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On the pigouvian tax rule in an open economy: the case of abatement technology trade

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Abstract

This note investigates the impact of international trade in pollution abatement technology on optimal pollution taxation. The abatement technology is licensed by an international eco-industry to domestic polluters at a fee that extracts the abatement rent (i.e. the abatement technology is subject to nonlinear pricing). The analysis highlights the trade-off between production efficiency and rent-shifting, faced by abatement technology importing countries: The emissions tax maximizing domestic welfare is below the marginal damage of emissions if some of the abatement rent is captured by foreign technology suppliers, and it decreases as the share of imported technologies increases.

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1 Introduction

Sound environmental policies take into account various complex economic factors. For example, to correct a pollution externality, the so-called pigouvian tax rule prescribes to levy a per unit emissions tax equal to the marginal damage of pollution.[1] In the absence of other economic distortions, applying this rule moves the competitive equilibrium of the economy to the social optimum. In second-best environments, however, this prescription must be amended. For example, it is well-known that the exercise of *market power in a polluting industry* might warrant to *under-internalize* the pollution externality (e.g., by levying an emissions tax *lower* than the marginal damage), so as to mitigate further distortion in the output market.[2] Moreover, a series of papers have recently revisited the pigouvian tax rule to take into account the impact of market power in the *eco-industry* on optimal policy design.[3]

As this recent literature argues, ever increasing ecological awareness and stricter environmental regulations worldwide have indeed given rise to a sizable market for environmental goods and services (EGS).[4] Ranging from end-of-pipe pollution control equipment and clean-up technologies, to recycling and professional services, these EGS are mainly supplied by a specialized eco-industry dominated by only a handful of large firms.[5] While environmental *services* such as contaminated soil and groundwater remediation, solid waste management and waste water treatment represent the bulk of this business, the licensing of environmental *equipment* also generates substantial revenue. Moreover, empirical evidence suggest that international trade in abatement technology plays an important role in many national environmental regulation and climate mitigation strategies.[6]

This note revisits the pigouvian tax rule, taking account of the possibility of international trade in EGS. It contributes to previous research by extending the analysis to the case of pollution abatement *technology* trade.[7] Implementing an abatement technology provides polluters subject to environmental regulation with the ability to reduce their compliance costs, thereby creating what might be called an "abatement rent". In the case of patented technologies, this rent partly returns to the technology suppliers through the proceeds of licensing. This note analyzes the impact of *international* licensing of such technologies on the optimal emissions tax in second-best environments. In line with conventional wisdom suggesting that governments of EGS-importing countries are less inclined to enforce stringent environmental policies, the present analysis shows that rent-shifting motives might induce such governments to strategically set lower emissions taxes than what they would have done in a closed economy and to *under-internalize* pollution externalities, so as to shift some rent from foreign EGS suppliers. In fact, the welfare-maximizing emissions tax to be levied in a *domestic* polluting industry decreases as the foreign share of the abatement rent accruing to the eco-industry increases.

In their pioneering work, David and Sinclair-Desgagné (2005) consider a *competitive* polluting industry *in a closed economy* and show that the exercise of market power on the supply side of EGS might warrant an emissions tax *exceeding* the marginal damage of emissions. Since they only consider a linear pricing schedule for EGS, the intuition behind this *over-internalization* result can be explained as follows: The exercise of market power in the eco-industry leads to EGS priced above their marginal cost and the polluters have to bear a positive markup for each unit of EGS they purchase. This distorts their abatement incentives downward. Therefore, *when the emissions tax is equal to the marginal damage*, the inadequate supply of (socially desirable) EGS moves the economy away from the welfare-maximizing equilibrium. To encourage

[1] The marginal damage of pollution depends on the estimated impact that environmental degradation has on various factors such as health, capital and labor productivity, etc. See e.g., Muller and Mendelsohn (2007).

[2] See e.g., Buchanan (1969) and Barnett (1980).

[3] See for example, David and Sinclair-Desgagné (2005, 2010), Perino (2010), Canton et al. (2008) and Nimubona and Sinclair-Desgagné (2013).

[4] The global market for eco-industries is estimated at roughly EUR 1.5 trillion a year in 2014 and the EU-27 has a strong export position vis-à-vis nearly all of the world's largest economies. See e.g., a study for the European Commission at http://ec.europa.eu/environment/enveco/jobs/.

[5] For tentative definitions of the eco-industry and EGS see e.g., OECD (2001).

[6] For example, using OECD patents data, Dechezleprêtre et al. (2011) report that, since the late 90's, environmental and climate policies have accelerated the pace of international diffusion of climate mitigation technologies and that environmental innovation remains concentrated within three countries (Japan, Germany and the USA) representing 60% of total innovation.

[7] The present analysis in fact applies as well to all EGS subject to nonlinear pricing.

more abatement and thereby mitigate this deadweight loss, the emissions tax must be raised above the pigouvian level.

Building on this work, Canton et al. (2008) and Nimubona and Sinclair-Desgagné (2013) extend the analysis to the case where *both* the polluting industry and the eco-industry are imperfectly competitive.[8] Essentially, what these papers suggest reads as follows: *When EGS are subject to linear pricing schedules*, the comparison between the welfare-maximizing emissions tax and the marginal damage depends on both industries' relative market power. More precisely, a relatively more concentrated polluting industry (resp. eco-industry) tilts the balance towards a lower (resp. higher) emissions tax. Importantly, however, underlying these results are two key assumptions which, in the light of available evidence on the eco-industry, deserve further examination.

The first questionable assumption concerns the rent redistribution induced by the emissions tax *within* the economy. In all the aforementioned papers the eco-industry's profits *entirely* contribute to *domestic* welfare. Therefore, the adverse impact a higher emissions tax might have on polluters and consumers' surpluses is somehow mitigated by an increase of these profits.[9] In many countries, however, polluters rely on imported EGS. In such cases, part of the eco-industry's profits "leaks" outside the boundaries of the domestic economy. Besides, while much of the eco-industry's turnover already results from international trade in EGS, ongoing discussions at the World Trade Organization include negotiations to remove the remaining trade barriers preventing their free flow.[10] This raises the question as to how the possibility of international trade in EGS does influence optimal environmental regulation. In fact, just like the present analysis, Canton (2007) and Nimubona (2012) show that the presence of an international eco-industry might drive governments of EGS-importing countries to strategically set lower emissions taxes than what they would have done in a closed economy, so as to shift some rent from foreign EGS suppliers. However, related to the second concern, following David and Sinclair-Desgagné (2005), these two papers exclusively focus on linear pricing schedules. Arguably, the assumption of a linear pricing schedule certainly is relevant for some EGS (e.g., for some environmental inputs to the polluters' abatement processes). It might however turn out to be less applicable to a lot of environmental *equipment* likely to be implemented in many polluting industries.[11] Unlike the previous literature, the present analysis examines the case of EGS subject to nonlinear pricing, with a focus on end-of-pipe abatement technologies.

Consider for example the case of end-of-pipe abatement *equipment* such as air pollution control devices (e.g., scrubbers, carbon capture technologies, filters, etc). Once having paid the cost for adopting this type of equipment, a polluter incurs only the operational costs associated with its desired level of pollution abatement. In the present model, adopting the patented abatement technology entails the upfront payment of fixed license fees to a (representative) technology supplier, whose licensing revenue are potentially shared among domestic and foreign owners.[12] The welfare-maximizing emissions tax is derived for both an imperfectly competitive polluting industry and a perfectly competitive one. The analysis suggests that even in the absence of economic distortions due to the exercise of market power in either industry, international rent-shifting motives might call for departing from the pigouvian tax rule. In the case of technology trade, regardless of the extent of market power in the polluting industry, the emissions tax that maximizes domestic welfare *never* exceeds the marginal damage and decreases as the share of the abatement rent accruing to the foreign eco-industry (e.g., as captured by the extent of *imported* technology) increases.

The intuition behind these results can be explained as follows. First, observe that, essentially, an emissions tax policy trades emissions (rights) off against tax revenue. Therefore, levying an emissions tax higher than the marginal damage is akin to pricing emissions above marginal cost. Such an emissions pricing generates

[8] David and Sinclair-Desgagné (2005) consider a Cournot oligopolistic eco-industry supplying EGS to a competitive polluting industry subject to environmental regulation. Canton et al. (2008) consider oligopolistic polluters taking the price of EGS as given, while Nimubona and Sinclair-Desgagné (2013) introduce monopsony power on the demand side of EGS.

[9] This line of reasoning is reminiscent of that suggesting that economic losses due to the enforcement of stringent environmental policies would be partially offset by the creation of "green jobs" in the eco-industry (see e.g., Martinez-Fernandez et al. (2010)).

[10] See e.g., The Environmental Goods Agreement at http://trade.ec.europa.eu/doclib/press/index.cfm?id=1116.

[11] Moreover, insofar as some environmental services are provided on a bilateral contractual base, it seems more natural to think of EGS suppliers' market power as their ability to extract most of the abatement rent from their customers with efficient bilateral contracts than as their ability to charge a markup on each unit of EGS they supply.

[12] By definition (of patents) the technology supplier is endowed with some monopoly rights over the use of its technology.

social inefficiency.[13] Turning then to the abatement side, note that as mentioned above, the polluters equipped with an abatement technology optimally reduce their emissions up to the point where the marginal cost of abatement is equal to the marginal benefit of abatement. By doing so, they realize some profit on infra-marginal abatement units. This profit, however, partly returns to the technology supplier through the payment of licensing fees. The optimal emissions tax therefore results from a trade-off between efficiency and *rent-shifting* motives. Lowering the emissions tax below the pigouvian level potentially accomplishes two beneficial operations. First, it alleviates the tax burden imposed on polluters and somehow passed on to consumers. This benefits society provided that the social marginal value of the good exceeds its social marginal cost. Second and in the case of international technology trade, lowering the tax reduces the technology suppliers' pie and thereby reduces the outflow of licensing revenue.

The remainder of the paper is organized as follows. The model is described in the next section. The welfare-maximizing emissions tax is derived in Section 3 and Section 4 contains concluding remarks.

2 Model

Consider a polluting industry where n ($n \geq 2$) symmetric producers (hereafter the *polluters*) compete à la Cournot to supply a homogenous good market characterized by the inverse demand $P(Q)$, where Q denotes the industry aggregate output. Let $P(Q)$ be twice continuously differentiable[14] and verify $P'(Q) < 0$, $\lim_{Q->0} P(Q) = +\infty$ and $\lim_{Q->+\infty} P(Q) = 0$. Each polluter can produce a quantity q of the good at a cost $C(q)$. This cost function is assumed to be increasing and convex in the production level i.e. for $q > 0$, $C'(q) > 0$, $C''(q) > 0$ and such that $C(0) = C'(0) = 0$.

The production process generates by-product emissions of a harmful pollutant and polluters are subject to a per unit emissions tax t. To reduce their emissions, the polluters can implement a patented *end-of-pipe* abatement technology allowing to remove part of the pollution generated during their production process. Equipped with such a technology, a polluter producing q units of the polluting good and a units of abatement would release $e(q, a)$ units of emissions into the environment and would accordingly pay an amount of emissions taxes equal to $te(q, a)$. The positive pollution function $e(q, a)$ is assumed to be increasing and convex in q. Producing more abatement reduces emissions but with decreasing returns to scale. Thus, $e(q, a)$ is decreasing and convex in a. Moreover, to capture the *end-of-pipe* characteristic of abatement, it is furthermore assumed that $e_{qa}(q, a) = 0$. This last assumption in fact implies that the pollution function is separable in q and a. Hence, let us write $e(q, a) = \max\{0, v(q) - w(a)\}$ and assume that $v(q)$ and $w(a)$ verify for $q > 0$, $v'(q) > 0$, $v''(q) > 0$ and for $a > 0$, $w'(a) > 0$, $w''(a) < 0$. Let us furthermore assume that $v(0) = v'(0) = 0 = w(0) = w'(0)$. Finally, the cost of producing a units of abatement is $G(a)$. This function is assumed to be increasing and convex in the abatement level i.e. for $a > 0$, $G'(a) > 0$ and $G''(a) > 0$ and such that $\lim_{a->+\infty} G'(a) = +\infty$ and $G(0) = G'(0) = 0$.[15]

Each polluter adopting this technology must pay a fixed license fee to a (representative) technology supplier whose licensing revenue are potentially shared among national and foreign owners. International competition within the eco-industry is modeled in a reduced form. It is simply assumed that a share $f \in [0, 1]$ of the eco-industry's profits ends up on foreign account. For simplicity, let us further assume that there are no costs of transferring and installing the technology. Moreover, to facilitate the analysis, the following reasonable assumption is maintained throughout the paper.

Assumption 1 *For all* $Q > 0$, $-\frac{P''(Q)Q}{P'(Q)} < (n+1)$ *and* $\lim_{Q->0}\left(-\frac{P'(Q)Q}{P(Q)}\right) < n$.

This merely technical assumption simply requires the demand function not be "too convex" nor "too elastic".

[13] Since the social marginal cost of emissions is equal to the marginal damage of emissions, levying an emissions tax higher than this marginal damage in an imperfectly competitive polluting industry causes a double marginalization problem.

[14] All the functions introduced below are assumed twice continuously differentiable on the relevant interval and $f'(x)$ and $f''(x)$ denote respectively the first and second derivatives of the function f.

[15] Along with the limit assumptions on $P(Q)$, these mildly restrictive assumptions on the polluters' production and abatement processes guarantee that every polluter's output and abatement level is strictly positive in equilibrium, and will thereby allow one to restrict attention to an interior symmetric equilibrium.

It ensures existence and uniqueness of a symmetric Cournot equilibrium (see e.g., Lemma 2 in Canton et al. (2008)).

3 Emissions tax with international technology trade

In this section, the welfare-maximizing emissions tax with international technology trade is derived assuming (as is the case in equilibrium) that the n polluters implement the end-of-pipe abatement technology.

The polluters' profit-maximization problem and the abatement rent. Faced with an emissions tax t, taking as given the output of its competitors, Q_{-q}, each polluter solves

$$\max_{q,a} \pi_a(q,a) = P(Q_{-q}+q)q - C(q) - G(a) - t\left[v(q) - w(a)\right]$$

Let q^t and a^t denote respectively the symmetric equilibrium individual production and abatement levels. Then, letting $Q^t = nq^t$ denote the aggregate equilibrium production, the necessary and sufficient first-order conditions with respect to q and a (at an interior solution) are then respectively[16]

$$P'(Q^t)q^t + P(Q^t) - C'(q^t) - tv'(q^t) = 0 \tag{1}$$

$$tw'(a^t) - G'(a^t) = 0 \tag{2}$$

Each polluter chooses its output level as if it was operating along the marginal cost curve $C'(q) + tv'(q)$ (i.e. just as if it was not implementing the abatement technology). Moreover, as condition (2) indicates, each polluter equipped with the end-of-pipe abatement technology will pursue abatement up to the point, a^t, where the marginal benefit of abatement, $\tau w'(a^t)$, is equal to the marginal cost of abatement, $G'(a^t)$. It is easy to show that the individual optimal output level q^t decreases with the emissions tax level, while the individual optimal abatement level increases. Indeed, total differentiation of the first-order condition (1) with respect to t yields:

$$\frac{dq^t}{dt} = \frac{v'(q^t)}{P''(Q^t)Q^t + (n+1)P'(Q^t) - C''(q^t) - tv''(q^t)} < 0, \tag{3}$$

where, for all $t > 0$, the inequality follows from $C'' > 0$, $v' > 0$, $v'' > 0$ and $P''(Q^t)Q^t + (n+1)P'(Q^t) < 0$ (by virtue of Assumption 1). Likewise, total differentiation of the first-order condition (2) with respect to t yields:

$$\frac{da^t}{dt} = -\frac{w'(a^t)}{tw''(a^t) - G''(a^t)} > 0, \tag{4}$$

where, for all $t > 0$, the inequality follows from $w' > 0$, $w'' < 0$, $G'' > 0$.

Now, let π_a^t and π_0^t denote respectively the equilibrium profit realized by a polluter implementing the patented abatement technology (gross of licensing fees) and that it would have realized without this technology. In this latter case, the pollution function would have been $e(q,0) = v(q)$. Hence,

$$\pi_a^t = P(Q^t)q^t - C(q^t) - t\left[v(q^t) - w(a^t)\right] - G(a^t), \tag{5}$$

while

$$\pi_0^t = P(Q^t)q^t - C(q^t) - tv(q^t). \tag{6}$$

The *abatement rent*, that is, the (gross) private gain of implementing the patented abatement technology is

[16] Throughout the paper it is assumed that for all $t > 0$, $v(q^t) > w(a^t)$.

given by the difference between these profits:

$$\pi_a^t - \pi_0^t = tw(a^t) - G(a^t) \tag{7}$$

In other words, the abatement rent (which provides an upper bound on the licensing revenue that can be extracted from each polluter) simply corresponds to the profit realized on infra-marginal abatement units.

Domestic welfare and the emissions tax. Turning now to the domestic welfare function, abstracting away from the subtlety of the licensing game, let us assume that the "multinationally-owned" technology supplier representing the international eco-industry fully extracts this rent with adequately set license fees. To take account of the international flow of abatement technologies, let $f \in [0,1]$ denote the share of licensing revenue "leaking" outside the boundaries of the domestic economy.[17] Recalling that the n polluters implement the abatement technology, the total abatement rent remaining on domestic accounts is thus given by $n(1-f)(\pi_a^t - \pi_0^t)$. Social welfare is the sum of consumer surplus, $\int_0^{Q^t} P(u)du - P(Q^t)Q^t$, the profits of domestic polluters and the domestic share of the total abatement rent, $n\left[\pi_0^t + (1-f)(\pi_a^t - \pi_0^t)\right]$, the emissions taxes revenue, tE^t, and the environmental damage, $-D(E^t)$. Therefore, domestic social welfare expressed as a function of f can be written:

$$W^t(f) = \int_0^{Q^t} P(u)du - P(Q^t)Q^t + n\left[\pi_0^t + (1-f)(\pi_a^t - \pi_0^t)\right] + tE^t - D(E^t) \tag{8}$$

Next, noting $\epsilon(Q^t) = -P'(Q^t)Q^t/P(Q^t)$ and making use of the first-order conditions (1) and (2), total differentiation of this equation with respect to t yields (see Appendix):

$$\frac{dW^t}{dt} = \frac{1}{n\epsilon(Q^t)} P(Q^t)\frac{dQ^t}{dt} - nfw(a^t) + \frac{dE^t}{dt}\left(t - D'(E^t)\right) \tag{9}$$

As it could be expected, the aggregate production and emissions levels decrease with the emissions tax level. Indeed, recalling that $Q^t = nq^t$ and $E^t = n\left[v(q^t) - w(a^t)\right]$ one immediately gets:

$$\frac{dQ^t}{dt} = n\frac{dq^t}{dt} < 0 \text{ and } \frac{dE^t}{dt} = n\left[v'(q^t)\frac{dq^t}{dt} - w'(a^t)\frac{da^t}{dt}\right] < 0$$

where the last inequality follows immediately from $\frac{dq^t}{dt} < 0$ and $\frac{da^t}{dt} > 0$ (see Eq. (3) and (4)). Thus, the welfare effect of a marginal increase of the emissions tax can be decomposed as follows. The first and last terms of the right-hand side of equation (9) capture respectively, the forgone social surplus due to a marginal reduction of aggregate production of the polluting good and the social benefits (resp. losses) if $t > D'(E^t)$ (resp. if $t < D'(E^t)$) arising from a marginal reduction of the aggregate emissions level. Next, the term $-nfw(a^t)$ represents the "leakage" of emissions tax revenue, accruing to foreign technology suppliers. Then, (assuming strict concavity in t of the welfare function) the welfare-maximizing tax solution to the equation $\frac{dW^t}{dt} = 0$ is given by :

$$t = D'(E^t) + \frac{1}{\frac{dE^t}{dt}}\left[nfw(a^t) - \frac{1}{n\epsilon(Q^t)}P(Q^t)\frac{dQ^t}{dt}\right] \tag{10}$$

The above expression leads to the following proposition.

Proposition 1 *In the presence of an international eco-industry and in the case of abatement technology licensing :*

(i) The welfare-maximizing emissions tax is lower than the marginal damage of emissions, if (a) the polluting industry is imperfectly competitive, or (b) the polluting industry is perfectly competitive and some technology is imported.

[17] The parameter f can be interpreted as the share of imported abatement technologies.

(ii) The welfare-maximizing emissions tax decreases as the share, f, of imported technology increases.

Proof. (i) a) When the polluting industry is imperfectly competitive, (since $\frac{dE^t}{dt} < 0$, $\epsilon(Q^t) > 0$, and $\frac{dE^t}{dt} < 0$) for all $f \in [0,1]$, $\frac{1}{\frac{dE^t}{dt}}\left[nfw(a^t) - \frac{1}{n\epsilon(Q^t)}P(Q^t)\frac{dQ^t}{dt}\right] < 0$ implies $t < D'(E^t)$.

b) When the polluting industry is perfectly competitive, the polluters produce up to the point where their (perceived) marginal cost $C'(q)+tv'(q)$ is equal to the market price $P(Q^t)$, so that the term $\frac{dQ^t}{dt}$ in Equation (14) disappears (see Appendix) and Equation (10) thus becomes:

$$t = D'(E^t) + f\frac{nw(a^t)}{\frac{dE^t}{dt}} \tag{11}$$

Hence, $f > 0 \Leftrightarrow t < D'(E^t)$ and $f = 0 \Rightarrow t = D'(E^t)$.

(ii) Note first that for given t, Q^t, a^t and therefore E^t, π_0^t and π_a^t are independent on f (since the constraints defined by Equations (1) and (2) are so). Thus, for all $f \in (0,1)$, total differentiation with respect to f of Equation (9) immediately yields $\frac{d^2W^t}{dtdf} = -nw(a^t) < 0$ whenever $a^t > 0$ and the function W^t is strictly submodular in (t,f). Thus, by the monotone comparative statics theorem (see e.g., Milgrom and Shannon (1994)), $\frac{dt^t(f)}{df} < 0$. ■

The proposition shows that in the case of abatement technology licensing, the emissions tax equals the marginal damage of emissions only under perfect competition without profit leakage. In this case, the tax implements an optimum. Else, the welfare-maximizing tax is lower than the marginal damage and the allocation is constrained efficient because of the distorted market structure or leakage. In contrast to the *over-internalization* prescription of David and Sinclair-Desgagné (2005), when the polluting industry is perfectly competitive and abatement is *not* subject to a linear pricing schedule, no distortion needs to be corrected *at the margin* by an emissions tax in excess or short of the pigouvian level. The only reason for departing from the pigouvian tax rule is thus to be found below the margin. When devising on the appropriate emissions tax level, the government weighs the surpluses of domestic consumers and polluters against that of the domestic EGS suppliers. Since the abatement rent accruing to the eco-industry is shared between domestic and foreign EGS suppliers, the welfare-maximizing emissions tax results from a trade-off between productive efficiency and international *rent-shifting*. Indeed, levying an emissions tax higher than the marginal damage amounts to an "implicit" subsidy granted by the government to the international eco-industry at the expense of its domestic consumers and polluters. Such a subsidy is costly to society since pricing emissions above their marginal cost entails a deadweight loss. Lowering the emissions tax below the pigouvian level thus potentially accomplishes two beneficial operations. First, it alleviates the tax burden imposed on domestic polluters and somehow passed on to consumers. Second, when EGS are traded internationally, it reduces the outflow of abatement expenditures. Therefore, when all the proceeds of licensing are recouped domestically (i.e. when $f = 0$), there is no need to depart from the pigouvian tax rule. In contrast, whenever some of these proceeds ends up on foreign accounts (i.e. when $f > 0$), *it is economically sound to lower the emissions tax below the pigouvian level so as to reduce the outflow of licensing revenue.*

Finally, observe furthermore that when the eco-industry is competitive, the unit price of EGS is equal to their marginal cost. Hence, the following proposition obtains as a corollary of Proposition 1

Proposition 2 *In the absence of market power in both the eco-industry and the polluting industry, the welfare-maximizing emissions tax is lower than the marginal damage of emissions whenever some EGS are imported.*

As this proposition indicates, even in the absence of distortions due to the exercise of market power in either industry, the emissions tax-induced international rent redistribution might call for departing from the pigouvian tax rule. This, however, should not be readily interpreted as attempts to manipulate environmental policies since, as recalled in Barrett (1994) from (GATT, 1992, p. 29):

> The existence of less strict environmental standards in a lower income country... is not a sufficient basis for claiming that the environmental standards are too low or that the country is manipulating its environmental standards in order to improve the competitiveness of its producers. To substantiate such a claim, it would be necessary at the very least to demonstrate that the standards are even lower than would be expected on the basis of such factors as the level of per capita income and the characteristics of the physical environment.

Convergence of national environmental and climate policies is often regarded as an important issue for the ongoing negociations on trade and climate change. It should however be well-understood that differences in domestic "endowment" of EGS between different countries warrant differing policies.

4 Concluding remarks

This note investigated the impact of international trade in pollution technology on optimal pollution taxation. The analysis reveals that the welfare-maximizing emissions tax results from a trade-off between productive efficiency and *rent-shifting* motives. In line with the well-known fact that governments whose polluters rely on abatement technology imports are less inclined to enforce stringent environmental policies, the emissions tax maximizing domestic welfare decreases as share of imported technology increases. When the polluting industry is imperfectly competitive, this tax is *always* lower than the marginal damage. In contrast, when the polluting industry is perfectly competitive, the welfare-maximizing emissions tax is lower than the marginal damage only in the case of abatement technology import. If the technology is supplied domestically, the welfare-maximizing emissions tax is equal to the marginal damage.

The impact of market power in the *environmental goods and services industry* or the *eco-industry* on optimal policy design is drawing a growing attention from academics and policymakers alike. By definition, patents endow technology suppliers with some monopoly power. However, these results contrast with the literature on the impact of market power in the eco-industry on optimal policy design initiated by David and Sinclair-Desgagné (2005). This literature focuses on end-of-pipe environmental goods and services subject to *linear pricing*. Instead, the present work shifts the focus on *environmental equipment* such as end-of-pipe pollution abatement *technologies*. It contributes to this literature by extending the analysis to the case of abatement technologies subject to licensing with the possibility of international technology trade. The main results apply as well as to the case of other EGS subject to nonlinear pricing.

5 Appendix

Derivation of Equation (9). Using expressions (6) and (7), equation (8) becomes:

$$W^t(t) = \int_0^{Q^t} P(u)du - nC(q^t) - ntv(q^t) + n(1-f)\left[tw'(a^t) - G'(a^t)\right] + tE^t - D(E^t) \tag{12}$$

Notice first that total differentiation of $tw'(a^t) - G'(a^t)$ with respect to t immediately yields:

$$w'(a^t) + \frac{da^t}{dt}\left[tw'(a^t) - G'(a^t)\right] = w'(a^t),$$

since by virtue of the first-order condition (2), $tw'(a^t) = G'(a^t)$. Thus, recalling that $q^t = Q^t/n$, total differentiation of Equation (12) yields the following equation:

$$\frac{dW^t}{dt} = \frac{dQ^t}{dt}\left[P(Q^t) - C'(q^t) - tv'(q^t)\right] - nv(q^t) + n(1-f)w(a^t) + E^t + \frac{dE^t}{dt}(t - D'(E^t)) \tag{13}$$

Rearranging terms in Equation (13) then gives:

$$\frac{dW^t}{dt} = \frac{dQ^t}{dt}\left[P(Q^t) - C'(q^t) - tv'(q^t)\right] - n\left[v(q^t) - w(a^t)\right] - nfw(a^t) + E^t + \frac{dE^t}{dt}(t - D'(E^t))$$

Next, recalling that $E^t = n\left[v(q^t) - w(a^t)\right]$ the above equation becomes:

$$\frac{dW^t}{dt} = \frac{dQ^t}{dt}\left[P(Q^t) - C'(q^t) - tv'(q^t)\right] - nfw(a^t) + \frac{dE^t}{dt}(t - D'(E^t)) \tag{14}$$

Finally, using the first-order condition (1) written as follows:

$$\frac{P(Q^t) - C'(q^t) - tv'(q^t)}{P(Q^t)} = -\frac{P'(Q^t)Q^t}{nP(Q^t)} = \frac{1}{n\epsilon Q^t}$$

yields the desired expression (9).

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