rate for which full diffusion is achieved in equilibrium and leads to the lowest emissions. We call this the "efficient full-diffusion equilibrium." On the contrary, Area II corresponds to the inefficient full-diffusion equilibrium, where the technology is fully diffused in equilibrium but partial diffusion is actually better for the environment. In Area III, the no adoption case provides the lowest level of total emissions.

As shown in Figure 4, when $\gamma > 0$, $\tau_1$ and $\tau^*$ do not overlap at the original point of A in Figure 3 as $\tau^*$ shifts downwards to A'K. The results from comparing the cases of $\gamma = 0$ and $\gamma > 0$, which can be observed by comparing Figures 3 and 4, are summarized in the following proposition.

**Proposition 6.** *The existence of green consumers (i.e., $\gamma > 0$)*

*(i) narrows the range of $(g, \tau)$ for which the clean technology is fully diffused in equilibrium and leads to the lowest total emissions, and*

*(ii) widens the range of $(g, \tau)$ for which the lowest total emissions are obtained when the clean technology is not adopted by either firm.*

*Proof.* See the Appendix. □

Both Area I and Area II are smaller in Figure 4 than they are in Figure 3. A smaller Area II means that the range of parameters that falls in the inefficient full-diffusion equilibrium reduces because of the existence of green consumers. However, the existence of green consumers also reduces the range of parameters for the efficient full-diffusion equilibrium (i.e., Area I). Green consumers reduce their consumption of goods when total emissions are higher. Conversely, they increase their consumption of goods when the emission rate is lower. This mechanism reinforces the expansion of output by firm(s) adopting the clean technology and the effect is stronger as the new technology becomes cleaner (i.e., $g$ is smaller). Thus, the range of emission taxes and clean technologies that allows full diffusion to be achieved in equilibrium and leads to the lowest total emissions narrows if consumers are green. The same logic applies to the expansion of Area III in Figure 4 compared with Figure 3. Area III indicates the range of parameters for which total emissions are smaller when no firm adopts the new technology.

When the emission tax is high, the cost-reducing effect of adopting the new technology is strong and hence total emissions could increase even when only one firm adopts. Indeed, the existence of green consumers strengthens such an effect, as Area III is larger in Figure 4.

# 5 Conclusion

In this paper, we explored the degree to which green consumers change how emission taxes influence aggregate pollution when the diffusion of a new, less polluting technology is taken into account. In our model, the upstream R&D sector that supplies the clean technology is monopolistic, while the downstream manufacturing sector from which pollution is generated is duopolistic. We followed the approach taken by Gil-Moltó and Varvarigos (2013) to model the behavior of green consumers. In particular, our green consumers change their demand for the good depending on the degree to which the sector as a whole is polluting. In addition, instead of modeling heterogeneous consumers that change their product demand levels according to the product's environmental characteristics as in many previous studies, we set demand for the good to expand when firms reduce their per output emission level by adopting a clean technology, which is the key factor to the main results presented herein.

We then found that in the absence of green consumers the new technology is fully diffused in equilibrium and yields the lowest level of aggregate pollution for any technology level if an emission tax is set below a particular threshold (i.e., the efficient full-diffusion equilibrium). If the emission tax is above this threshold, however, full diffusion occurs in equilibrium but leads to a greater level of aggregate pollution compared with partial diffusion. The levels of both the new technology and the emission tax thereby affect the ranking of the states of technology diffusion in terms of aggregate pollution. In another case, full diffusion may not occur in equilibrium and aggregate pollution may be lowest in the no diffusion case. Again, the combination of an emission tax and the level of the new technology determines the equilibrium state of technology diffusion.

Most importantly, we found that the presence of green consumers narrows the range of parameters for the efficient full-diffusion equilibrium and widens the range of parameters for which aggregate pollution is lowest under the no diffusion scenario.

Our findings suggest that when market demand for the good responds to total emissions, an emission tax should be set at a low level in order to ensure that a newly developed, clean technology is fully diffused as well as attains the lowest level of aggregate pollution. Moreover, the emission tax rate should be adjusted according to the level of the new technology. In general, as the new technology becomes cleaner, the rate at which the emission tax for the efficient full-diffusion equilibrium emerges drops.

An important policy implication of our analysis is that environmental policy should be properly adjusted as consumers become more and more environmentally friendly and as green innovation makes production technology cleaner and cleaner. If such an adjustment does not occur, green innovation may not achieve its intended outcome (i.e., reducing aggregate pollution), or be discouraged altogether. In short, the importance of this information for the policy decision is emphasized, and policymakers should be sensitive to such changes in society.

# Appendix

## Proof of Lemma 1

*Proof.* When $0 < \tau < (a-c)/(2-g)$, by using Eqs. (18) and (20), we find that

$$\omega_2 - \omega_1 = -\frac{\tau(1-g)^2[2(a-c)\gamma + \tau(4+\gamma+g\gamma)]}{9(1+\gamma)(1+g\gamma)} < 0. \tag{29}$$

Similarly, when $(a-c)/(2-g) \leq \tau < a-c$,

$$\begin{aligned} \omega_2 - \omega_1 &= \frac{(a-c-\tau)^2}{9(\gamma+1)} - \frac{5(a-c-g\tau)^2}{36(g\gamma+1)} \\ &= \frac{(a-c-\tau)^2}{9(\gamma+1)} - \frac{(a-c-g\tau)^2}{9(g\gamma+1)} - \frac{1(a-c-g\tau)^2}{36(g\gamma+1)} \\ &= \frac{(1-g)\left[-(a-c)^2\gamma - 2(a-c)\tau + t^2(g\gamma+g+1)\right]}{9(\gamma+1)(g\gamma+1)} - \frac{(a-c-g\tau)^2}{36(g\gamma+1)} \end{aligned}. \tag{30}$$

Define

$$f(\tau) = -(a-c)^2\gamma - 2(a-c)\tau + t^2(g\gamma+g+1).$$

Obviously, $f(\tau)$ reaches its minimum when $\tau = (a-c)/(g\gamma+g+1)$, and the maximum must be obtained at either of the endpoints of $\tau$. Hence, we have

$$f(\tau)|_{\tau=(a-c)} = (a-c)^2[-2-\gamma+(1+g+g\gamma)] < 0,$$

$$f(\tau)|_{\tau=\frac{(a-c)}{(2-g)}} = (a-c)^2\left[\frac{g\gamma+g+1}{(2-g)^2} - \frac{2}{2-g} - \gamma\right] < 0.$$

Thus, $f(\tau) < 0$ holds for $\tau \in [(a-c)/(2-g), (a-c)]$. Substituting $f(\tau)$ into Eq. (30) yields

$$\omega_2 - \omega_1 = \frac{(1-g)f(\tau)}{9(\gamma+1)(g\gamma+1)} - \frac{(a-c-g\tau)^2}{36(g\gamma+1)} < 0,$$

which completes the proof of $\omega_2 - \omega_1 < 0$ for $\tau \in (0, a-c)$. □

## Proof of Proposition 2

*Proof.* ($i$) By combining Eqs. (12) and (13), the diffusion benefits are given by

$$\Omega = \frac{(1-g)}{9(\gamma+1)(g\gamma+1)}\left\{-\left[(8-4g)+(4g\gamma-2g^2\gamma)+\gamma\right]\tau^2 + 2(a-c)[2+(2g-1)\gamma]\tau + (a-c)^2\gamma\right\}. \tag{31}$$

Partially differentiating Eq. (18) with respect to $\tau$ yields

$$\frac{\partial\Omega}{\partial\tau} = \frac{2(1-g)}{9(1+\gamma g)(1+\gamma)}\left\{(a-c)[2+(2g-1)\gamma] - [8-4g+\gamma(1-2g^2+4g)]\tau\right\}.$$

Since the first term on the RHS is positive, $\partial\Omega/\partial\tau$ evaluated at $\tau = 0$ is positive. However, for $\tau > 0$, the second term on the RHS is subtracted from the first term. Then, at a certain level of $\tau^{**}$, $\partial\Omega/\partial\tau$ becomes zero, yielding

$$\tau^{**} = (a-c)\frac{2+(2g-1)\gamma}{(8-4g)\gamma(1-2g^2+4g)}.$$

Note that the denominator of the equation above is $8 - 4bg + +\gamma(1-2g^2+4g) > 8-4g$, while $[2+\gamma(2g-1)] < 3$ leads to $\gamma \in [0, 1/(2g-1)]$. Then, we have

$$\tau^{**} < (a-c)\frac{2+\gamma(2g-1)}{4(2-g)} < \frac{3}{4}\frac{(a-c)}{(2-g)},$$

which means that $\tau^{**}$ exists in $(0, [3(a-c)]/[4(2-g)])$. In addition, for $\tau > \tau^{**}$, it holds that $\partial\Omega/\partial\tau < 0$. From this, we can see that $\Omega$ is an inverted U-shaped curve and that the positive solution of $\Omega = 0$ must be on the RHS of $\tau^{**}$.

Next, we first consider the situation $\gamma = 0$. By solving $\tau$ with $\Omega = 0$, we derive that

$$\tau^*_{1,\gamma=0} = 0, \text{and } \tau^*_{2,\gamma=0} = \frac{(a-c)}{(2-g)}. \tag{32}$$

$(ii)$ When $\gamma > 0$, there is only one positive solution of $\tau$:

$$\tau^* = \frac{(a-c)}{8-4g+(1-2g^2+4g)\gamma}\Big[(2g-1)\gamma + 2 + \sqrt{2}\sqrt{\gamma[g(g\gamma+2)+\gamma+2]+2}\Big]. \tag{33}$$

Partially differentiating $\tau^*$ with respect to $\gamma$ yields

$$\frac{\partial\tau^*}{\partial\gamma} = (a-c)^2\frac{\sqrt{2}\{7\gamma+6-[(2g^2-6g+9)\gamma+4]g\} - 2(2g^2-6g+5)\sqrt{\gamma[g(g\gamma+2)+\gamma+2]+2}}{[2g(2\gamma-g\gamma-2)+\gamma+8]^2\sqrt{\gamma(g^2\gamma+2g+\gamma+2)+2}}. \tag{34}$$

The sign of $\partial\tau^*/\partial\gamma$ depends on the numerator of the above equation. Let us denote

$$\mathcal{A} = \sqrt{2}\{7\gamma+6-[(2g^2-6g+9)\gamma+4]g\} - 2(2g^2-6g+5)\sqrt{\gamma[g(g\gamma+2)+\gamma+2]+2}$$

and

$$\mathcal{B} = \sqrt{2}\{7\gamma+6-[(2g^2-6g+9)\gamma+4]g\} + 2(2g^2-6g+5)\sqrt{\gamma[g(g\gamma+2)+\gamma+2]+2},$$

where $\mathcal{A}$ decides the sign of the numerator in Eq. (34). Observe that as $\mathcal{B} > 0$, the sign of $\mathcal{A}$ must be the same as the product of $\mathcal{A}\cdot\mathcal{B}$. Therefore, we have

$$\mathcal{AB} = -2(1-g)^2\{-2g[2-(2-g)\gamma]+\gamma+8\}^2,$$

which is negative for all $g \in (0,1)$ and $\gamma \in (0,1)$. Therefore, $\mathcal{A} < 0$ and then $\partial\tau^*/\partial\gamma < 0$. Thus, $\tau^* < \tau^*_{2,\gamma=0}$ exists in $(0, (a-c)/(2-g))$.

$(iii)$ We consider the high tax rate $(a-c)/(2-g) \le \tau \le a-c$. Using Eqs. (18) and (20) yields

$$\Omega = \frac{(a-c-\tau)^2}{9(\gamma+1)} - \frac{(a-c-g\tau)^2}{36(g\gamma+1)}.$$

By observing that the second term is increasing in g, and that it is easy to get $g \leq 2-(a-c)/\tau$, we have

$$\Omega \leq \Omega|_{g=2-\frac{a-c}{\tau}} = \frac{\gamma(a-c-\tau)^3}{9(1+\gamma)\Theta},$$

where $\Theta = (a-c)\gamma - (1+2\gamma)\tau$. Obviously, the sign of $\Omega|_{g=2-(a-c)/\tau}$ is decided by $\Theta$. In addition, $\tau \geq (a-c)/(2-g) > (a-c)/2$ holds for $0 < g < 1$. Because $\Theta$ is linear and decreasing in $\tau$, we have

$$\Theta < \Theta|_{\tau=\frac{a-c}{2}} = (a-c)\gamma - \frac{a-c}{2}(1+2\gamma) < 0,$$

leading to the conclusion that $\Omega < 0$. □

## Proof of Proposition 3.

*Proof.* From Eq. (18),

$$\partial\omega_1/\partial g = \begin{cases} -\frac{\gamma[(a-c)-(2g-1)\tau]^2}{9(g-\gamma+1)^2} - \frac{4\tau[(a-c)-(2g-1)\tau]}{9(g\gamma+1)} < 0 & \text{if } 0 < \tau \leq \frac{a-c}{2-g} \\ -\frac{\gamma(a-c-g\tau)^2}{4(g\gamma+1)^2} - \frac{t(a-g\tau)}{2(g\gamma+1)} < 0 & \text{if } \frac{a-c}{2-g} < \tau < a-c \end{cases}$$

holds for $g \in (0,1)$, and from Eq. (20),

$$\partial\omega_2/\partial g = -\frac{\gamma(a-c-g\tau)^2}{9(g\gamma+1)^2} - \frac{2\tau(a-c-g\tau)}{9(g\gamma+1)} - \frac{2\tau[a-c-(2-g)\tau]}{9(\gamma+1)} < 0$$

when $\tau \in (0,(a-c)/(2-g)]$ holds for $g \in (0,1)$ as well.

From the proof of Proposition 2, we know that $\tau^*$ must be larger than $\tau^{**}$, leading to $\partial\Omega/\partial\tau^*|_{\tau=\tau^*} < 0$ holding. In addition, substituting Eq. (33) into the expression of $\Omega$ and partially differentiating $\Omega$ with respect to $g$ yields

$$\begin{aligned} \left.\frac{\partial\Omega}{\partial g}\right|_{\tau=\tau^*} &= \frac{4(a-c)^2(1-g)\left[\left(2g^3+5g-4\right)\gamma^3+3\left(2g^2+4g-1\right)\gamma^2+4(3g+2)\gamma+8\right]}{9(\gamma+1)(g\gamma+1)[8-4g(1+4g-2b^2)\gamma]^2} \\ &+ \frac{4\sqrt{2}(a-c)(1-g)[4+(2+4g)\gamma+(3-2g+2b^2)\gamma^2]\sqrt{a^2[2(1+g)\gamma+(1+g^2)\gamma^2]}}{9(\gamma+1)(g\gamma+1)[8-4g(1+4g-2b^2)\gamma]^2} > 0. \end{aligned} \tag{35}$$

By totally differentiating $\Omega$, we obtain

$$d\Omega = \frac{\partial\Omega}{\partial\tau}d\tau^* + \frac{\partial\Omega}{\partial g}dg = 0. \tag{36}$$

$\partial\Omega/\partial\tau < 0$ and $\partial\Omega/\partial g > 0$ hold at the point of $\tau = \tau^*$, yielding

$$\left.\frac{d\tau}{dg}\right|_{\tau=\tau^*} = -\frac{\partial\Omega/\partial g}{\partial\Omega/\partial\tau} > 0. \tag{37}$$

□

### Proof of Proposition 6

*Proof.* $(i)$ The border of the range of $(g,\tau)$ in question consists of the curves $\tau_1$, $\tau^*$, $\tau = 0$, $g = 0$, and $g = 1$ as $\tau \leq (a-c)/(2+g\gamma)$, $\tau \leq \tau^*$, $\tau > 0$, and $g \in [0,1]$. This corresponds to Area I in Figures 3 and 4. We prove part $(i)$ of the proposition by showing that both the $\tau_1$ and the $\tau^*$ curves shift down as $\gamma$ increases.

By using Eq. (28), it is easy to verify that $\partial\tau_1/\partial\gamma < 0$ for $\forall g > 0$, which means that the locus of the $\tau_1$ curve shifts down for $g > 0$ in the $(g,\tau)$ space as $\gamma$ increases. From Eq. (34), we also have $\partial\tau^*/\partial\gamma < 0$, which means that the locus of the $\tau^*$ curve shifts down for $g > 0$ in the $(g,\tau)$ space as $\gamma$ increases as well.

$(ii)$ For $\tau \leq (a-c)$ and $g \leq 1$, any $\tau \geq (a-c)/(2g+g\gamma)$, which is defined by the $\tau_3$ curve, gives the case in question. This corresponds to Area III in Figures 3 and 4. Since $\partial\tau_3/\partial\gamma < 0$ for $\forall g > 0$, the locus of the $\tau_3$ curve shifts up in the $(g,\tau)$ space as $\gamma$ increases. Therefore, Area III expands for a larger $\gamma$, and the range of $(g,\tau)$ inside Area III widens. □

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