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Optimal emission taxation and the Porter hypothesis under Bertrand competition[*]

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Abstract

Is socially efficient taxation conducive to the win-win solution associated with the strong version of the Porter Hypothesis? Using a Bertrand duopoly yielding a *continuum* of Nash equilibria, we show that this is true for *almost* any level of environmental damage and equilibrium pricing strategy. We also prove that the only case in which no conflict arises between private and public incentives is where firms price at marginal cost. This finding suggests that coordination between environmental and competition authorities would be highly desirable.

JEL Codes: L13, L51, Q50

Keywords: Porter hypothesis, green innovation; emission taxation; price competition; win-win solution

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1   Introduction

In this paper, we deal with the so-called *Porter Hypothesis* (Porter, 1991; Porter and van der Linde, 1995) in its strong version, according to which firms may react to environmental regulation by investing in green technologies and discover that this is profitable, in such a way that the resulting equilibrium identifies a win-win solution.

The state of the art of the debate about the Porter Hypothesis (in particular, in its strong form) can be summarised as follows. To begin with, the flow of empirical research on the matter has brought about evidence supporting the weak form, whereby firms do react to the whole set of environmental regulatory tools (taxation, standards and costly allocations of polluting quotas) by investing in either abatement or replacement green technologies (see, e.g., Jaffe and Palmer, 1997; Lanoie *et al.*, 2011; Rexhäuser and Rammer, 2014). Thus far, empirical confirmations for the strong form (i.e., the win-win solution) are comprehensibly still out of reach. On the theoretical ground, instead, the win-win solution systematically emerges, irrespective of the assumption underlying the shape of consumer preferences. Indeed, this holds true in models relying on the presence of a representative consumer (see Xepapadeas and de Zeeuw, 1999; Ambec and Barla, 2002; Greaker, 2003; 2006; Constantatos and Herrmann, 2011, *inter alia*) or a population of heterogeneous consumers making discrete choices (André *et al.*, 2009; Lambertini and Tampieri, 2012). As for the first stream of literature, it must be stressed that it consistently refers to Cournot competition in the product market, admitting the possibility for green technologies to entail higher or lower marginal production costs as compared to brown ones.[1]

The only contribution we are aware of, in which Bertrand behaviour is

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[1]For exhaustive overviews of the literature, see Ambec and Barla (2006), Lanoie *et al.* (2011), Ambec *et al.* (2013) and Lambertini (2013, 2017).

assumed, is André *et al.* (2009). This leaves a gap concerning the implications of price competition on the Porter Hypothesis in the perimeter of models based upon the figure of a representative consumer. In this paper, we aim at filling such a gap.

Indeed, we model a homogeneous-good duopoly under price competition, where firms' strategic interaction yields a *continuum* of Nash equilibria, including uncountably many with price above marginal cost, as in Dastidar (1995). Production entails a convex environmental externality and the regulator may adopt welfare-maximising taxation to induce firms to switch to green technology, whose attainment involves a sunk cost. Thus far, the extant research on the Porter Hypothesis has consistently highlighted that environmental policies, in particular emission taxation, can be *tailored* so as to deliver the win-win solution. This has been done modelling it as a lump-sum tax (André *et al.*, 2009; Lambertini and Tampieri, 2012) or as an exogenous tax rate (for a summary of these models, see Lambertini, 2013, 2017), while little attention has been paid to the possibility that socially efficient taxation may trigger a validation of the strong form of the Porter Hypothesis. In itself, this is a relevant point as the *ex ante* brown configuration of an industry would require the adoption of the optimal tax rate. The ensuing analysis explicitly aims at verifying whether this tax can induce a win-win solution, and, if so, to what extent the pricing strategy of firms affects this possibility.

We show that, in general, there always exists an admissible parameter constellation wherein the win-win solution emerges, irrespective of the pricing rule followed by firms in equilibrium. Yet, the only case in which there is absolutely no conflict between private and social incentives towards the attainment of a fully green industry is that of marginal cost pricing, the only obvious constraint being dictated by the size of the investment. If firms depart from marginal cost pricing, they can do so in two opposite directions.

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When price lies between average and marginal cost, a conflict emerges if the environmental damage is comparatively flat, as here output is large and the policy maker is tempted by the revenue generated by the tax. If instead firms behave quasi-collusively by pricing above marginal cost, the output reduction induces the policy maker to transform the tax into a subsidy when the damage is not too steep and, when this happens, the win-win solution is ruled out.

Our findings hint at a policy implication suggesting an explicit coordination between environmental and competition authorities. Were the latter able to force marginal cost pricing, private and social incentives would be systematically aligned for any level of the environmental damage. Finally, our model allows one to see under a different light the long-standing debate concerning the effort duplication problem usually associated with technical progress. While the consequences of traditional process and product innovations are spontaneously internalised by firms insofar as they are profitable, green innovations are triggered by regulation and their immediate consequences impact on welfare, and therefore one may expect the duplication issue to be resolved.

The remainder of the paper is structured as follows. Section 2 illustrates the model. Private and social incentives are described in section 3 and the equilibrium analysis is in section 4. Section 5 concludes with a short discussion of the main results.

2   The model

Consider a market supplied by two identical firms producing a homogeneous good whose demand function is $p = a - Q$, where $Q = q_1 + q_2$ is aggregate output, p is the market price and a is the choke price. Firms use the same technology, described by the cost function $C_i = cq_i^2/2$, where c is a positive

parameter. As a result, the profit function of firm $i = 1, 2$ is

$$\pi_i = \left(p - \frac{cq_i}{2}\right) q_i = \left(a - q_i - q_j - \frac{cq_i}{2}\right) q_i \tag{1}$$

Production entails polluting emissions $E = Q$ and an environmental damage $D = dQ^2$. If the regulator adopts an emission tax $t > 0$, this modifies the cost function of firms, which becomes $C_i = tq_i + cq_i^2/2$ and therefore also the individual profit function,

$$\pi_i = \left(p - t - \frac{cq_i}{2}\right) q_i = \left(a - q_i - q_j - t - \frac{cq_i}{2}\right) q_i \tag{2}$$

Firms compete in prices. From Dastidar (1995),[2] we know that there exists a *continuum* of Bertrand-Nash equilibria identified by

$$p_{bb}^{BN} = \frac{ac + 2t (2 - \alpha)}{c + 2 (2 - \alpha)} \tag{3}$$

where superscript BN and subscript bb mnemonic, respectively, for Bertrand-Nash and the fully brown industry configuration, while α is a non-negative parameter whose value determines the *continuum* of equilibrium prices. If the emission tax is absent, in (3) $t = 0$. Individual equilibrium output and profits are

$$q_{bb}^{BN} = \frac{(a - t) (2 - \alpha)}{c + 2 (2 - \alpha)} \tag{4}$$

$$\pi_{bb}^{BN} = \frac{(a - t)^2 \alpha c (2 - \alpha)}{2 [c + 2 (2 - \alpha)]^2} \tag{5}$$

and social welfare is

$$SW_{bb}^{BN} = 2\pi_{bb}^{BN} + CS_{bb}^{BN} + tQ_{bb}^{BN} - D_{bb} \tag{6}$$

in which consumer surplus $CS_{bb}^{BN} = \left(Q_{bb}^{BN}\right)^2 /2$. We know from André *et al.* (2009) that the admissible range of α is $[0, 4/3]$. If $\alpha = 0$, the equilibrium

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[2] For the explicit derivation of the continuum of Bertrand-Nash prices appearing in (3), see also Gori *et al.* (2014) and Delbono and Lambertini (2016).

price equals average variable cost; if $\alpha = 1$, firms price at marginal cost; when $\alpha = 4/3$, each firm is indifferent between undercutting to get monopoly power or keeping the duopolistic regime alive.

If both firms invest an amount of resources $k > 0$ in the green technology, their emissions fall below the threshold compatible with the efficiency of natural carbon sinks, and therefore no tax is levied. The corresponding equilibrium magnitudes become

$$p_{gg}^{BN} = \frac{ac}{c + 2(2 - \alpha)} \, ; \, q_{gg}^{BN} = \frac{a(2 - \alpha)}{c + 2(2 - \alpha)} \tag{7}$$

$$\pi_{gg}^{BN} = \frac{a^2 c (2 - \alpha) \alpha}{2 [c + 2(2 - \alpha)]^2} - k \, ; \, SW_{gg}^{BN} = 2\pi_{gg}^{BN} + CS_{gg}^{BN} \tag{8}$$

where $CS_{gg}^{BN} = \left(Q_{gg}^{BN}\right)^2 / 2$ and subscript gg indicates the fully green industry configuration. In order for the green equilibrium to be feasible, we assume $k \in \left(0, a^2 c (2 - \alpha) \alpha / \left[2 (c + 2(2 - \alpha))^2\right]\right)$.

In (7-8), we adopt the assumption that the cost function (in particular, its steepness determined by parameter c) does not change if firms switch from the brown to the green technology. This assumption, which is not commonly used in the literature on the Porter Hypothesis,[3] can be justified on three different grounds. First, the green technology relies, in general, on a mix of renewables, whose average variable cost may be comparable to those of the fossil sources being replaced (for example, one may think of a mix of solar energy and windmills, with the latter compensating the higher costs of the former). Second, this assumption may fit a scenario in which the green technology is mature, in the sense that it is competitive with the brown one

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[3] For instance, André *et al.* (2009) and Lambertini and Tampieri (2012) use quadratic cost functions which shifts up as soon as firms adopt green technologies. Constantatos and Herrmann (2011), instead, envisage the opposite situation in which the green technology is cost-efficient, which may be fit the case of green energy produced by windmills, but does not apply systematically.

currently in use; indeed, this is the situation at the basis of Hotelling's (1931) model, in which, at the time of its adoption, the replacement technology has the same average cost and 'commands' the same market price (say, of a kW/h) as the old technology. Third, focusing on the situation in which the green technology has a cost disadvantage means looking at the transition period along which the innovation enters the market and, for some time, coexists with the old and brown one, leaving totally aside the medium to long run perspective in which the new technology is at least as cost-effective as the old one being replaced. By the way, this is the case even outside the realm of environmental innovations, with plenty of examples, among which the introduction of CD players in consumer electronics back in the early 1980s. Evaluating the introductory prices against those prevailing a few years later, when the technology and the final product were mature.

To complete the picture of the strategic interaction between firms, observe that, on the basis of Lemma 1 and Proposition 1 in Gori *et al.* (2014, pp. 375-76), we may disregard the asymmetric outcomes in which one firm goes green while the other remains brown.[4] In a nutshell, the argument in Gori *et al.* (2014) proves that, if a firm has indeed invested in green innovation, the other has a strict incentive to go green itself, for all k such that $\pi_{gg}^{BN} > 0$. This can be shown in the following way.

Imagine that one firm invests in green technologies, while the other does not. If so, their profit functions can be labelled as π_{gb} and π_{bg}, respectively. While the former contains a quadratic cost function complemented by the fixed cost k, the latter contains a linear-quadratic variable due to the presence of the emission tax. The first task consists in identifying the lower and upper bound of the admissible price interval. The lower bound necessarily coincides

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[4]In Gori *et al.* (2014), the same model is used to analyze the choice between export and foreign direct investment in a model of trade. Aside from the different nature of the subject matter, both models share this formal property.

with the average variable cost of the brown firm, $\underline{p} = C_{bg}/q_{bg} = t + cq_i/2$, while the upper bound is $\overline{p} = \min\left\{p_{bg}^u, p_{gb}^u\right\}$, that is, the lowest undercutting price.

Now note that below that at any price at most equal to $\underline{p}$, the green firm becomes a monopolist. Accordingly, $\underline{p}$ qualifies as the highest (and more profitable) undercutting price for the firm which has decided to invest, and it can be determined by solving

$$p\left(q_{gb} + q_{gb}\right) - \frac{c\left(q_{gb} + q_{bg}\right)^2}{2} - k = pq_{gb} - \frac{cq_{gb}^2}{2} - k \tag{9}$$

yielding $p_{gb}^u = c\left(q_{gb} + 2q_{bg}\right)/2 = \underline{p}$. Clearly, the brown firm cannot match this price because of the linear cost component brought about by the emission tax, and the green firm may indeed stand alone with positive profits π_{gb}^u, for all k such that $\pi_{gg} > 0$.[5] Conversely, the brown firm is out of the market (or, equivalently, does not produce). This implies that the asymmetric outcome cannot be an equilibrium, since the brown firm will find it profitable to invest as well to obtain π_{gg}.

3 Private and social incentives

As long as firms are both brown, the optimal policy for the regulator is to identify the socially efficient tax rate. Given the concavity of the social welfare function SW_{bb}^{BN} w.r.t. t, its maximization requires

$$t^* = \frac{a\left[4d\left(2 - \alpha\right) + c\left(1 - \alpha\right)\right]}{\left[2\left(2d + 1\right) + c\right]\left(2 - \alpha\right)} \tag{10}$$

Unsurprisingly, t^* monotonically increases with d (as can be quickly verified). By inspection, one may detect:

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[5]Indeed, any k ensuring the positivity of π_{gg} is *sufficient* to ensure the positivity of monopoly profits π_{gb}^u attained through the undercutting price.

Proposition 1 $t^* > 0$ *for all* $d > \max\left\{0, \widehat{d}\right\}$, *with* $\widehat{d} \equiv c\left(\alpha - 1\right) / \left[4\left(2 - \alpha\right)\right]$.

Before interpreting the Proposition, it is appropriate to note that, in oligopoly, the welfare-maximising tax rate may be either higher or lower than the marginal environmental damage, that is, the proper Pigouvian tax, as we know from Buchanan (1969) in the monopoly case and Katsoulacos and Xepapadeas (1995) and Simpson (1995) in the Cournot oligopoly, in which, the welfare-maximizing tax will fall short of the marginal damage, with two relevant exceptions: (i) when firms use of asymmetric technologies (Simpson, 1995) and (ii) under free entry (Katsoulacos and Xepapadeas, 1995), in which cases the tax will be higher than the marginal damage.[6]

The threshold $\widehat{d}$ in Proposition 1 becomes relevant for $\alpha > 1$, i.e., when firms price above marginal cost. If this happens and t^* becomes negative, it is because consumer surplus becomes more relevant than the environmental damage: in a situation like this, the optimal policy amounts to subsidizing production. We may intuitively anticipate that, if t^* is a subsidy to production, then the win-win solution associated with the strong version of the Porter hypothesis cannot arise.

Now we may comparatively assess the two symmetric outcomes in order to characterise private and social incentives towards the attainment of the win-win solution. Taking the firms' standpoint, we begin by checking the positivity of profits in the green scenario:

$$\pi_{gg}^{BN} > 0 \Leftrightarrow k < \frac{a^2 c\left(2 - \alpha\right)\alpha}{2\left[c + 2\left(2 - \alpha\right)\right]^2} \equiv \overline{k} \tag{11}$$

which poses an upper bound to the size of the investment required to go green. Next, relying on Gori *et al.* (2014), the private incentive to go green

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[6]In both Simpson (1995) and Katsoulacos and Xepapadeas (1995), where marginal cost is constant, the optimal emission tax level can be lower or higher than the Pigouvian level. Under general demand and cost functions, the ranking depends on the curvature of the demand function, as shown in Lee (1999). We owe this remark to an anonymous referee.

exists if and only if

$$\pi_{gg}^{BN} > \pi_{bb}^{BN} \Leftrightarrow k < a^2 c \left[\frac{(2-\alpha)^2 (c + 2(1+2d))^2 - (c + 2(2-\alpha))^2}{2(2-\alpha)(c + 2(1+2d))^2 (c + 2(2-\alpha))^2} \right] \alpha \equiv \widehat{k} \tag{12}$$

provided that $\widehat{k} > 0$, which holds true for all $d > \max\left\{0, \widehat{d}\right\}$. This fact, in combination with Proposition 1, implies:

Proposition 2 *If $\alpha \in (1, 4/3]$ and therefore $\widehat{d} > 0$, then $t^* \leq 0$ and $\widehat{k} \leq 0$ for all $d \in \left(0, \widehat{d}\right]$. Hence, in this parameter constellation, the win-win solution cannot obtain.*

Proposition 2 says that if firms are in the quasi-collusive range (when α is above one), the regulator faces the paradoxical scenario in which the optimal policy consists in subsidizing firms (because they produce too little as they are pricing above marginal cost), while indeed they are polluting less than they would, were they pricing between average and marginal cost.

Simple algebra suffices to verify that

$$\overline{k} - \widehat{k} = \frac{a^2 c \alpha}{2(2-\alpha)[c + 2(1+2d)]^2} > 0 \tag{13}$$

We may now turn our attention to the welfare ranking:

$$SW_{gg}^{BN} > SW_{bb}^{BN} \Leftrightarrow k < \frac{a^2 \left[4d(2-\alpha)(c\alpha + 2(2-\alpha)) - c^2 (1-\alpha)^2 \right]}{2[c + 2(1+2d)][c + 2(2-\alpha)]^2} \equiv \widetilde{k} \tag{14}$$

provided $\widetilde{k}$ is positive, which happens for all

$$d > \frac{c^2 (1-\alpha)^2}{4(2-\alpha)[c\alpha + 2(2-\alpha)]} \equiv \widetilde{d} \tag{15}$$

Moreover,

$$\widetilde{d} - \widehat{d} = \frac{c(1-\alpha)[c + 2(2-\alpha)]}{4(2-\alpha)[c\alpha + 2(2-\alpha)]} \tag{16}$$

which is positive for all $\alpha \in (1, 4/3]$ (and conversely).

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4 Equilibrium analysis

We are going to characterise the equilibrium configuration of the industry according to the value of α. We will do so by distinguishing three different cases. The first is that in which $\alpha \in [0,1)$; the second is the singleton at $\alpha = 1$; the third covers the range identified by $\alpha \in (1, 4/3]$.

4.1 Case I

For all $\alpha \in [0,1)$, the equilibrium price is at least equal to the relevant average variable cost and arbitrarily close but lower than marginal cost. In this range, $t^* > 0, \widehat{k} > 0$ for all $d > 0$, while $\widetilde{k} > 0$ for all $d > \widetilde{d}$. Hence, private and social incentives, as well as the nature of the resulting equilibrium, are described by Figure 1.

Figure 1 The win-win solution for $\alpha \in [0,1)$

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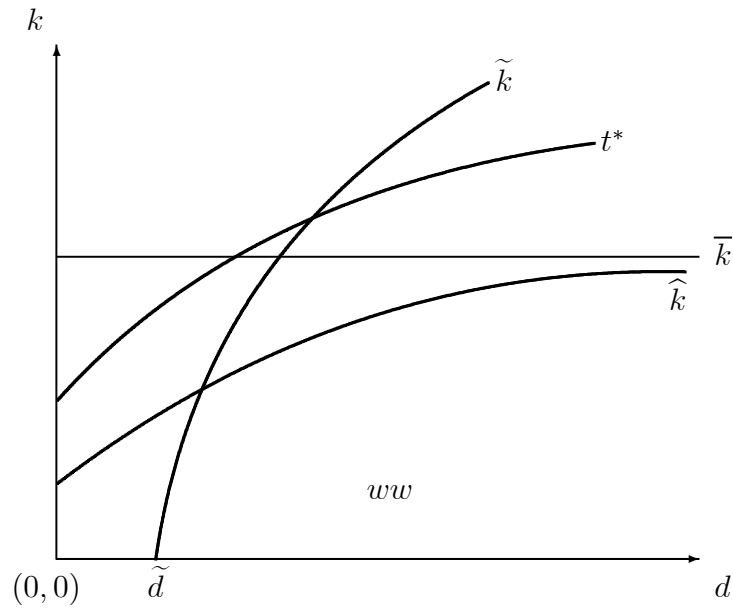
The inspection of Figure 1 immediately shows that the alignment between private and social incentives on the industry-wide adoption of the green technology occurs below the lower envelope of the curves representing $\widehat{k}$ and $\widetilde{k}$ (in region ww). That is,

Proposition 3 *If $\alpha \in [0, 1)$, the win-win solution arises at equilibrium for all $d > \widetilde{d}$ and $k \in \left(0, \min\left\{\widehat{k}, \widetilde{k}\right\}\right)$.*

The requirement $d > \widetilde{d}$ entails that, if the environmental damage is not steep enough, what drives the regulator's preferences is the sum of consumer surplus and fiscal revenue. The intuition can be spelled out as follows. Industry output is large because price is below marginal cost; hence, consumer surplus and fiscal revenue are both large. This, if indeed the environmental damage is not so steep, induces the regulator to prefer the brown outcome. In this region, profits incentives induce overinvestment as compared to the socially efficient configuration.

4.2 Case II

Here we focus on marginal cost pricing at $\alpha = 1$. This case is depicted in Figure 2, which shows that t^*, $\widehat{k}$, and $\widetilde{k}$ intersect each other at the origin, since $\widetilde{d} = \widehat{d} = 0$. Since $\widetilde{k} > \widehat{k}$ always,

Proposition 4 *If $\alpha = 1$, the win-win solution arises for all $d > 0$ and $k \in \left(0, \widehat{k}\right)$.*

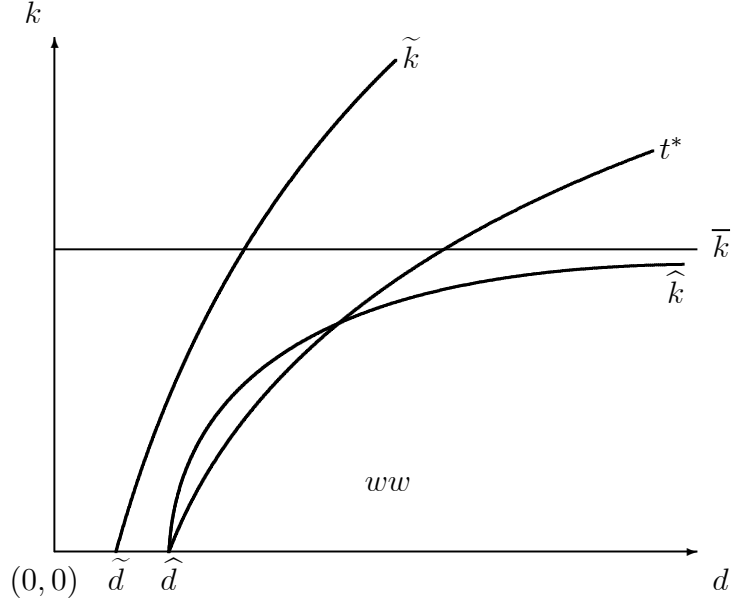**Figure 2** The win-win solution for $\alpha = 1$
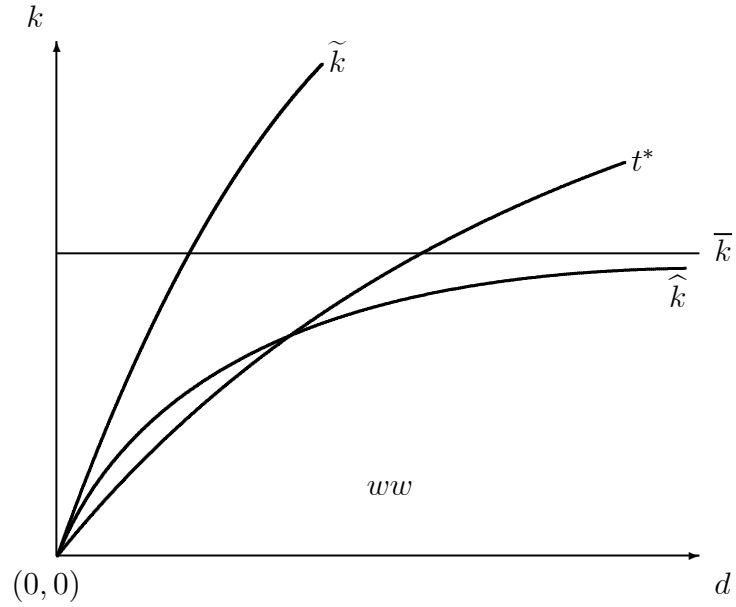
In this case, it all depends on the firms' incentive to go green. If they do so because the investment is not too costly, then this automatically implies the confirmation of the Porter hypothesis. It is also worth stressing that this holds for any admissible pair (a, c).

4.3 Case III

Here firms' pricing behaviour takes a collusive flavour, as $\alpha \in (1, 4/3]$. In this case, which looks as in Figure 3, t^* becomes a subsidy and $\widehat{k} = 0$ for all $d \in \left(0, \widehat{d}\right)$.

Figure 3 The win-win solution for $\alpha \in (1, 4/3]$

As we already know from Proposition 2, firms cannot go green for all $d \in \left(0, \widehat{d}\right)$, and, as a result, the win-win solution cannot obtain in this range. However,

Proposition 5 *If $\alpha \in (1, 4/3]$, the win-win solution arises for all $d > \widehat{d}$ and $k \in \left(0, \widehat{k}\right)$.*

It is worth clarifying the impossibility of the win-win solution for all $d \in \left(0, \widehat{d}\right)$. We know that firms are adopting a quasi-collusive behaviour by pricing above marginal cost, which shrinks output and therefore also consumer surplus. Consequently, if the environmental damage is low, the authority is led to preserve consumer surplus through a subsidy to production. If this happens, firms have no incentive to go green. Notice that, for all $d \in \left(\widetilde{d}, \widehat{d}\right)$, the policy maker subsidises production and therefore prevents

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firms from going green, but, if it were in control of these firms, it would produce the green outcome for all $k \in \left(0, \widetilde{k} \right)$. This amounts to saying that, in the region identified by $d \in \left(\widetilde{d}, \widehat{d} \right)$ and $k \in \left(0, \widetilde{k} \right)$, private firms under-invest in green R&D as compared to the social optimum precisely because they receive a subsidy from the regulator. The only way of enforcing social optimality would consists in the nationalization of the whole industry.

5 Discussion

The foregoing analysis delivers a new standpoint from which the traditional issue of the social optimality of R&D can be assessed. Environmental externalities being absent, the acquired wisdom inherited from the bulk of the R&D literature (see, e.g., Tirole, 1988; and Reinganum, 1989) holds it that profit incentives almost systematically imply a socially wasteful effort duplication. This simple model illustrates that this may no longer be true when innovation has an environmental nature, that is, firms' efforts remain sunk but yield the elimination of the externality (or, a substantial reduction thereof).

This is also accompanied by the fact that, firms going symmetrically green, the absence of an emission tax also benefits consumers, as the pressure of this policy instrument, when present, increases marginal cost from the firms' standpoint and therefore is necessarily incorporated into the equilibrium price. In this sense, the foregoing analysis shows that investing in green technologies can indeed be equivalent to investing in process innovation whenever environmental regulation takes the form of an emission tax.

Let us now focus on the case of marginal cost pricing. This is the only setting in which static efficiency goes along with dynamic efficiency and industry-wide R&D efforts are systematically welcome. In view of this, en-

vironmental and competition policies should be coordinated. That is to say, were the competition authority able to enforce marginal cost pricing, firms would then go green (provided the investment is not too sizeable), no matter how intense the environmental damage and the emission tax are. Notice that firms, when pricing at marginal cost, make strictly positive profits. Hence, they do not necessarily need to be subsidized to finance the adoption of the green technology. Or, in case they need, the ability to reap profits make their access to credit easier.

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