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ENVIRONMENTAL IMPACT OF TECHNOLOGY POLICY: R&D SUBSIDIES VERSUS R&D COOPERATION

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Abstract

In this paper we study a neglected aspect of technology policy, namely the adverse impact it might have on the environment through increased production when R&D expenditure leads to cost reduction. Although technology policy measures that encourage firms to reduce their production costs would usually reduce energy inputs and therefore generate less pollution per unit of output production, we explore here the case where with reorganisation of production output generally increases. So even if per unit of production pollution is less, total pollution generated by the increased production induced by the innovative efforts of films increases. In this context it is therefore necessary to address the issue of tying-in technology and environmental policy, which is the issue we raise in this paper. We show that, irrespective of whether technology policy takes the form of R&D subsidies or R&D cooperation, R&D would generally lead to increased pollution and thus have a negative impact on the environment. Policies that might be optimal in the absence of concern for the environment cease to be so. We claim that not only is a comparison between policy instruments more delicate but the optimal R&D subsidy might be negative. Finally, we propose and evaluate a specific policy in the form of a targeted subsidy tied-in to abatement activities and show that it is welfare improving.

Key words: Technology Policy, Process Innovation, Pollution, R&D Cooperation, R&D Subsidies.

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ENVIRONMENTAL IMPACT OF TECHNOLOGY POLICY: SUBSIDIES VS R&D COOPERATION

1. Introduction

The issue of technology policy in imperfectly competitive markets has received considerable attention both in the theoretical and applied literature. Several papers in the Industrial Organization literature discuss the relative merits of different policy instruments, such as R&D subsidies and the encouragement of cooperative R&D, in raising R&D output, firm profitability and social welfare, e.g. see Kamien et al. (1992), Vonortas (1994), Hinloopen (1995) and Poyago-Theotoky (1995). In this paper we study a neglected aspect of technology policy, namely the adverse impact it might have on the environment through increased production when R&D expenditure leads to cost reduction. Although technology policy measures, such as e.g. R&D subsidies or the formation of Research Joint Ventures (RJVs), that encourage firms to reduce their production costs would usually reduce energy inputs and therefore generate less pollution per unit of output production, we explore here the case where with reorganization of production output generally increases. So even if per unit of production pollution is less, total pollution generated by the increased production which is induced by the innovative efforts of firms increases. In this context it is therefore necessary to address the issue of tying-in technology and environmental policy, which is the issue we raise in this paper.

To motivate our point we mention a few examples that throw some light on the issue at hand. The oil refinery industry in Greece which is highly concentrated has enjoyed major gains in productive efficiency and has expanded output due, most probably, to technology policy measures encouraging innovation. At the same time there is no clear environmental policy to regulate this particular industry. The same is true, to a lesser extent, for the Greek food industry. On the other hand, firms in the agriculture and the milking industry in Spain receive both national and EU aid, usually in the form of subsidies, to promote the use of efficient productive practices without a concurrent interest or policy measure for the environmental effect of these practices. Implementing these more efficient practices might have a considerable negative impact on the environment, e.g. use of pesticides, associated with a considerable increase in production.

From the existing theoretical literature on technology policy note that Hinloopen (1995), when comparing R&D subsidies to R&D cooperation under deterministic innovation, comes to the conclusion that, when these policies are implemented in isolation subsidising non-collusive R&D optimally is the more effective policy in raising R&D. Stenbacka and Tombak (1996) in a model with stochastic innovation show that RJVs yield lower research intensities in the absence of subsidies. Both papers find a positive optimal R&D subsidy in equilibrium but do not consider any environmental effect of R&D. Contributions from the environmental literature on strategic innovation consider the relative performance of taxes versus standards on abatement related R&D expenditure in the context of international trade, see e.g. Ulph (1994) and Ulph (1996), i.e. they examine the effect that environmental policy has on R&D. In contrast, we examine the opposite link, namely the effect that different technology policy instruments have on the environment. In the context of our model, which is presented in the next section, irrespective of whether technology policy takes the form of R&D subsidies or R&D cooperation, R&D would generally lead to increased pollution and thus a negative impact on the environment. As a consequence, policies that might be optimal in the absence of any concern for the environment cease to be so. We claim than not only is a comparison between policy instruments more delicate but, in addition, the optimal R&D subsidy might be negative (i.e. an R&D tax) depending on the extent of appropriability conditions and the degree of environmental consciousness. From our analysis, the need of a tying-in technology and environmental policy becomes obvious. We propose a targeted subsidy on R&D provided that a minimum amount of abatement is undertaken by firms and show that under this policy social welfare improves.

In section 2 the model is presented and the non-cooperative R&D, and cooperative R&D (RJV with full information-sharing) equilibria are derived. Further, the optimal R&D subsidy is obtained. Section 3 compares R&D subsidies and RJVs in case that environmental damages are taken into account. In section 4 we study and evaluate a particular form of tying-in policy. Finally, section 5 concludes.

2. The model

We consider a duopoly with firms producing a homogeneous good under constant returns to scale. There are no fixed costs. Unit costs can be reduced by R&D spending while one firm can benefit from the other firm's R&D, i.e. there are technological spillovers. We use a simple two stage game: in the first stage the two firms invest in cost-reducing R&D and in the second stage they compete in quantities. R&D is characterised by decreasing returns. We examine three different policy set-ups: non-cooperative R&D, where each firm selects its R&D to maximise own profit; cooperative R&D, where the two firms cooperate in the R&D stage only and at the same time share their R&D results fully (the spillover is set at its maximum value); subsidised R&D, where a social planner chooses the optimal subsidy for R&D and firms compete in both stages. Initially we consider the case where there is no concern for the environmental impact of cost-reducing innovation (this is captured in the welfare function) and compare this to the case where the social planner cares for the environment.

Let demand for the product be linear, $P = A - Q$, where $Q = q_1 + q_2$, and unit costs of production constant, c_i, $i = 1,2$. Second stage Cournot profits per firm can be easily computed and are given by $\hat{\pi}_i = (1/9)(A - 2c_i + c_j)^2$. In the first stage firms choose their cost-reducing R&D expenditure. In addition, a firm can benefit from its rival's R&D through spillovers. Thus costs of production can be written as $c_i = a - z_i - \beta z_j$, $i \neq j, i, j = 1,2$, z_i is firm i's R&D output (i.e. cost reduction), $\beta \in [0,1]$ is the spillover rate, $a < A$ and $a > z_i + \beta z_j$. The cost of R&D is assumed convex, indicating decreasing returns in R&D, and given by $c(z_i) = \gamma z_i^2 / 2, \gamma > 0$, where γ captures the relative effectiveness of R&D.

We consider three different set-ups concerning technology policy with respect to R&D: no policy, cooperative R&D and subsidised R&D. In what follows we shall characterise the subgame perfect equilibrium in these three cases paying particular attention to the case where there is no concern for the environmental impact of R&D.

2.1 Non-cooperative R&D

We keep the discussion in this section and the next brief as the analysis is very similar to D'Aspremont and Jacquemin (1988) and Poyago-Theotoky (1995); see these papers for more details. First-stage profits per firm are given by $\pi_i = \hat{\pi}_i - c(z_i)$, which after performing the relevant substitutions become

$$\pi_i = (1/9)[\sigma + (2-\beta)z_i + (2\beta - 1)z_j]^2 - (\gamma z_i^2)/2 \tag{1}$$

where $\sigma = A - a > 0$, is a measure of market size. The necessary first-order condition for the maximization of (1) is

$$(2/9)[\sigma + (2-\beta)z_i + (2\beta - 1)z_j](2-\beta) - \gamma z_i = 0 \tag{2}$$

while the second order and stability conditions require $\gamma > 8/9$ and $\gamma > 12/9$ respectively. [1]

[1] We shall need to impose a stricter condition on γ, see section 2.3, p.

From (2) we can solve for the equilibrium values of R&D output; in the symmetric equilibrium $z_i = z_j = z$, where z is given by

$$z = \frac{\sigma}{\frac{4.5\gamma}{2-\beta} - (1+\beta)} \tag{3}$$

while equilibrium R&D expenditure is

$$c(z) = \frac{\gamma}{2}\left[\frac{2(2-\beta)\sigma}{9\gamma - 2(2-\beta)(1+\beta)}\right]^2. \tag{3a}$$

Next, we can easily compute equilibrium profit per firm and total equilibrium output:

$$\pi_i = \frac{\gamma\sigma^2[9\gamma - 2(2-\beta)^2]}{[9\gamma - 2(2-\beta)(1+\beta)]^2}, \qquad Q = \frac{6\gamma\sigma}{9\gamma - 2(2-\beta)(1+\beta)}.$$

To model the effect that R&D has on the environment we postulate that production generates harmful emissions so that the more output is being produced the higher the damage to the environment.[2] We use a very simple functional form to capture this: $E = \lambda Q$, where E stands for emissions and $\lambda>0$ is the emissions-output ratio and the damage function is written as $D = kE = k\lambda Q = uQ$, $k, u \geq 0$, $u = k\lambda$. The parameter u captures the notion of environmental consciousness. Thus, environmental damage in this case would be $D = u\frac{6\gamma\sigma}{9\gamma - 2(2-\beta)(1+\beta)}$. In the context of our model, and irrespective of which form of technology policy we examine, R&D would generally lead to increased production and thus to a negative impact on the environment.

[2] This is an oversimplification given that in most countries there are regulations associated with pollution reducing activities. However, there regulations are not tied-in to the technology policy framework, especially when considering particular industries, or less developed countries.

As a measure of welfare we use the sum of consumer and producer surplus, given, in this case, by $W_{nc} = AQ - Q^2/2 - \sum_{i=1}^{2}(a - z_i - \beta z_j)q_i - (\gamma/2)\sum_{i=1}^{2} z_i^2 - D$, which after substituting for the equilibrium values becomes

$$W_{nc} = \frac{4\gamma\sigma^2[9\gamma - (2-\beta)^2]}{[9\gamma - 2(2-\beta)(1+\beta)]^2} - \frac{6\gamma\sigma u}{9\gamma - 2(2-\beta)(1+\beta)}. \tag{4}$$

Notice that when $u = 0$, there is no concern for the environmental impact of R&D; this is the general case looked at by the literature on R&D. It is evident from (4) that when the effects of simple cost-reducing R&D are taken into account there is a clear reduction in welfare, an aspect which has been largely overlooked in discussions on technology policy. In the following two sections we examine in more detail two popular forms of R&D policy: R&D cooperation and R&D subsidies and point out the differences that emerge when one takes into account the environmental impact of R&D.

2.2 Cooperative R&D

Here technology policy takes form of encouraging R&D by allowing firms to cooperate at the R&D stage.[3] In the context of our model, R&D cooperation means that firms set their R&D cooperatively to maximise joint first-stage profits while competing in the second stage, i.e. we consider a Research Joint Venture (RJV). Moreover, we assume that within the RJV there is full information sharing of research results or, equivalently, that the spillover is set at its maximal value.[4] We keep the exposition brief as the model presented

[3] On R&D cooperation see, e.g. Jacquemin (1988), Kamien, Mueller and Zang (1992), Poyago-Theotoky (1995) and Vonortas (1994).

[4] The majority of papers on R&D cooperation make this assumption on the spillover in the RJV; e.g. see Beath et. al (1997). Note that this choice can be justified if one treats the spillover as a choice variable suitably reinterpreted as disclosure rate. It can be shown that it is optimal for an RJV to set $\beta = 1$.

here is very similar to the one used by Poyago-Theotoky (1995) (with $n = 2$) and refer the reader to that paper.

In the first stage the objective function of the RJV is written as

$$\Pi = (1/9)\sum_{i=1}^{2}(\sigma + z_i + z_j)^2 - (\gamma/2)\sum_{i=1}^{2} z_i^2 . \qquad (5)$$

The first order conditions for the maximization of (5) are $\partial\Pi/\partial z_i = 0 = \partial\Pi/\partial z_j$.[5] Solving for the symmetric equilibrium, $z_i = z_j = z_c$ we obtain

$$z_c = \frac{4\sigma}{9\gamma - 8} \qquad (6)$$

with associated equilibrium R&D expenditure per firm

$$c(z_c) = (\gamma/2)\left[\frac{4\sigma}{9\gamma - 8}\right]^2 . \qquad (6a)$$

Given the symmetric solution, it seems reasonable to assume an equal split of profits, so that equilibrium profit per firm and total output are

$$\pi_c = \frac{\gamma\sigma^2}{9\gamma - 8} \quad \text{and} \quad Q_c = \frac{6\gamma\sigma}{9\gamma - 8} .$$

Noting that the damage function is in this case, $D = 6\gamma\sigma u/(9\gamma - 8)$, we find the relevant expression for social welfare

$$W_c = \frac{4\gamma\sigma^2(9\gamma - 2)}{(9\gamma - 8)^2} - \frac{6\gamma\sigma u}{(9\gamma - 8)} . \qquad (7)$$

Again, relative to the case when there is no environmental concern, $u = 0$, there is a decrease in welfare when $u > 0$. We provide a detailed welfare comparison together with some preliminary policy conclusions in section 3, after the discussion of the R&D subsidization case.

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[5] The second order condition is satisfied.

2.3 R&D Subsidies

Here technology policy takes the form of subsidising R&D expenditure but without allowing R&D cooperation.[6] In the first stage firms compete in R&D while at the same time receiving a subsidy, s, on their R&D costs. Thus, the R&D cost function becomes $c(z_i) = (1-s)(\gamma/2)z_i^2$, $-\infty \leq s \leq 1$.[7] First stage profits per firm can be written as

$$\pi_i = (1/9)[\sigma + (2-\beta)z_i + (2\beta-1)z_j]^2 - (1-s)(\gamma/2)z_i^2 \tag{8}$$

with associated first-order condition given by

$$(2/9)[\sigma + (2-\beta)z_i + (2\beta-1)z_j](2-\beta) - (1-s)\gamma z_i = 0. \tag{9}$$

From (9) we solve for the symmetric equilibrium R&D output[8], $z_i = z_j = z_s$

$$z_s = \frac{2\sigma(2-\beta)}{9\gamma(1-s) - 2(2-\beta)(1+\beta)} \tag{10}$$

and equilibrium R&D expenditure,

$$c(z_s) = (\gamma/2)\left[\frac{2\sigma(2-\beta)}{9\gamma(1-s) - 2(2-\beta)(1+\beta)}\right]^2. \tag{10a}$$

In line with the two previous sections, equilibrium profits and total production are given by

$$\pi_s = \frac{\gamma\sigma^2[9\gamma(1-s)^2 - 2(2-\beta)^2]}{[9\gamma(1-s) - 2(2-\beta)(1+\beta)]^2}$$

$$Q_s = \frac{6\gamma(1-s)\sigma}{9\gamma(1-s) - 2(2-\beta)(1+\beta)}.$$

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[6] See Hinloopen (1995) and Stenbacka and Tombak (1996) for a related analysis.

[7] Notice that we allow for a negative subsidy, i.e. a tax on R&D. As will become clear later, depending on the value of spillover it might be optimal to tax R&D when there is concern for its environmental effects.

[8] Second order and stability conditions are checked to be satisfied.

Given equilibrium output, we can easily compute the pollution level and the associated damage as $D_s = 6\gamma(1-s)\sigma u/[9\gamma(1-s)-2(2-\beta)(1+\beta)]$ and using this we obtain welfare, for a given level of subsidy(tax) s:

$$W_s = \frac{4\gamma\sigma^2[9\gamma(1-s)^2-(2-\beta)^2]}{[9\gamma(1-s)-2(2-\beta)(1+\beta)]^2} - u\frac{6\gamma(1-s)\sigma}{[9\gamma(1-s)-2(2-\beta)(1+\beta)]} \quad (11)$$

In order to compare welfare levels in the three regimes, we need to solve for the optimal subsidy that a social planner would choose. Maximising (11) with respect to s yields the following expression for the optimal subsidy/tax:

$$\hat{s} = \frac{-18\beta\gamma\sigma + u(2\beta^3-6\beta-4)+9\gamma u(1+\beta)}{3\gamma(1+\beta)(3u-4\sigma)} \quad (12)$$

which for $u = 0$ becomes

$$\hat{s}_{u=0} = \frac{3\beta}{2(1+\beta)}. \quad (12a)$$

It is obvious from (12a) that $\hat{s}_{u=0} \geq 0$; in the presence of spillovers R&D should be subsidised and the optimal subsidy is increasing as the spillover increases, and does not depend on the size of the market, σ, or the effectiveness of R&D, γ. Note also that $\hat{s}_{u=0} \in [0,0.75]$ for $\beta \in [0,1]$. This result is intuitively clear; as the spillover increases firms face diminished R&D incentives and the subsidy is a way of restoring these incentives.

We then proceed to examine in detail the optimal subsidy/tax when $u > 0$. Differentiation of (12) w.r.t. u results in

$$\frac{\partial\hat{s}}{\partial u} = \frac{2(\beta-2)(9\gamma-4\beta^2-8\beta-4)\sigma}{3(1+\beta)\gamma(3u-4\sigma)^2} < 0 \textit{ iff } \gamma > \frac{4(1+\beta)^2}{9}$$

so that in what follows we impose the sufficient restriction $\gamma > 16/9$ to ensure the monotonicity of $\hat{s}$. We can then state and prove the following proposition.[9]

[9] All proofs are in the Appendix.

Proposition 1. *(i) When u = 0 the optimal subsidy is given by* $\hat{s}_{u=0} = \frac{3\beta}{2(1+\beta)}$ *with* $\hat{s}_{u=0} = 0$ *for* $\beta = 0$ *and* $1 > \hat{s}_{u=0} > 0$ *for* $0 < \beta \leq 1$.

(ii) For $0 < u < 4\sigma/3$, *we have the following: (a) when* $\beta = 0$, $\hat{s} < 0$, *i.e. an R&D tax; (b) when* $0 < \beta \leq 1$, $\hat{s} \geq 0$ *iff* $u \leq \bar{u} < 4\sigma/3$, *i.e. an R&D subsidy, and* $\hat{s} < 0$ *iff* $\bar{u} < u$, *i.e. an R&D tax, where* $\bar{u} \equiv \frac{18\beta\gamma\sigma}{9\gamma(1+\beta)+(2\beta^3-6\beta-4)}$ *(value of u such that a zero subsidy is optimal).*

(iii) The optimal subsidy when u = 0 always exceeds the optimal subsidy/tax when $u > 0$, $\hat{s}_{u=0} > \hat{s}$.

In contrast to the literature on R&D subsidies, we identify conditions on the spillover rate and the environmental parameter, *u*, under which R&D should be taxed. A tax on R&D is optimal when the damage on the environment from increased production is quite substantial.[10] Figures 1 and 2 illustrate Proposition 1.

[Insert figures 1 and 2 about here]

Notice also that the optimal subsidy/tax increases as the R&D cost function parameter, γ, increases. From (12) we find that $\frac{\partial \hat{s}}{\partial \gamma} = \frac{2u(1+\beta)(2-\beta)}{3\gamma^2(3u-4\sigma)} > 0$, so that the more difficult R&D becomes the higher the subsidy(or, the lower the tax) should be, for given *u* and β.[11]

Finally, in order to compare welfare across the three cases meaningfully, we substitute the optimal subsidy as given by (12) into the expression of welfare (11), to obtain

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[10] Notice also that Proposition 1 identifies an upper bound on the value of the environmental parameter, *u*.

[11] Notice that in the particular case where $-1 \leq s \leq 1$, a sufficient condition is $u < \sigma/3$.

$$W_s = \frac{4\gamma\sigma^2 - 6\gamma\sigma u + u^2(1+\beta)^2}{9\gamma - 4(1+\beta)^2}. \qquad (11a)$$

We next proceed to compare in some detail welfare in the three scenarios.[12]

3. Welfare Comparisons

Having discussed the conditions for an optimal subsidy/tax we are now in a position to examine the welfare consequences of the two policies and the no-policy option. We then compare expressions (4), (7) and (11a) both for $u = 0$ and $u > 0$. At this point it is necessary to obtain conditions such that welfare in (4), (7) and (11a) is non-negative. We thus have the following.

Lemma 1. *A sufficient condition for welfare to be non-negative is given by* $u \leq 2\sigma/3$.

Note that this condition on u requires a lower upper bound than the one identified by Proposition 1; accordingly, in what follows we impose this latter restriction on u. We then state the following proposition regarding welfare in the absence of environmental concerns.

Proposition 2. *When* $u = 0$ *and* $\gamma > 16/9$ *(i)* $W_c > W_{nc}$ *for* $0 \leq \beta \leq 1$; *(ii)* $W_s = W_{nc}$ *for* $\beta = 0$ *and* $W_s > W_{nc}$ *for* $0 < \beta \leq 1$ *and (iii)* $W_s \geq W_c$ *for* $\beta \geq \overline{\beta}$ *and* $W_s < W_c$ *for* $\beta < \overline{\beta}$, $0 \leq \beta, \overline{\beta} \leq 1$, *and* $\overline{\beta} = \frac{(4-18\gamma)+\sqrt{2}\sqrt{567\gamma^2 - 414\gamma + 64}}{2(9\gamma - 2)}$, *where* $\overline{\beta} \equiv \{\beta | W_s = W_c\}$.

[12] We do not provide a detailed comparison of R&D output, R&D expenditure and profit per firm for the three scenarios, as this lies outside the scope of this paper. This can be obtained from the authors upon request.

Parts (i) of Proposition 2 should be familiar from the R&D literature, see e.g. Kamien et al. (1992), giving support to the encouragement of cooperative R&D agreements where information is fully shared. Parts (ii) and (iii) though throw some new light on the technology policy debate. Thus, when either policy is implemented on its own, it is obvious that the non-cooperative scenario is the worst possible when technological spillovers are positive (see part (ii)). This is consistent with the negative effect of spillovers on firms' R&D incentives. R&D subsidies aim to restore firms incentives for R&D, innovation is induced, output and profit increases and, consequently, welfare rises relative to the non-cooperative outcome. Part (iii) identifies conditions on the value of the spillover parameter such that welfare in the presence of R&D subsidies is higher (lower) than welfare when there is an RJV.[13] For spillover values below the critical value $\overline{\beta}$ an RJV results in higher welfare, whereas when the spillover is above the critical value the opposite holds. For relatively large spillover values ($\beta > \overline{\beta}$) when R&D is being subsidised, firms face a greater incentive to engage in cost-reducing innovation despite the fact that within the RJV the spillover is set at its maximal value; this result contrasts with those obtained by Hinloopen (1995) and Stenbacka and Tombak (1996).[14] Figures 3-6 illustrate Proposition 2.

[Insert Figures 3-6 about here]

We now consider the relevant welfare comparisons in the case where production is linked to pollution. Proposition 3 summarises our results.

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[13] Notice also that $\partial\overline{\beta} / \partial\gamma > 0$, i.e as the efficiency of R&D decreases, R&D cooperation improves welfare relative to R&D subsidisation.

[14] Note though that Hinloopen (1995) uses a different specification for the subsidy function (subsidy per unit of R&D input), whereas Stenbacka and Tombak (1996) use the same R&D subsidy function but consider stochastic innovation.

Proposition 3. *When* $0 < u < 2\sigma / 3$ *and* $\gamma > 16/9$ *(i)* $W_c > W_{nc}$ *for* $0 \leq \beta \leq 1$*; (ii)* $W_s > W_{nc}$ *for* $0 \leq \beta \leq 1$*, (iii) for* $u < \tilde{u} < 2\sigma/3$*,* $W_s \geq W_c$ *if* $\beta \geq \bar{\bar{\beta}}$ *and* $W_s < W_c$ *if* $\beta < \bar{\bar{\beta}}$*, where* $\bar{\bar{\beta}} \equiv \{\beta | W_s = W_c\}$ *and* $\tilde{u} \equiv \{u | \bar{\bar{\beta}} = 1\}$*; for* $\tilde{u} < u$*,* $W_c > W_s$ *for* $0 \leq \beta \leq 1$.

It is also useful to state the following corollary.

Corollary 1. $\bar{\bar{\beta}} > \bar{\beta}$*, i.e. the critical spillover such that* $W_s = W_c$ *increases in the case of environmental concern,* $u > 0$*.*

Part (i) of Proposition 3 is similar to Proposition 2 in the sense that here too cooperative R&D results in higher welfare relative to non-cooperation in R&D. Part (ii) is slightly different in that R&D subsidies lead to higher welfare compared to non-cooperative R&D for any value of technological spillover. However, part (iii) is qualitatively different in that for relatively large values of u, $u > \tilde{u}$, R&D cooperation is always better than R&D subsidisation for any spillover value. For any other value of u, $0 < u < \tilde{u}$, we obtain a result similar to proposition 2, i.e. there is a critical spillover value above which R&D subsidies are a better instrument than RJVs. Notice, that from Corollary 1, this critical spillover is greater than the equivalent spillover in Proposition 2. Thus, the range of spillovers for which R&D subsidies are better diminishes when pollution effects are taken into account. Figures 7 and 8 illustrate Proposition 3.

[Insert figures 7 and 8 about here]

4. Tying-in Environmental and Technology Policy

In the light of our observation that social welfare decreases in the case when cost-reducing innovation leads to increased pollution due to output expansion and the results contained in Proposition 3, it seems necessary to examine the way in which welfare can be improved. We thus consider tying-in technology policy instruments with environmental regulation/policy.

We shall propose one particular type of policy that ties-in concern for the environment in the form of a subsidy towards R&D only if firms spend a minimum acceptable amount on abatement.

Let $K(r_i) = \delta r_i^2 / 2$ be the abatement expenditure for firm *i*, *i* = 1,2, where r_i is the reduction in per unit of output emissions and $\delta > 0$ measures the effectiveness of the abatement technology, i.e. by spending $K(r_i)$ firm *i* reduces its emissions-output ratio, λ, to $\lambda - r_i$, so that $u = k(\lambda - r_i)$. Note that abatement expenditure is an increasing and convex function of the per unit reduction in emissions but does not affect in any way the costs of production of a firm. We propose the following policy: *A subsidy s on R&D costs if $r_i \geq r_c$.*[15] *Otherwise, no subsidy*, where r_c is the critical level of abatement (to be defined later). The purpose of this policy is to give incentives to cost-reducing innovation only as long as some minimum necessary amount is spent on abatement. Under the proposed policy a firm faces the following cost structure in addition to the constant unit costs of production

$$\begin{cases} (1-s)(\gamma z_i^2 / 2) + \delta r_i^2 / 2 & if \quad r_i \geq r_c \quad (*) \\ \gamma z_i^2 / 2 & otherwise \end{cases} \qquad (13)$$

We then state the following result which will be useful in discussing the optimality and effectiveness of the proposed tied-in policy.

Lemma 2. *In the case of R&D subsidisation, social welfare is decreasing in u for* $u < 4\sigma / 3$.[16]

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[15] The critical value r_c is derived later on, see p.

[16] Note that Lemma 1 imposes a stricter upper bound on *u*, $u<2\sigma/3$, so that welfare is decreasing in *u* for this bound also.

As a result of Lemma 2, note that $\partial W_s / \partial r_c > 0$ because $\frac{\partial W_s}{\partial r_c} = \frac{\partial W_s}{\partial u}\frac{\partial u}{\partial r_c} = -k\frac{\partial W_s}{\partial u}$, where $u = k(\lambda - r_c)$ and it is implicitly assumed that a firm optimally chooses $r_i = r_c$ (this is checked later). Total welfare can be written as $\widetilde{W}_s = W_s - \delta r_c^2$, so that $\frac{\partial \widetilde{W}_s}{\partial r_c} = \frac{\partial W_s}{\partial r_c} - 2\delta r_c$, with W_s given by (11a). Notice that $\left.\frac{\partial \widetilde{W}_s}{\partial r_c}\right|_{r_c=0} = \left.\frac{\partial W_s}{\partial r_c}\right|_{r_c=0} > 0$, so that total welfare initially increases with r_c and the proposed policy is welfare improving. Given that $\frac{\partial^2 W_s}{\partial r_c^2} \propto 2(1+\beta)^2 k^2 > 0$, it follows that there is a critical abatement level, $r_c^* > 0$, which maximises total welfare, $\widetilde{W}_s$, if δ is sufficiently high, i.e. $\delta > \frac{(1+\beta)^2 k^2}{9\gamma - 4(1+\beta)^2}$.

Under the proposed policy, as given by (13), firm i's decision considering its R&D expenditure, z_i, is described by expression (9) - see page 10, with the symmetric equilibrium, z_s, given by expression (10). In the case where no subsidy is given the analysis of section 2.1 carries through. However, in the case when (13) (*) is applicable, gross profits and output are as on page 11, with net profits being $\pi_s - \delta r_c^2 / 2$ (where firm i optimally chooses r_i = r_c). Turning to the question of finding the critical abatement level, r_c, we proceed as follows.

Define social welfare under the proposed policy as

$$\widetilde{\widetilde{W}}_s = W_s - \delta r_c^2 \qquad (14)$$

where W_s is given by (11). The aim is to maximise (14) with respect to the subsidy rate, s, and the abatement level, r_c. We proceed in two steps. Notice that, for a given r_c, the optimal subsidy, s_c^*, is given by expression (12) suitably reinterpreted, so the first step consisted in $\max_s \widetilde{W}_s$. Next, we use the following

$$\widetilde{W}_s \equiv W_s - \delta r_c^2 = \frac{4\gamma\sigma^2 - 6\gamma\sigma k(\lambda - r_c) + k^2(\lambda - r_c)^2(1+\beta)^2}{9\gamma - 4(1+\beta)^2} - \delta r_c^2 \tag{15}$$

where W_s is given from (11a) and we have used $u = k(\lambda - r_c)$. The second step involves the maximisation of (15) with respect to r_c, yielding the optimal abatement level, r_c^*

$$r_c^* = \frac{k(3\gamma\sigma - \lambda k(1+\beta)^2)}{9\delta\gamma - (4\delta + k^2)(1+\beta)^2} > 0. \tag{16}$$

Substituting r_c^* into (15) we obtain

$$\widetilde{W}_s^* = \frac{\delta\lambda^2 k^2 (1+\beta)^2 - 6\delta\gamma\lambda k\sigma + \gamma\sigma^2(4\delta + k^2)}{9\delta\gamma - (4\delta + k^2)(1+\beta)^2} \tag{17}$$

i.e. the maximal social welfare when both the subsidy and the abatement level are chosen optimally. We are thus in a position to state the following

Proposition 4. In the case on non-cooperative R&D the optimal tie-in policy for welfare improvement takes the form "provide a subsidy $s(r_c^*)$ on R&D costs if $r_i \geq r_c^*$, otherwise provide no subsidy". [17]

The essence of proposition 4 consists in that it identifies a technology policy instrument in the form of an R&D subsidy that, in addition, aims to improve the environmental damage associated with the output expansion effect caused by cost-reducing R&D. Out analysis has shown that spending on R&D and obtaining a subsidy can have some beneficial side effects on the environment through firm's abatement activities. That is, the R&D subsidy can also help in pollution control without being targeted directly on abatement

[17] We have assumed that the relevant participation constraint is satisfied, i.e. a firm has an incentive to undertake abatement and receive the R&D subsidy as its profits in this case exceed the profits from not receiving the subsidy and doing no abatement. If the participation constraint is not satisfied, i.e $\pi_s(r_c^*) - \delta r_c^{*2}/2 < \pi_i$, in order to force firms undertake abatement a lump sum T can be given to restore incentives, $\pi_s(r_c^*) - \delta r_c^{*2}/2 + T = \pi_i$, where π_i is the equilibrium profit in the non-cooperative R&D scenario.

expenditure. The R&D subsidy can thus have a dual effect: to correct partly the R&D underinvestment problem - due to the market failure caused by the appropriability problem, and to encourage pollution control through abatement activities thus aiming at the market failure associated with the environmental problem.

We should note here that an alternative tying-in policy could take the form of allowing R&D cooperation - in the absence of any R&D subsidies- only if abatement expenditures are undertaken.[18] This latter policy can be shown to improve welfare as well. However, it seems questionable whether such a policy can be easily enforced and/or monitored and is not pursued any further.

5. Conclusion

In this paper we have studied a neglected aspect of technology policy resulting from the adverse impact that such policy might have on the environment through an output expansion effect due to firm's innovative activities. In the limited context of our analysis, irrespective of whether technology policy takes the form of R&D subsidies or the encouragement of Research Joint Ventures (RJVs), R&D leads to increased pollution and thus a negative impact on the environment and a decrease in social welfare. As a result, policies that might have been optimal in the absence of any environmental effect cease to be so. In particular, we have identified conditions on the spillover and environmental parameters under which the optimal R&D subsidy becomes negative, i.e. an R&D tax is necessary when the damage on the environment is quite substantial. Comparing social welfare in the three different set-ups under consideration, i.e. non-cooperative R&D, pre-competitive R&D cooperation and R&D subsidization, we find that such comparisons hinge on the relative magnitudes of the spillover rate and the environmental consciousness

[18] An analysis of this policy can be obtained from the authors upon request.

parameter but it is always the case than the non-cooperative R&D set-up is the worst outcome. In order to improve social welfare, we propose to tie-in technology and environmental policies. We have shown that the specific policy of using a targeted subsidy on R&D costs provided that a minimum critical amount of abatement is undertaken results in a clear improvement in social welfare. Moreover, the targeted R&D subsidy can be seen as having a dual effect: it corrects partly the R&D underinvestment problem and it encourages pollution control.

There are a number of dimensions in which this research can be extended. First, one could consider a policy that allows RJVs as long as a certain share of the R&D budget of the RJV is spent on abatement activities, in the absence of R&D subsidies. This opens up the possibility of R&D specialisation by the cooperating firms provided that information-sharing takes place within the RJV. This type of policy could induce complementary research projects which would benefit the RJV partners. Second, asymmetric or differential subsidies could be examined. For example, within an RJV, one of the partners could receive a subsidy on cost-reducing innovation while the other receives a subsidy on abatement. Of course, this latter option would entail coordination issues between the partners and might also require a maximum of emissions imposed on each firm.

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APPENDIX

Proof of Proposition 1

(i) Follows directly from (12a).

(ii) We proceed in three steps. Step (1). Minimum technology spillover, $\beta = 0$. In this case, $\hat{s}\big|_{u>0} = \dfrac{u(9\gamma - 4)}{3\gamma(3u - 4\sigma)} < 0$ *iff* $0 < u < \dfrac{4\sigma}{3}$. To see why it is optimal to impose an R&D tax when $u > 0$ note the following: $\hat{s} < 0$ if and only if $u > \bar{u}$, given the monotonicity of $\hat{s}$, where $\bar{u} = 0$ when $\beta = 0$, and $3u - 4\sigma < 0$; putting these together gives $0 < u < 4\sigma / 3$. On the contrary, $\hat{s}>0$ if and only if $u < \bar{u}$ and $3u - 4\sigma > 0$ and it is immediately evident that these two inequalities are not compatible. Step (2). Maximum technology spillover, $\beta = 1$. Here we have $\hat{s}\big|_{u>0} = \dfrac{18\gamma(u-\sigma) - 8u}{6\gamma(3u - 4\sigma)}$. We shall show that the optimal subsidy can be negative (i.e. a tax), positive or zero, depending on the value of the environmental parameter u. Thus $\hat{s}\big|_{u>0} < 0$ if and only if (a) $u > \bar{u}\big|_{\beta=1}$, or $u > 18\gamma\sigma / (18\gamma - 8)$ and (b) $18\gamma(u - \sigma) - 8u > 0$ and $3u - 4\sigma < 0$. From (a) and (b) it is established that an R&D tax is optimal for $\bar{u}\big|_{\beta=1} < u < 4\sigma / 3$. Similarly, an R&D subsidy is optimal for $u < \bar{u}\big|_{\beta=1} < 4\sigma / 3$, while a zero subsidy is chosen for $u = \bar{u}\big|_{\beta=1} < 4\sigma / 3$.[1] Step (3). Intermediate technology spillover, $\beta \in (0,1)$. Here we need to examine the behaviour of the optimal subsidy with respect to the spillover; we find

$$\frac{\partial \hat{s}}{\partial \beta} = \frac{u(2\beta^3 + 3\beta^2 - 1) - 90\sigma}{18(1+\beta)^2(3u - 4\sigma)} \qquad \text{(A1)}$$

[1] Given that $\gamma > 16/9$, it is always true that $\bar{u}\big|_{\beta=1} < 4\sigma / 3$.

As we have showed in steps (1) and (2), $3u-4\sigma<0$, so that $\partial\hat{s}/\partial\beta>0$ if and only if $u(2\beta^3+3\beta^2-1)-90\sigma<0$. The latter is always true as long as $3u-4\sigma<0$, for any value of β. Thus $\partial\hat{s}/\partial\beta>0$ for $\beta\in[0,1]$. Combining with step (2) the result follows.

(iii) Combining the result that $\partial\hat{s}/\partial\beta>0$ with the findings in (i) and (ii) above, it is clear that the optimal subsidy/tax when $u>0$ is always lower than the optimal subsidy when $u=0$ for any value of the spillover.

Notice that we have identified an upper bound on u, i.e. $0<u<4\sigma/3$. QED.

Proof of Lemma 1

From expression (4) we find that $W_{nc}\geq 0$ if and only if $u\leq\dfrac{2\sigma[9\gamma-(2-\beta)^2]}{3[9\gamma-2(2-\beta)(1+\beta)]}$. Taking the minimum value of the r.h.s. of this last inequality with respect to β yields $u\leq\dfrac{2\sigma(9\gamma-4)}{(9\gamma-4.5)}$, which reaches a minimum as $\gamma\to+\infty$, or $u\leq 2\sigma/3$. From expression (7) we have $W_c\geq 0$ if and only if $u\leq\dfrac{2\sigma(9\gamma-2)}{3(9\gamma-8)}$. The r.h.s. of the latter inequality is minimised as $\gamma\to+\infty$, or $u\leq 2\sigma/3$. Finally, from (11) and (11a) note that $W_{\hat{s}}\geq W_{\hat{s}=0}$ by the optimality of $\hat{s}$. Given that $\dfrac{\partial\hat{s}}{\partial u}<0$, $W_{\hat{s}=0}\geq 0$ for all $u\leq 2\sigma/3$. Q.E.D.

Proof of Proposition 2

(i) From (4) and (7) notice that

$$W_c>W_{nc}\Rightarrow\frac{9\gamma-2}{(9\gamma-8)^2}>\frac{9\gamma-(2-\beta)^2}{[9\gamma-2(2-\beta)(1+\beta)]^2},\ \text{or}\ \frac{9\gamma-2}{(9\gamma-8)^2}>\frac{9\gamma-1}{(9\gamma-4.5)^2},$$ where

the r.h.s. of the latter inequality is the maximum value w.r.t. β of the r.h.s. of the former inequality. It is then easy to establish that $\lim_{\gamma\to+\infty}\left[\frac{9\gamma-2}{(9\gamma-8)^2}/\frac{9\gamma-1}{(9\gamma-4.5)^2}\right]=1$, so that for any (admissible) value of γ $\left[\frac{9\gamma-2}{(9\gamma-8)^2}/\frac{9\gamma-1}{(9\gamma-4.5)^2}\right]>1$.

(ii) Using (4) and (11a) straightforward calculations show that for $\beta = 0$, $W_s = W_{nc}$ and for $0<\beta\le 1$, $W_s > W_{nc}$.

(iii) From (7) and (11a) we have $W_s \ge W_c$ if and only if

$\frac{8\gamma\sigma^2(18\beta^2\gamma+36\beta\gamma-45\gamma-4\beta^2-8\beta-28)}{(9\gamma-8)^2(9\gamma-4(1+\beta)^2)}\ge 0$, which gives two solutions for β, one negative and one positive. Selecting the positive root, $W_s \ge W_c$ iff $\beta\ge\overline{\beta}$ and $W_s < W_c$ iff $\beta<\overline{\beta}$, where $\overline{\beta}=\frac{(4-18\gamma)+\sqrt{2}\sqrt{567\gamma^2-414\gamma+64}}{2(9\gamma-2)}$ and $\overline{\beta}\equiv\{\beta|W_s=W_c\}$, $0<\overline{\beta}<1$. Q.E.D.

Proof of Proposition 3

(i) From (4) and (7) we have $\partial W_{nc}/\partial u<0$ and $\partial W_c/\partial u<0$ respectively. Proposition 2 establishes that $W_c|_{u=0} > W_{nc}|_{u=0}$. From Lemma 1 we know that $u<2\sigma/3$. To show that $W_c > W_{nc}$ when $u > 0$ it suffices to show that $W_c|_{u=2\sigma/3} > W_{nc}|_{u=2\sigma/3}$. Substituting $u=2\sigma/3$ in (4) and (7) we have $W_c > W_{nc}$ if and only if $\frac{12[9\gamma-2(2-\beta)(1+\beta)]^2}{\beta(2-\beta)(9\gamma-8)^2}>1$.

Taking the minimum value of the l.h.s. of the last inequality w.r.t. β we then have $\frac{12(9\gamma-4.5)^2}{(9\gamma-8)^2}>1$. Taking the limit as $\gamma\to+\infty$ establishes that $W_c > W_{nc}$.

(ii) From (4) and (11a) we obtain $W_s > W_{nc}$ if and only if $\frac{(2\beta^3 u - 6\beta u + 9\beta\gamma u + 9\gamma u - 4u - 18\beta\gamma\sigma)^2}{(9\gamma + 2\beta^2 - 2\beta - 4)^2[9\gamma - 4(1+\beta)^2]} > 0$. Given that $\gamma > 16/9$ (by assumption) the last inequality is always positive and thus establishes the result.

(iii) From (7) and (11a) we have $W_s \geq W_c$ if the following inequality holds

$$\frac{4\gamma\sigma^2 - 6\gamma\sigma u + u^2(1+\beta)^2}{9\gamma - 4(1+\beta)^2} \geq \frac{4\gamma\sigma^2(9\gamma-2) - 6\gamma\sigma u(9\gamma-8)}{(9\gamma-8)^2}. \tag{A2}$$

This gives two solutions for β one of which is negative and thus is discarded. The positive solution is given by $\beta \geq \overline{\overline{\beta}}$ where $\overline{\overline{\beta}} \equiv \{\beta | W_s = W_c\}$ and $\overline{\overline{\beta}} = f(u,\gamma,\sigma)$.[2] It is possible although tedious to show that $\overline{\overline{\beta}} > 0$. It also necessary that $\overline{\overline{\beta}} \leq 1$; setting $\overline{\overline{\beta}} = 1$ and solving for u gives two solutions, $u_1 < 2\sigma/3$ and $u_2 > 2\sigma/3$, which is not acceptable as it violates Corollary 1. We thus are left with

$u_1 = \frac{54\gamma\sigma^2 - 48\gamma\sigma + \sqrt{2}\sqrt{\gamma(9\gamma-16)(9\gamma-8)^2\sigma^2}}{(9\gamma-8)^2} = \tilde{u}$. If $u > \tilde{u}$ then $\overline{\overline{\beta}} > 1$ and (A2) cannot be satisfied, i.e. $W_c > W_s \ \forall \beta \in [0,1]$. If $u \leq \tilde{u}$ it is obvious that (A2) is satisfied for $\beta \geq \overline{\overline{\beta}}$, while the opposite is true, i.e. $W_c > W_s$ for $\beta < \overline{\overline{\beta}}$. Q.E.D.

Proof of Corollary 1

To prove this it is sufficient to show that $\lim_{u\to 0}\overline{\overline{\beta}} = \overline{\beta}$. From the expression for $\overline{\overline{\beta}}$ (see footnote 2) we have

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[2] The exact solution is given by

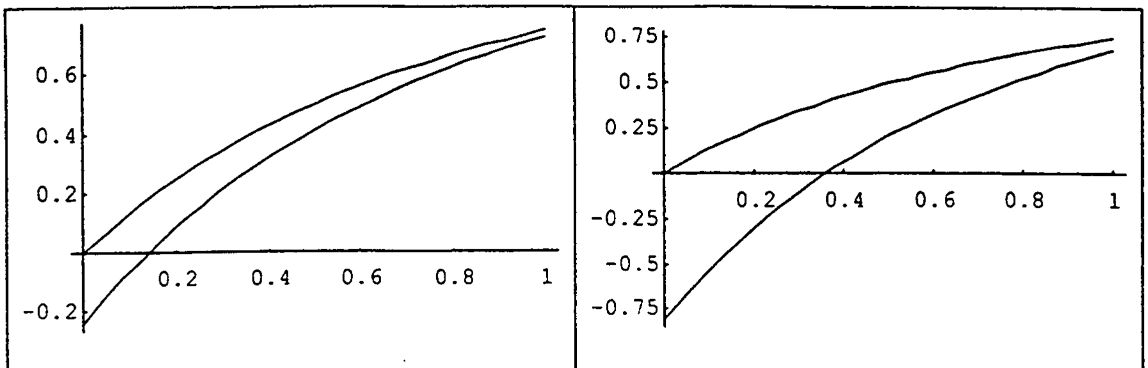
$$\overline{\overline{\beta}} = \frac{\begin{array}{c}32\gamma\sigma^2 - 144\gamma^2\sigma^2 - 192\gamma\sigma u + 216\gamma^2\sigma u - 64u^2 + 144\gamma u^2 - 81\gamma^2u^2 \\ +2\sqrt{2}\sqrt{\gamma\sigma(63\gamma\sigma - 32\sigma + 48u - 54\gamma u)(-32\gamma\sigma^2 + 144\gamma^2\sigma^2 + 192\gamma\sigma u - 216\gamma^2\sigma u + 64u^2 - 144\gamma u^2 + 81\gamma^2u^2)}\end{array}}{-32\gamma\sigma^2 + 144\gamma^2\sigma^2 + 192\gamma\sigma u - 216\gamma^2\sigma u + 64u^2 - 144\gamma u^2 + 81\gamma^2u^2}$$

$$\lim_{u\to 0}\overline{\overline{\beta}} = \frac{4-18\gamma+\sqrt{2}\sqrt{(9\gamma-2)(63\gamma-32)}}{2(9\gamma-2)}$$

which is the expression we have found for $\overline{\beta}$. Q.E.D.

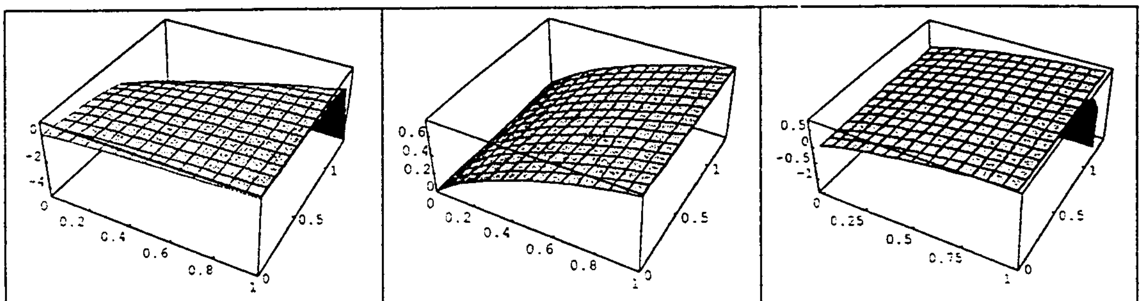
Proof of Lemma 2

Consider equation (11a) which gives social welfare when the optimal R&D subsidy is implemented. Differentiating with respect to u we obtain $\frac{\partial W_s}{\partial u} \propto -6\gamma\sigma + 2u(1+\beta)^2$. It is then evident that $\partial W_s / \partial u < 0$ if and only if $2u(1+\beta)^2 < 6\gamma\sigma$ for given β, or $\partial W_s / \partial u < 0$ if and only if $8u < 6\gamma\sigma$ for all β. Thus, given $\gamma > 16/9$, the above condition becomes $u < 4\sigma/3$. Q.E.D.



u = 0.3, γ = 2.5   u = 0.66, γ = 2.5

Figure 1: Optimal subsidy/tax (top line when u = 0, bottom line when u > 0), σ = 1.



Optimal Subsidy when u > 0   Optimal Subsidy when u = 0   Comparison of optimal subsidies

Figure 2: Optimal Subsidy/tax, ($\sigma = 1$, $\gamma = 2.5$).

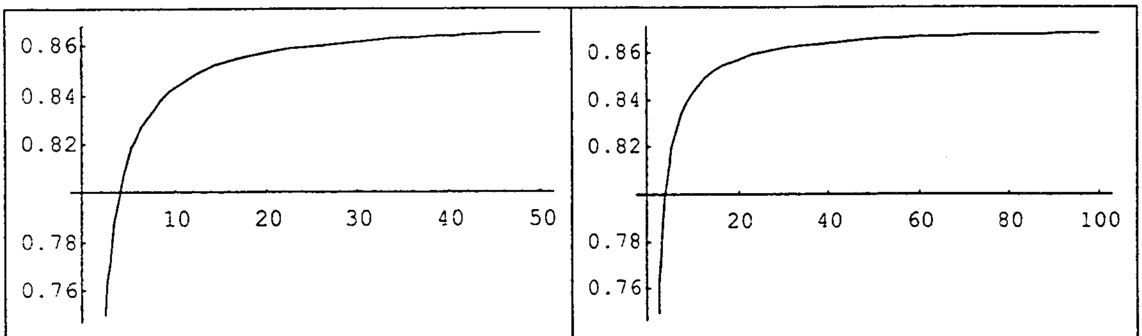


Figure 3a: Critical spillover rate, $\bar{\beta}$ for $W_c = W_s$, u = 0, σ = 1, 2.5 < γ < 50

Figure 3b: Critical spillover rate, $\bar{\beta}$ for $W_c = W_s$, u = 0, σ = 1, 2.5 < γ < 100

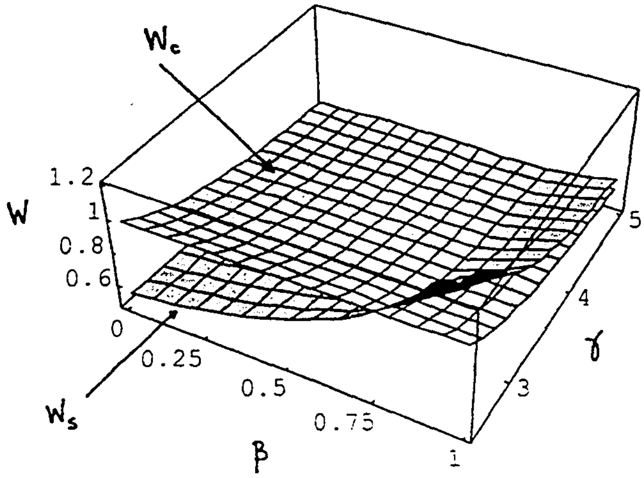


Figure 4: Welfare Comparison between W_s and W_c, $u = 0$, $0 \leq \beta \leq 1$, $2.5 < \gamma \leq 5$.

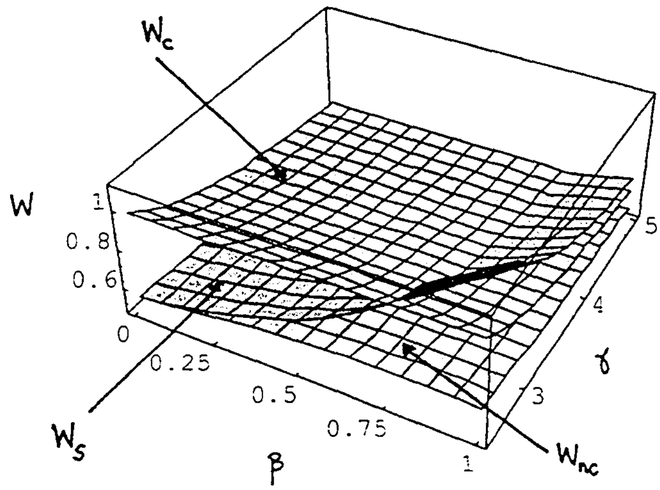


Figure 5: Welfare Comparisons, $u = 0$, $0 \leq \beta \leq 1$, $2.5 < \gamma \leq 5$.

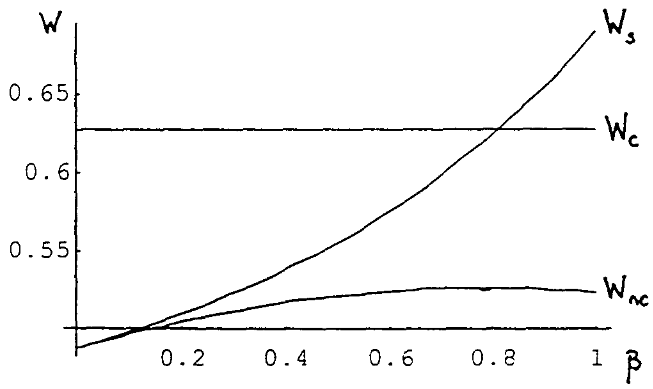


Figure 5a: Welfare Comparisons, $u = 0$, $0 \leq \beta \leq 1$, $\gamma = 5$.

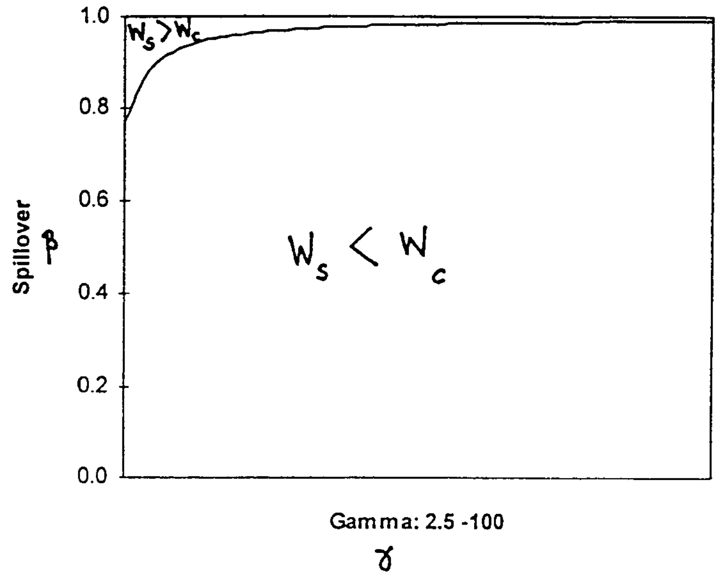


Figure 6: Welfare Comparison; RJV versus R&D Subsidies, $u = 0$, $\sigma = 1$.

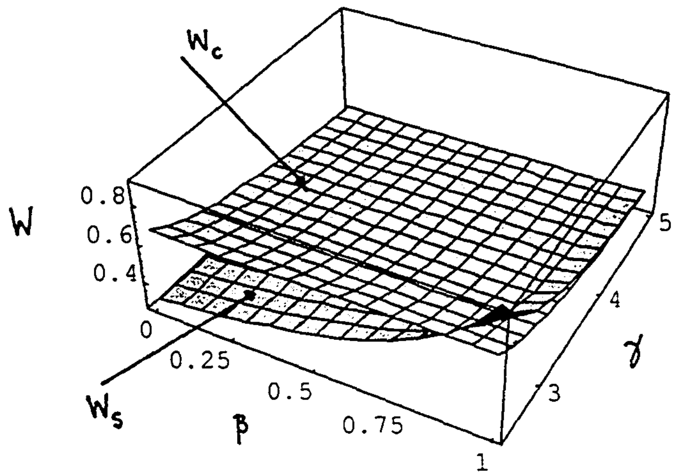


Figure 7a: Welfare comparison: RJV vs R&D subsidies, u=0.3, σ = 1, $u < \tilde{u}$

Note: For definition of $\tilde{u}$ see Proposition 3.

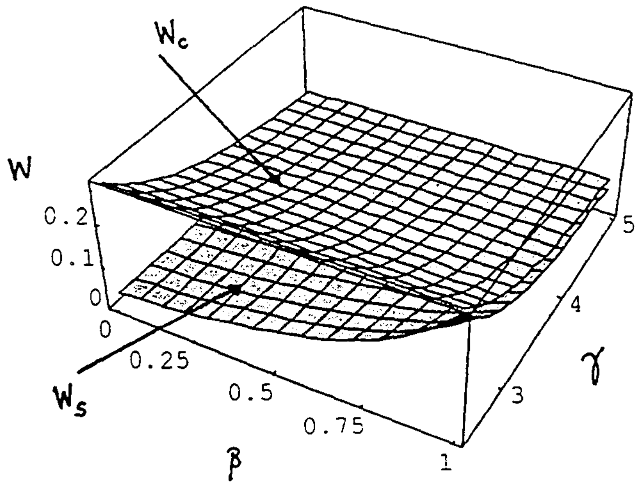


Figure 7b: Welfare comparison; RJV versus R&D subsidies, u=0.66, σ = 1

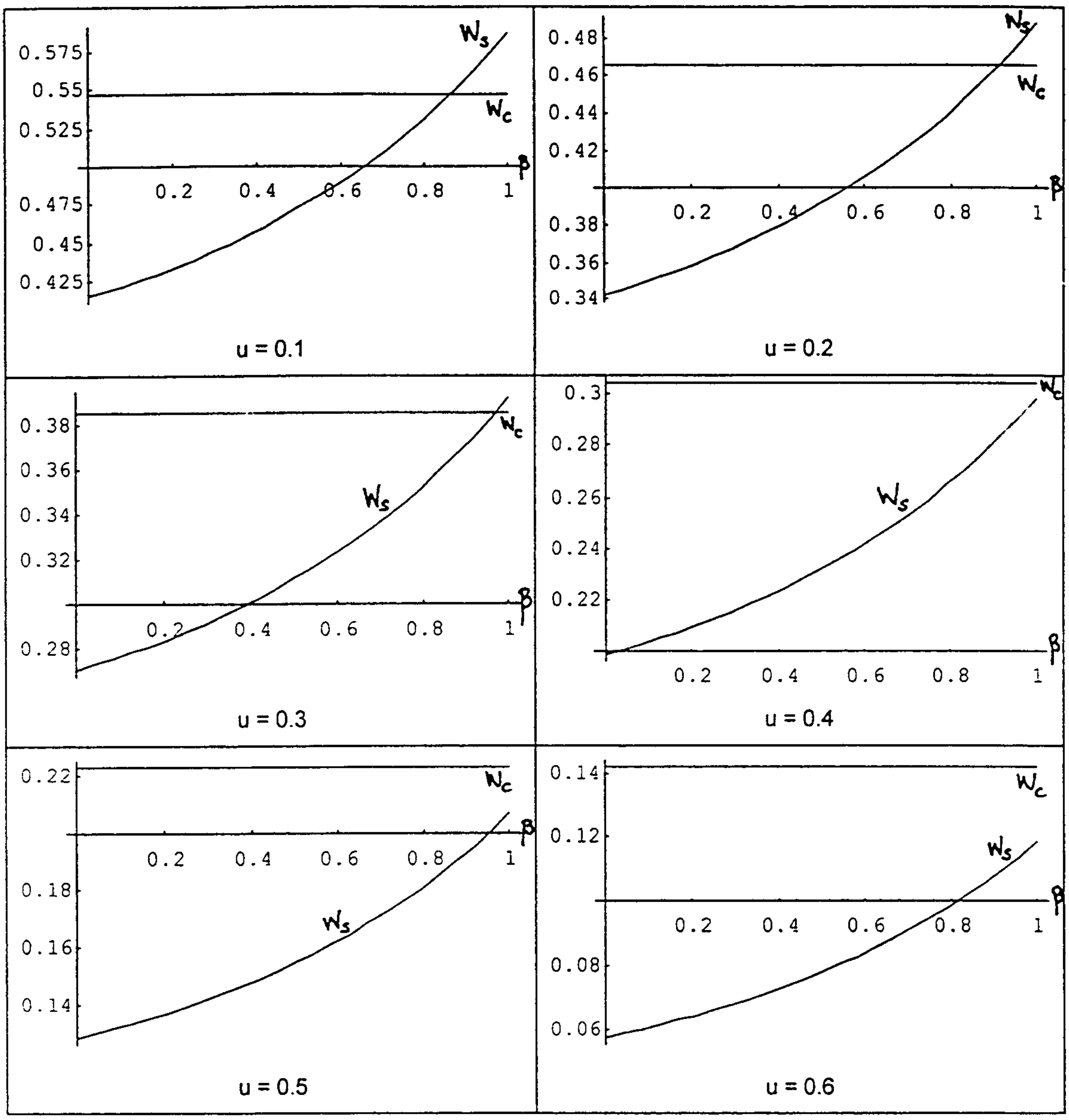


Figure 8: Welfare comparison: RJV vs R&D subsidies, $\sigma = 1$, $\gamma = 2.5$, $\tilde{u} = 0.35$.

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