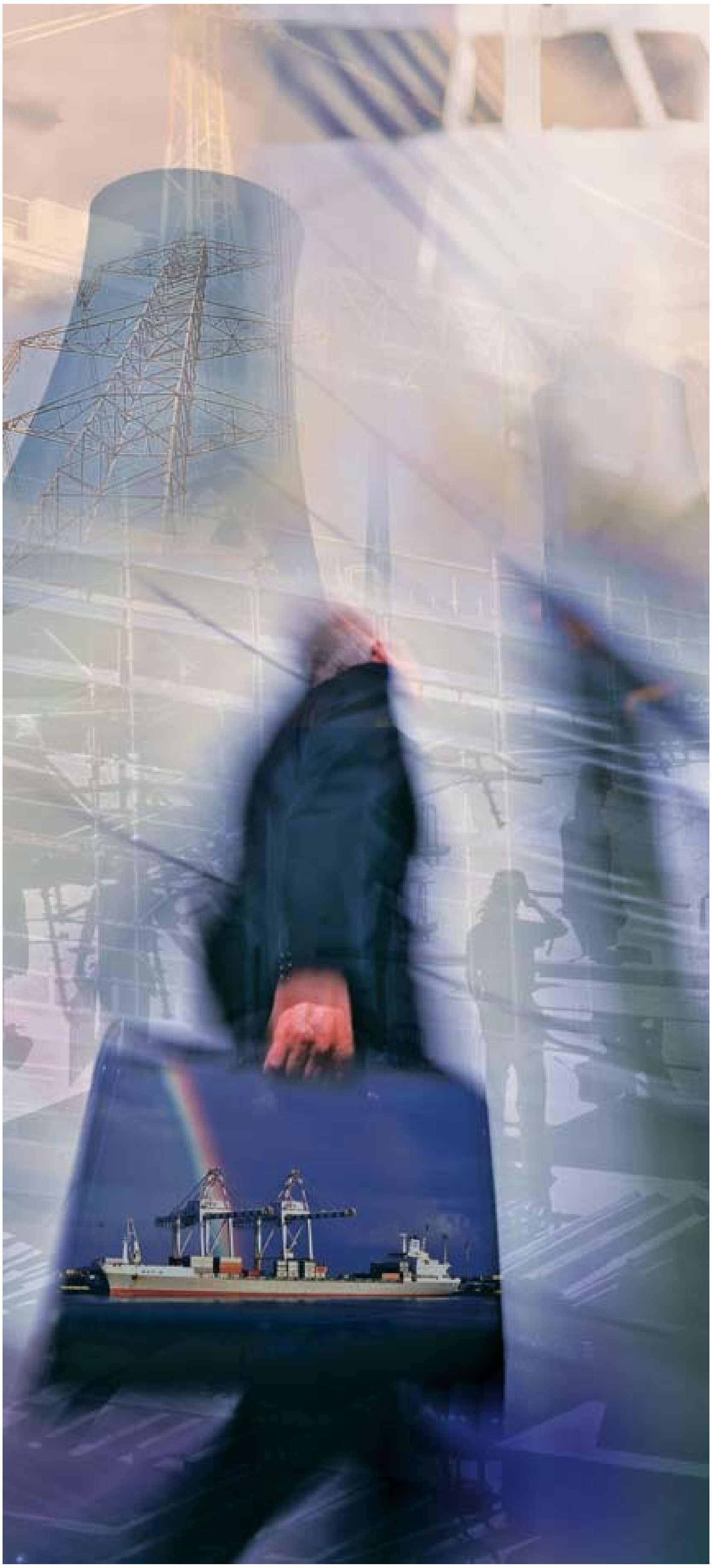

Queensland

The Economic Society of Australia Inc.

Proceedings of the 37th Australian Conference of Economists

Papers delivered at ACE 08

30th September to 4th October 2008
Gold Coast Queensland Australia

ISBN 978-0-9591806-4-0

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Published November 2008

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The Paper following forms part of - *Proceedings of the 37th Australian Conference of Economists*
ISBN 978-0-9591806-4-0

Liberalizing Trade in Environmental Goods

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Abstract

Trade liberalization in environmental goods is high on the agenda of the current Doha round. We examine its effects in a model with one domestic downstream polluting firm and two upstream firms (one domestic, one foreign). The domestic government sets the emission tax rate after the outcome of R&D is known. The upstream firms offer their technologies to the downstream firm at a flat fee. The domestic upstream firm's R&D incentive may increase or decrease with trade liberalization. It will decrease when its own existing technology is relatively inefficient and when the foreign firm's existing technology is relatively efficient. The expected pollution, consumer surplus and the welfare is generally higher under free trade.

JEL Classification: F12, F18, L24, O32, Q55, Q58

Keywords: Pollution Abatement Technology, R&D, Trade and Environment

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1 Introduction

The issue of trade and environment has mostly been perceived with the notion that the mutilfolded increase in international trade is detrimental to the environment. However over the past decade or so, there has been an increasing emergence of the idea that international trade could also play an instrumental role in protecting the environment.

Trade and Environment became one of the key issues for the 4th WTO Ministerial Conference at Doha in November 2001. With a view to enhance the mutual supportiveness of trade and environment, the WTO member countries adopted the mandate to prioritize the liberalization of environmental goods and services, and further agreed to the negotiation on 'reduction or, as appropriate, elimination of tariff and non-tariff barriers to environmental goods and services' (WTO, 2001). The rationale for initiating specific negotiations on environmental goods and services, in addition to the other goods and services was to prioritize the areas where ongoing trade liberalization negotiations can deliver cleaner environmental benefits as well as economic development. This was perceived by many as a 'win-win' outcome as on one hand it fosters trade and on the other hand it facilitates the protection and improvement of environmental standards. due to the greater movement of environmentally friendly goods, services and technologies. This was also reiterated in OECD (2003): '*Reducing tariffs and other trade restricting measures could increase the availability of green goods in global markets, which would benefit both consumers and the environment'*.

Thus, the advocates of free trade points out that liberalization will help in fostering the environment of the countries as polluting firms in these countries could now adopt new cleaner or efficient goods (as inputs) and technologies of production available to them as a result of trade liberalisation. However, the important concern that arises from these view point is how such a liberalization would affect the domestic firms producing in these sectors and more importantnly whether it will further lead to a decrease in the environmental pollution.

In the literature, there are some evidences of how (in this case international) interactions in oligopoly markets could affect the domestic firms particularly in the context of its R&D initiative,(Brander and Spencer, 1983; Spence, 1984; Fudenberg and Tirole, 1984). Long et al. (2007) points to increasing evidence of how domestic firms increases their productivity when exposed to foreign competition as they are now forced to become more efficient to survive the tougher import competitions or because they now have more access to better technology and management techniques. Alvarez and Lopez (2005), Hallward-Driermeier et al. (2002) and Emami-Namini and Lopez (2006) all found empirical evidence of firms pursuing strategies to boost their productivity to increase their chances of entering export markets when undergoing trade liberalization. Ederington and McCalman (2007) study the effect of trade liberalization on the incentives of firms to adopt a better foreign technology and show both theoretically and in an empirical study of Colombian firms that the effect of trade policy on the speed of technology adoption depends on firm and industry specific factors.

Hence from the literature we see evidence of R&D incentive and productivity increasing with the adoption of trade liberalization policy dragging us to the conclusion that liberalization could be beneficial for the domestic industry. However, none of these studies have taken into consideration the implications of trade liberalization of environmental goods and services and whether it will be instrumental in reducing the pollution. Thus the contribution of this paper is to complement the literature by analysing how trade liberalization could affect the environmental goods and services producing domestic firms and the impact it will have on the environment, i.e. to see whether the '*win-win*' outcome could really exist?

We are interested in indentifying the strategic behaviour of firms which undertake R&D to reduce polluting emissions. The paper tries to identify how trade liberalization affects the R&D incentive of the domestic supplier of pollution abatement technology. For this we consider a model where the downstream good's production is polluting and the upstream industry is engaged in R&D to develop a pollution abatement technology which it can sell to the downstream firm for a license fee. The upstream firm faces competition with a foreign firm under the free trade regime. We analyze how the R&D incentive changes when the country undergoes trade liberalization. In stage 1, the upstream firms decide whether or not to do R&D. After observing the R&D outcome, the government sets its environmental tax rate in stage 2. In stage 3, the upstream firms set their technology fees and in stage 4, the downstream firm chooses which technology to use and sets its output level. We find that the incentive for the domestic firm to do R&D increases with trade liberalization for sufficiently inefficient technology of the foreign firm. This is because the worse the foreign firm's technology, the larger is the fee that the domestic firm can command in case it succeeds in R&D.

Requate (2005) gives a detailed survey of the many papers that have studied the interaction between environmental policy regimes and the incentive to adopt new abatement technologies. As in our paper, Parry (1995) sharply separates the polluting firm from the pollution abatement technology R&D sector to derive the second best optimal tax rate for the cases of linear and convex damage with and without the possibility of costless imitation. He finds that if imitation is not possible, the second best optimal tax rate is smaller than marginal damage. In his paper, each upstream firm conducts one R&D project to develop a new abatement technology to provide for the polluting downstream sector and if a firm is successful, it is granted a patent and becomes a monopolist. Similar to our model, the ex ante symmetric downstream firms can adopt the new technology by paying a license fee. Parry (1995) also shows that a rising environmental tax rate leads to a smaller number of polluting firms in the downstream market. Since those with the highest willingness to pay for the new technology stay in the market, a higher tax also induces a higher license fee. One of the differences from our model is that, since the main focus of our paper is to identify the relationship between trade liberalization and R&D incentive of the firm, we consider a international duopolistic interaction setting. Unlike his paper the assumption of free entry in both markets is applied only in the free trade regime and not under Autarky. Also we assume in our model, that the downstream firm is the sole producer.

Fisher et al. (2003) set up a model with large number of competitive polluting firms, one of which is the innovator of the new abatement technology. They compare the effect of different ex-post environmental policy regimes on the R&D outcome and find that the ranking of policy instruments depends on a number of factors: the scope for imitation, the costs of innovation, the relative level and slope of the marginal environmental benefit function, and the number of firms producing emissions.

Laffont and Tirole (1996) consider a model similar to ours where one upstream firms does R&D to develop a pollution abatement technology to produce the downstream industry good to point out the various inefficiencies induced by markets for pollution permits with regard to innovation and diffusion of new technologies. The authors show that if the regulator commits to its environmental policy of a permit price after the R&D outcome but before the innovator's pricing decision, the innovator does not engage in R&D because he will make no profit as the innovator will have to undercut the permit price which driving down the license fee to zero. However in the case where the regulator commits to a credible environmental pollution permit price prior to the R&D outcome, then the innovation incentive is always smaller than optimal, and the induced level of adoption may be sub-optimal.

In an imperfect competition set up where the regulator ex-ante commits to both an emission tax and an R&D subsidy, Katsoulacos and Xepapadeas (1996) study a Cournot duopoly model. In the model firms are able to reduce their emissions-per-output ratio by investing in R&D with the possibility of spill-over of technology and they find that the optimal tax rate will be less than the marginal damage and the government might subsidize the R&D effort of firms if the spillover effects are sufficiently high, and negative otherwise.

Denicolo (1999) compares the different timings and commitment strategies with respect to welfare in a model with an upstream monopolistic R&D firm and many polluting downstream firms. The downstream perfectly competitive firms can obtain a new cleaner technology from the upstream firm. Denicolo (1999) finds that that taxes and permits are equivalent for ex post regulation and not equivalent for the ex ante commitment and both always lead to underinvestment in R&D.

To compare the different forms of timing and committments, Requate (1995) considers a model with a polluting downstream industry and an upstream industry which engages in R&D to develop an abatement technology to sell to the downstream firms. Unlike our paper, he assumes that the upstream firm is a monopolist where as in our model, it is a monopolist only under Autarky.

Montero (2002) compares the effect of different environmental policy instruments on the R&D incentive of firms using a Cournot duopoly model with imperfect competition and found that the R&D incentive is greater under environmental standards than under environmental permits.

Theotoky (2003) compares the environmental tax and R&D (for environmental pollution abatement) subsidy under Cournot and Bertrand competition with differentiated goods and when the government pre-commits its environmental policy. The author finds that the second best emission tax is always higher under Bertrand competition. In the case of R&D subsidy, the author finds that the comparison between the two modes of competition can be higher or lower depending on the degree of differentiation and environmental tax.

Poyago-Theotoky (2007) addresses a model with an upstream firm undertaking R&D in environmental pollution abatement technology to highlight the significance of firms forming a cartel for such R&D investments. The author shows that environmental R&D and the subsequent welfare is higher in the case of an environmental cartel compared to independent R&D except in the case of relatively large environmental damage coefficients and efficient R&D. However in the Poyago-Theotoky (2007) paper, the main focus is to identify which is the best strategic response of the firms, i.e. whether to undertake R&D jointly or individually.

The rest of the paper is organised as follows. In Section 2, we describe the model and outline the game. In Section 3 we solve in the general form the strategic responses of the firms under consideration and outline the different possible R&D outcomes. In Section 4, we disucss the game under both the autarky and free trade regime and derive the payoff matrix of the firms. Section 5 discusses the R&D decisions of the firms following which we carry out a detailed comparison of the two R&D regimes. We offer some concluding remarks in Section 6.

2 The model

We consider a model where there is one consumption good, for which domestic market demand is given by $P = A - q$, with P the product price, q production and $A > 0$.

There is one domestic producer of the good (the downstream firm), with constant marginal cost of production c. We will normalize $A - c = 1$, so that:

$$P - c = 1 - q \tag{1}$$

and consumer surplus C is:

$$C = \frac{1}{2}q^2 \tag{2}$$

There is no international trade in this good. Production of the good is polluting. Environmental damage of emissions E is:

$$D(E) = \frac{1}{2}\lambda E^2 \tag{3}$$

The emissions-to-output ratio e depends on the abatement technology that the downstream firm is using. If it does not use any abatement technology, $e = 1$. The downstream firm can also use an abatement technology that an upstream firm has developed, for a flat fee F.

The domestic (foreign) upstream firm has an abatement technology available with $e = e_h$ (e_f), with $e_f < e_h < 1$, i.e. the foreign firm's technology is more efficient. Both firms can do R&D into a new technology with $e = e_n,\ e_n < e_f$. The cost of R&D is R and the probability of finding the new technology is p. Environmental policy consists of an emission tax. The domestic government sets the tax rate at the level that maximizes domestic welfare.

We compare the scenarios of autarky A and free trade T. With autarky, the domestic downstream firm cannot use the technology from the foreign upstream firm; with free trade it can.

The game under autarky A is as follows:

1. The domestic upstream firm decides whether or not to do R&D, and the outcome of R&D is observed.

2. The domestic government sets the emission tax rate.

3. The domestic upstream firm sets the technology fee.

4. The downstream firm decides which abatement technology to use and sets its output level.

The game under free trade T is:

1. The domestic and foreign upstream firms decide whether or not to do R&D, and the outcome of R&D is observed.
2. The domestic government sets the emission tax rate.
3. The domestic and foreign upstream firms set their technology fee.
4. The downstream firm decides which abatement technology to use and sets its output level.

3 General analysis

In stage 3, denote the firm with the most (least) efficient technology e_1 (e_2) by firm 1 (2). Firms 1 and 2 engage in price competition to sell their technology to the downstream firm. In autarky, the domestic upstream firm is always firm 1 and there is no firm 2.

There are several scenarios s for stage 3, depending on which technologies are available. In equilibrium, firm 1 will charge a fee of $F^s = \pi_1^s - \pi_2^s$ with π_1^s the downstream firm's profits (gross of the fee) with firm 1's technology. In autarky, π_2^s is the downstream firm's profit without abatement technology. With free trade, π_2^s is the downstream firm's gross profit with firm 2's technology. In equilibrium, firm 2 will charge a fee of 0. Strictly speaking, the downstream firm will then be indifferent between the technology offered by firm 1 and the technology offered by firm 2 (with free trade) or no abatement technology (in autarky). We assume that the firm will choose firm 1's technology.

In autarky, the scenarios are $n0$ and $h0$ when the domestic upstream firm has and has not found the new technology, respectively. In both scenarios, the downstream firm chooses to use the domestic upstream firm's technology. With free trade, the scenarios with their equilibrium outcomes are:

- fh : Neither the domestic nor the foreign firm has found the new technology. Then the foreign firm will supply the technology e_f to the downstream firm.

- nh : Only the foreign firm has found the new technology. The foreign firm will supply the technology e_n to the downstream firm.

- nf : Only the domestic firm has found the new technology. The domestic firm will supply the technology e_n to the downstream firm.

- nn : Both firms have found the new technology. They compete the fee down to zero. The domestic firm is indifferent between the two upstream firms' offers.

Denoting the downstream firm's profit net of the license fee in scenario s by Π^s, we have:

$$\Pi^s = \pi_1^s - F^s \tag{4}$$

where from (1):

$$\pi_1^s = (1 - q_1^s - te_1)\, q_1^s \tag{5}$$

Differentiating (5) and solving for q_1^s

$$q_1^s = \frac{1 - te_1}{2} \tag{6}$$

Substituting (6) in (5), we get the profit of the downstream firm as

$$\pi_1^s = \left[\frac{1 - te_1}{2}\right]^2 \tag{7}$$

$$\Pi^s = \left[\frac{1 - te_1}{2}\right]^2 - F \tag{8}$$

Similary if the downstream firm uses the less efficient technology:

$$\pi_2^s = (1 - q_2^s - te_2)\, q_2^s \tag{9}$$

Differentiating (9) and solving for q_2^s yields:

$$q_2^s = \frac{1 - te_2}{2} \tag{10}$$

Substituting (10) into (9), the profit of the downstream firm in case it uses the less efficient technology is:

$$\pi_2^s = \left[\frac{1 - te_2}{2}\right]^2 \tag{11}$$

As argued above, upstream firm 1 will charge a fee of

$$F^s = \pi_1^s - \pi_2^s \tag{12}$$

Therefore, substituting (7) and (11), upstream firm 1's fee in scenario s is:

$$F^s = \left[\frac{1 - te_1}{2}\right]^2 - \left[\frac{1 - te_2}{2}\right]^2 \tag{13}$$

Substituting (12) into (8), we get the profit of the downstream firm (given it uses the efficient technology e_1) as:

$$\Pi^s = \pi_1^s - (\pi_1^s - \pi_2^s) = \pi_2^s \tag{14}$$

In the second stage, the goverment sets the emission tax rate that maximizes domestic welfare W_h^s in scenario s, given that the domestic firm uses the most efficient technology e_1. Social welfare is the sum of the domestic upstream and downstream firms' profits, consumer surplus (2) and tax revenues, minus environmental damage (3):

$$W_h^s = \Pi^s + F_h^s + \frac{1}{2}\left[q_1^s\right]^2 + te_1 q_1^s - \frac{1}{2}\lambda\left[e_1 q_1^s\right]^2 \tag{15}$$

Two conflicting forces are at work when the government sets the tax rate. On the one hand the government wants to tax pollution, because there is too much of it. On the other hand, it wants to subsidize the downstream firm's production, because there is too little of it, due to monopoly power. The government cannot subsidize production directly, therefore it lowers the pollution tax instead. When e_1 is low enough, the government is not very worried about pollution, and the need to reduce pollution is exactly balanced by the need to increase production.

In fact, we shall see in Section 4 that from the point where $t = 0$, the licence fee is first increasing and then decreasing in e_1. As we will explain in Section 4, we would like to limit our analysis to cases where the licence fee is decreasing in e_1. Anticipating the analysis from Section 4, Figure 1 shows the admissible values of e_n and e_h for different

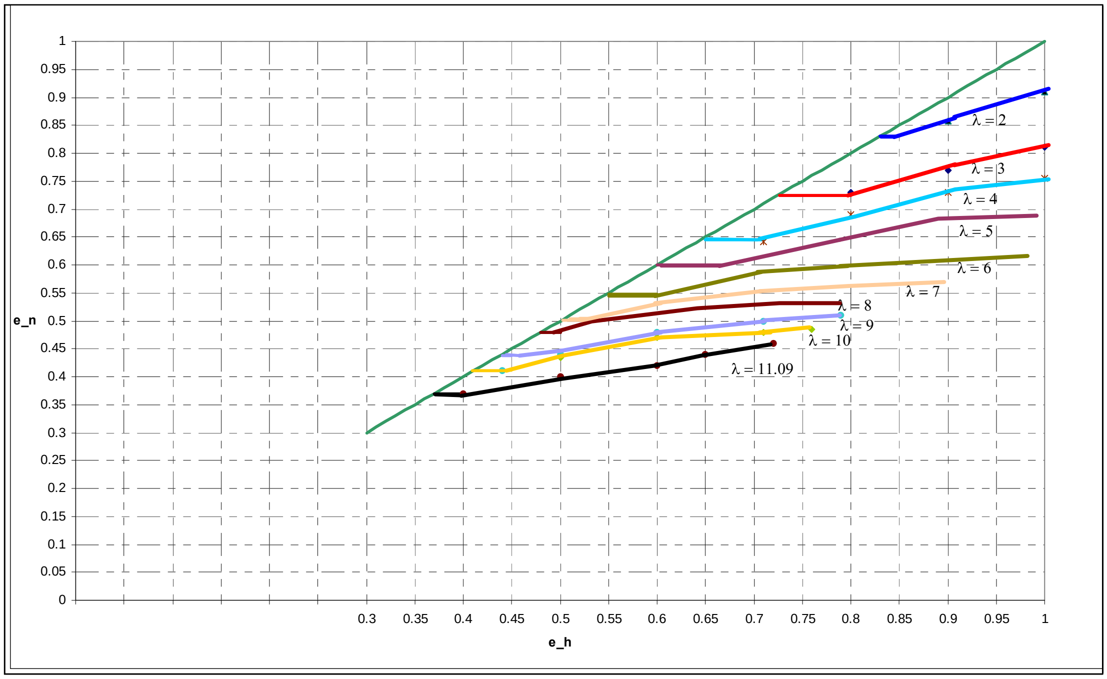

Figure 1: Admissible values for the domestic and the new technology parameters e_h and e_n respectively, for different values of the environmental damage parameter λ.

values of λ (note that e_f must be between e_n and e_h). For a given value of λ, say λ^*, e_h and e_n must be between the $\lambda-$curve marked "$\lambda = \lambda^*$" and the 45-degree line $e_n = e_h$. Some $\lambda-$curves stop at e_h values less than one. These are the maximum e_h values according to (17).

In order to avoid complications with corner solutions, we wish to restrict our analysis such that $q_2^s > 0$. In subsection 4.1, we will see

that $q_2^s > 0$ always holds under autarky for

$$\lambda < \lambda_0^A \equiv \frac{5}{2}\sqrt{5} + \frac{11}{2} \approx 11.09 \tag{16}$$

In subsection 4.2, we will see that $q_2^s > 0$ always holds under free trade for

$$\lambda < \lambda_0^T \equiv \frac{3\sqrt{5}+5}{2e_h^2} \approx \frac{5.8541}{e_h^2} \tag{17}$$

In fact we will impose a slightly stonger restriction than (17) on λ, namely:

$$\lambda < \lambda^E \equiv \frac{2\sqrt{2}+3}{e_h^2} \approx \frac{5.8284}{e_h^2} \tag{18}$$

We shall see in subsection 6.1.1 that under this restriction,emissions under free trade are higher than under autarky in case of no R&D.

4 Government Policy

4.1 Autarky

Denote the domestic upstream firm's technology in stage 3 by $e_i,\ i = h, n$. Substituting $e_1 = e_i$ and $e_2 = 1$ into (15), social welfare in scenario $i0$ is given by:

$$W^{i0} = \left[\frac{1 - te_i}{2}\right]^2 + \frac{1}{2}\left[\frac{1 - te_i}{2}\right]^2 + te_i\left(\frac{1 - te_i}{2}\right) - \frac{1}{2}\lambda\left[e_i\left(\frac{1 - te_i}{2}\right)\right]^2 \tag{19}$$

Differentiating and solving for t^{i0} yields:

$$t^{i0} = \frac{\lambda e_i^2 - 1}{e_i\left(1 + \lambda e_i^2\right)} \tag{20}$$

The tax rate is positive if and only if:

$$\lambda e_i^2 > 1 \tag{21}$$

Substituting this into (6), we get the equilibrium output and profits as:

$$q_i^{i0} = \frac{1}{\lambda e_i^2 + 1} \tag{22}$$

$$\pi_i^{i0} = \frac{1}{\left(\lambda e_i^2 + 1\right)^2} \tag{23}$$

Substituting (20) into (10) and (11), we see that output without any abatement technology would be:

$$q_0^{i0} = \frac{\lambda e_i^3 - \lambda e_i^2 + e_i + 1}{2e_i\left(\lambda e_i^2 + 1\right)} \tag{24}$$

In order to avoid corner solutions, we would like q_0^{i0} to be positive. In Appendix 1, we will see that $q_0^{i0} > 0$ as long as $\lambda < \lambda_0^A$ as defined in (16).

Substituting (20) into (14) and (11), we get the downstream firm's net profit (after paying the license fee):

$$\Pi^{i0} = \pi_0^{i0} = \left[\frac{\lambda e_i^3 - \lambda e_i^2 + e_i + 1}{2e_i\left(\lambda e_i^2 + 1\right)}\right]^2 \tag{25}$$

Substituting (23) and (25) into (12), we get the technology fee as:

$$F_h^{i0} = \left[\frac{1}{\lambda e_i^2 + 1}\right]^2 - \left[\frac{\lambda e_i^3 - \lambda e_i^2 + e_i + 1}{2e_i\left(\lambda e_i^2 + 1\right)}\right]^2 \tag{26}$$

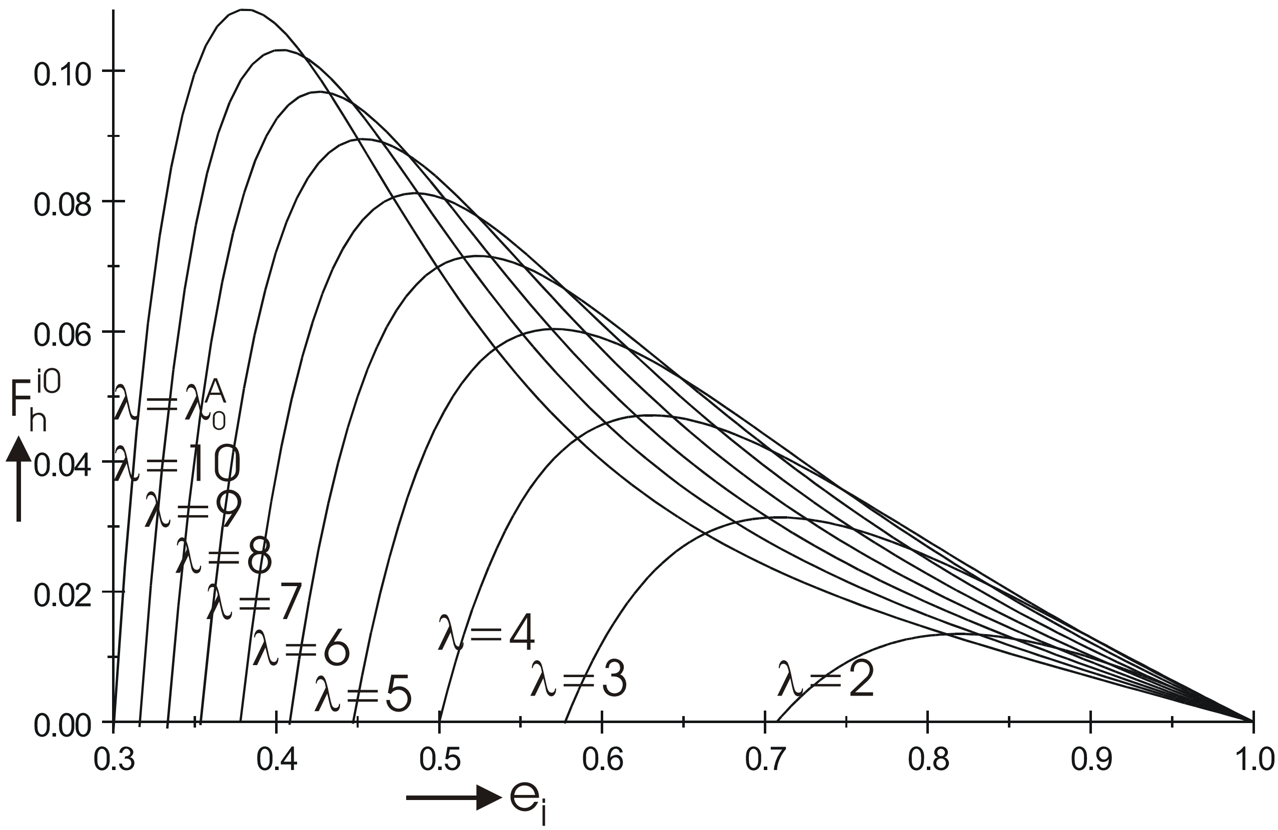

Figure 2: The domestic firm's licence fee F_h^{j0} under autarky when the domestic firm has technology e_i, $i = h, n$.

From (22), we get consumer surplus and emissions respectively as:

$$C^{i0} = \frac{1}{2}\left(q^{i0}\right)^2 = \frac{1}{2}\left(\frac{1}{e_i^2\lambda + 1}\right)^2 \tag{27}$$

$$E^{i0} = \frac{e_i}{e_i^2\lambda + 1} \tag{28}$$

Substituting (20), (22), (23), (25) and (26) into the (19) we get the welfare under Autarky as:

$$W^{i0} = \frac{1}{2\left(1 + \lambda e_i^2\right)} \tag{29}$$

At a certain value of e_i, the fee is zero because the tax rate is zero. For $e_i = 1$, the fee would also be zero because the technology would be just as bad as no technology at all. Figure 2 shows the fee as a function of e_i for different values of $\lambda < \lambda_0^A$ (where λ_0^A is defined in (16)). As e_i declines from 1, the downstream firm is initially willing to pay more and more for the abatement technology, as it becomes better and better relative to the alternative of no abatement. However, as e_i declines, production becomes less polluting and the government reduces the tax rate. For smaller values of e_i, the latter effect dominates and the fee declines as e_i falls.

We restrict our analysis to a level of abatement technology such that the license fee is decreasing in e_i, where $i \in \{h, n\}$. This is a sufficient condition for $F_h^{n0} > F_h^{h0}$, i.e. the upstream firm gains a larger fee with the new technology n than with the existing technology h. The latter is a necessary condition for the firm to do R&D into the new technology. Furthermore, if F_h^{i0} were increasing in e_i, the upstream firm would realize that it could gain a higher fee with a worse technology. This would give the firm an incentive to tinker with or sabotage the technology, increasing its e_i and gaining a higher licence fee.

We solved $dF_h^{i0}/de_i = 0$ from (26) numerically for different values of λ. The results are shown in Figure 1 as the points where the $\lambda-$curves intersect the 45 degree line $e_n = e_h$.

4.2 Free Trade

As explained in Section 3, there are four scenarios in stage three. We shall treat scenarios fh and nh together and then discuss scenarios nf and nn.

4.2.1 Scenario jh where $j \in \{f, n\}$

In these scenarios, the foreign firm supplies the technology to the downstream firm. Substituting $e_1 = e_j$, $e_2 = e_h$, $F_h^{jh} = 0$ and $\Pi^{jh} = \pi_h^{jh}$ into (15), we get the social welfare function as:

$$W_f^{jh} = \left[\frac{1-te_h}{2}\right]^2 + \frac{1}{2}\left[\frac{1-te_j}{2}\right]^2 + te_j\left(\frac{1-te_j}{2}\right) - \frac{1}{2}\lambda\left[e_j\left(\frac{1-te_j}{2}\right)\right]^2 \tag{30}$$

Differentiating and solving for t^{jh} yields:

$$t^{jh} = \frac{e_j - 2e_h + \lambda e_j^3}{\lambda e_j^4 + 3e_j^2 - 2e_h^2} \tag{31}$$

Substituting this into (6), we get the equilibrium output and profit as:

$$q_j^{jh} = \frac{e_j^2 + e_j e_h - e_h^2}{\lambda e_j^4 + 3ej^2 - 2e_h^2} \tag{32}$$

$$\pi_j^{jh} = \left[\frac{e_j^2 + e_j e_h - e_h^2}{\lambda e_j^4 + 3ej^2 - 2e_h^2} \right]^2 \tag{33}$$

Substituting (31) into (10) and (11), we find the output of the downstream firm when using the less efficient technology e_h:

$$q_h^{jh} = \frac{e_j \left(3e_j - e_h + e_j^3 \lambda - \lambda e_j^2 e_h\right)}{2\left(\lambda e_j^4 + 3e_j^2 - 2e_h^2\right)} \tag{34}$$

In order to avoid corner solutions, we would like q_h^{jh} to be positive. In Appendix 2 we will see that $q_h^{jh} > 0$ as long as $\lambda < \lambda_0^T$ as defined in (17).

Substituting (31) into (11) and (14), we get the dowstream firm's net profit (after paying the license fee) as

$$\Pi^{jh} = \pi_h^{jh} = \left[\frac{e_j \left(3e_j - e_h + e_j^3 \lambda - \lambda e_j^2 e_h\right)}{2\left(\lambda e_j^4 + 3e_j^2 - 2e_h^2\right)} \right]^2 \tag{35}$$

Substituting (33) and (35) into (12), we get the technology fee as:

$$F_f^{jh} = \left[\frac{e_j^2 + e_j e_h - e_h^2}{\lambda e_j^4 + 3e_j^2 - 2e_h^2} \right]^2 - \left[\frac{e_j \left(3e_j - e_h + e_j^3 \lambda - \lambda e_j^2 e_h\right)}{2\left(\lambda e_j^4 + 3e_j^2 - 2e_h^2\right)} \right]^2 \tag{36}$$

From (32), we get the consumer surplus and emissions respectively as:

$$C^{jh} = \frac{1}{2}\left(q^{jh}\right)^2 = \frac{1}{2}\left(\frac{e_j^2 + e_j e_h - e_h^2}{\lambda e_j^4 + 3ej^2 - 2e_h^2} \right)^2 \tag{37}$$

$$E^{jh} = \frac{e_j \left(e_j e_h + e_j^2 - e_h^2\right)}{\lambda e_j^4 + 3e_j^2 - 2e_h^2} \tag{38}$$

Substituting (31), (32), (33), (35) and (36) into (30) we find welfare as:

$$W^{jh} = \frac{\lambda e_j^4 - 2e_h e_j^3 \lambda + e_h^2 e_j^2 \lambda + 5e_j^2 - 2e_h e_j - e_h^2}{4\left(\lambda e_j^4 + 3e_j^2 - 2e_h^2\right)} \tag{39}$$

At a certain value of $e_j < e_h$, the fee is zero because the tax rate is zero. For $e_j = e_h$, the fee would also be zero because the foreign firm's technology would be just as good as the domestic firm's technology. Figure 3 shows the fee as a function of e_j for different values of $\lambda < \lambda_0^T$ (where λ_0^T is defined in (17)) with $e_h = 0.8$. The curves, and the forces behind them, are very much similar to those in Figure 2 for autarky. As e_j declines from e_h, the downstream firm is initially willing to pay more and more

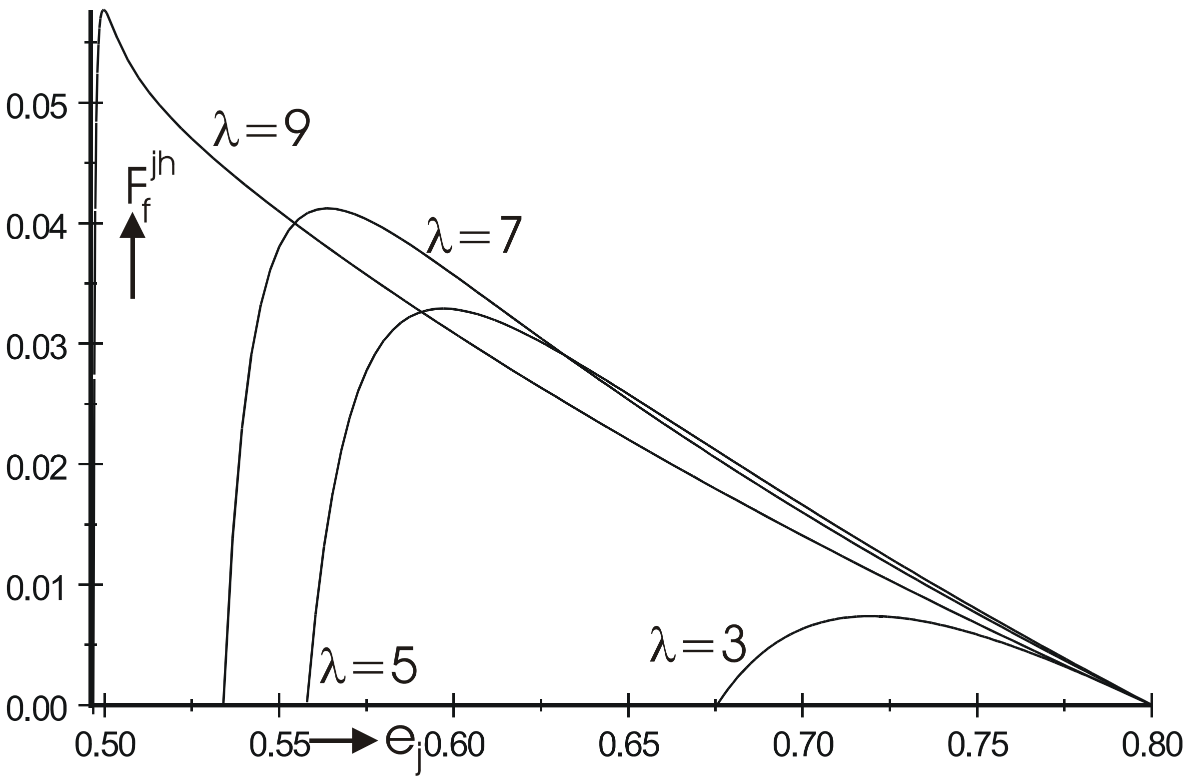

Figure 3: The foreign firm's licence fee F_f^{jh} when the foreign firm has technology e_j, $j = f, n$, and the domestic firm has technology $e_h = 0.8$.

for the foreign firm's abatement technology, as it becomes better and better relative to the domestic firm's technology. However, as e_i declines, production becomes less polluting and the government reduces the tax rate. For smaller values of e_j, the latter effect dominates and the fee declines as e_j falls.

We restrict our analysis to a level of abatement technology such that the license fee is decreasing in e_j, where $j \in \{f, n\}$. This is a sufficient condition for $F_f^{n0} > F_f^{f0}$, i.e. the foreign upstream firm gains a larger fee with the new technology n than with the existing technology f. The latter is a necessary condition for the firm to do R&D into the new technology. Furthermore, if F_f^{jh} were increasing in e_j, the upstream firm would realize that it could gain a higher fee with a worse technology. This would give the firm an incentive to tinker with or sabotage the technology, increasing its e_j and gaining a higher licence fee.

We solved $dF_f^{jh}/de_j = 0$ from (36) numerically for different values of λ. The results are shown in Figure 1 as the increasing branches of the $\lambda-$curves.

4.2.2 Scenario nf

In this case:

$$e_1 = e_n, \qquad e_2 = e_f \tag{40}$$

and the domestic upstream firm supplies the technology, so that (4) becomes:

$$\Pi^{nf} + F_h^{nf} = \pi_f^{nf} \tag{41}$$

Substituting (40) and (41) into (15), we get the social welfare as:

$$W_h^{nf} = \left[\frac{1-te_n}{2}\right]^2 + \frac{1}{2}\left[\frac{1-te_n}{2}\right]^2 + t^{nf}e_n\left(\frac{1-te_n}{2}\right) - \frac{1}{2}\lambda\left[e_n\left(\frac{1-te_n}{2}\right)\right]^2 \tag{42}$$

Differentiating and solving for t^{nf} yields

$$t^{nf} = \frac{\lambda e_n^2 - 1}{e_n\left(\lambda e_n^2 + 1\right)} \tag{43}$$

Substituting this into (7) and (11), we get the equilibrium outputs and profits as:

$$q_n^{nf} = \frac{1}{\lambda e_n^2 + 1} \tag{44}$$

$$\pi_n^{nf} = \frac{1}{\left(\lambda e_n^2 + 1\right)^2} \tag{45}$$

Substituting (43) into (10) and (11), we find the equilibrium output of the downstream firm when it uses the less efficient technology e_f:

$$q_f^{nf} = \frac{\lambda e_n^3 - e_f\lambda e_n^2 + e_n + e_f}{2e_n\left(\lambda e_n^2 + 1\right)} \tag{46}$$

In order to avoid corner solutions, we would like q_h^{nf} to be positive. In Appendix 2 we will see that $q_h^{nf} > 0$ as long as $\lambda < \lambda_0^T$ as defined in (17).

Substituting (43) into (14) and (11), we get the downstream firm's net profit (after paying the technology license fee) as:

$$\Pi^{nf} = \pi_f^{nf} = \left[\frac{\lambda e_n^3 - e_f\lambda e_n^2 + e_n + e_f}{2e_n\left(\lambda e_n^2 + 1\right)}\right]^2 \tag{47}$$

Substituting (45) and (47) into (12), we get

$$F_h^{nf} = \left[\frac{1}{\lambda e_n^2 + 1}\right]^2 - \left[\frac{\lambda e_n^3 - e_f\lambda e_n^2 + e_n + e_f}{2e_n\left(\lambda e_n^2 + 1\right)}\right]^2 \tag{48}$$

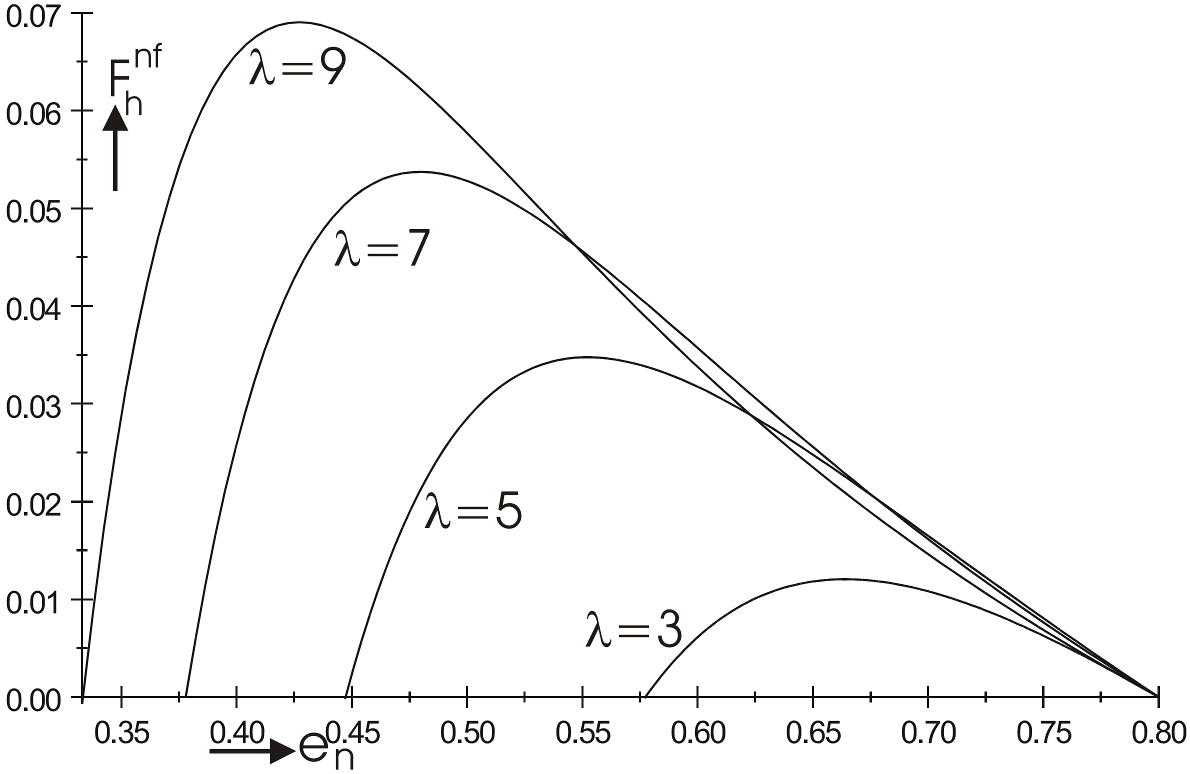

Figure 4: The domestic firm's licence fee F_h^{nf} when the foreign firm has technology $e_f = 0.8$.

From (44), we get the consumer surplus and emissions respectively as:

$$C^{nf} = \frac{1}{2}\left(\frac{1}{\lambda e_n^2 + 1}\right)^2 \tag{49}$$

$$E^{nf} = \frac{e_n}{\lambda e_n^2 + 1} \tag{50}$$

Substituting (43), (44), (47) and (48) into (42) we find welfare as:

$$W_h^{nf} = \frac{1}{2\left(\lambda e_n^2 + 1\right)} \tag{51}$$

Figure 4 shows F_h^{nf} as a function of e_n for $e_f = 0.8$. Again we would like F_h^{nf} to be decreasing in e_n. Comparing Figures 3 and 4, both of which were drawn with a rival technology (e_h and e_f respectively) of $e = 0.8$, we see that the domestic firm's fee peaks at lower e-values of the winning technology than the foreign firm's fee.[1] For instance, for $\lambda = 7$, the foreign firm's licence fee F_f^{jh} in Figure 3 peaks at around $e_j = 0.56$,

[1] In Appendix 3 we show that this is a general result.

whereas the domestic firm's licence fee F_h^{nf} in Figure 4 peaks at around $e_n = 0.47$. As a result, the condition that F_h^{nf} is decreasing in e_n is never binding.

Consider, for instance, the case where $e_h = 0.8$ and $\lambda = 7$. Then $e_n > 0.56$ by Figure 3. Figure 4 implies that $e_n > 0.47$ for $e_f = 0.8$. With $e_h = 0.8$, $e_f < 0.8$ and the minimum value of e_n is even lower than 0.47. But this is irrelevant, because Figure 3 reveals a higher minimum value for e_n of 0.56.

4.2.3 Scenario *nn*

In this case, both upstream firms have found the new technology ($e_1 = e_2 = e_n$) so that they compete the fee down to zero ($F_f^{nn} = F_h^{nn} = 0$) and the downstream firm's net profits equal its gross profits ($\Pi^{nn} = \pi_n^{nn}$). Substituting this and (7) into (15), we get the welfare function as

$$W_h^{nn} = \left[\frac{1 - t^{nn}e_n}{2}\right]^2 + \frac{1}{2}\left[\frac{1 - t^{nn}e_n}{2}\right]^2 + t^{nn}e_n\left(\frac{1 - t^{nn}e_n}{2}\right) - \frac{1}{2}\lambda\left[e_n\left(\frac{1 - t^{nn}e_n}{2}\right)\right]^2 \tag{52}$$

Differentiating with respect to t^{nn} and solving for the tax rate yields:

$$t^{nn} = \frac{\lambda e_n^2 - 1}{e_n\left(\lambda e_n^2 + 1\right)} \tag{53}$$

Substituting this into (6) and (7) we get the equilibrium outputs and profits as:

$$q^{nn} = \frac{1}{\lambda e_n^2 + 1} \tag{54}$$

$$\Pi^{nn} = \pi^{nn} = \frac{1}{\left(\lambda e_n^2 + 1\right)^2} \tag{55}$$

From (54), we get the consumer surplus and emissions respectively as:

$$C^{nn} = \frac{1}{2}\left(\frac{1}{\lambda e_n^2 + 1}\right)^2 \tag{56}$$

$$E^{nn} = \frac{e_n}{\lambda e_n^2 + 1} \tag{57}$$

Substituting (55), (53) and (54) into (52) we find welfare as:

$$W^{nn} = \frac{1}{2\left(\lambda e_n^2 + 1\right)} \tag{58}$$

Table 1: Payoff matrix for the domestic and foreign firms' Research and Development decisions

Home/Foreign	R&D	No R&D
R&D	$p\left(1-p\right)F_h^{nf}-R;\ \left(1-p\right)^2F_f^{fh}+p\left(1-p\right)F_f^{nh}-R$	$0;\ pF_f^{nh}+\left(1-p\right)F_f^{fh}-R$
No R&D	$pF_h^{nf}-R;\ \left(1-p\right)F_f^{fh}$	$0;\ F_f^{fh}$

Note: F_h^{nf} given by (48), F_f^{fh} given by (36) with $j=f$, F_f^{nh}given by (36) with $j=n$.

5 R&D decisions

5.1 Autarky

In autarky, the domestic firm will undertake R&D if its expected payoff from undertaking R&D exceeds its payoff from not doing R&D:

$$pF_h^{n0}+(1-p)F_h^{h0}-R>F_h^{h0}$$

Thus the firm will do R&D if and only if:

$$R<R_h^A\equiv p\left(F_h^{n0}-F_h^{h0}\right) \tag{59}$$

with $F_h^{i0},\ i=n,h,$ given by (26). R_h^A is positive by our assumption, introduced in subsection 4.1, that F_h^{i0} is decreasing in $e_i,\ i=h,n.$

5.2 Free trade

Table 1 shows the payoff matrix for the domestic and foreign upstream firms in stage one, depending on either firm's decision whether or not to do R&D. The first term in each cell shows the payoff to the domestic firm and the second term shows the payoff to the foreign firm.

Comparing the domestic and foreign firm's threshold to do R&D

Let us first look at the foreign firm's incentive to do R&D. In case the domestic firm does R&D, the foreign firm will do R&D when:

$$R<R_f^1\equiv p\left(1-p\right)\left(F_f^{nh}-F_f^{fh}\right) \tag{60}$$

R_f^1 is positive by our assumption, introduced in subsection 4.2.1, that F_f^{jh} is decreasing in $e_j,\ j=n,f.$

In case the domestic firm does not do R&D, the foreign firm will not do R&D when:

$$R > R_f^2 \equiv p\left(F_f^{nh} - F_f^{fh}\right) \tag{61}$$

Like R_f^1, R_f^2 is positive by our assumption that F_f^{jh} is decreasing in $e_j,\ j = n, f$.

It is easily seen from (60) and (61) that when the domestic firm does R&D the critical R&D cost level for the foreign firm is lower:

$$R_f^1 < R_f^2 \tag{62}$$

The intuition behind this is that the foreign firm's incentive to do R&D will be higher when the domestic firm doesn't do R&D as the expected payoff is higher. This is because if the domestic firm succeeds in R&D, then the foreign firm will either not be able to sell its technology (when the foreign firm doesn't suceed in R&D) or will earn a zero license fee (when the foreign firm succeeds in R&D as well). Thus the R&D threshold level is lower as compared to the scenario where the domestic firm does not do R&D.

Now we turn to the domestic upstream firm's incentive to do R&D. If the foreign firm does R&D, the domestic firm will undertake R&D when:

$$R < R_h^1 \equiv p\,(1-p)\,F_h^{nf} \tag{63}$$

R_h^1 is positive by our assumption, introduced in subsection 4.2.2, that F_h^{nf} is decreasing in $e_n < e_f$.

In case the foreign firm does not do R&D, the domestic firm does not do R&D for:

$$R > R_h^2 \equiv pF_h^{nf} \tag{64}$$

Like R_h^1, R_h^2 is positive by our assumption that F_h^{nf} is decreasing in $e_n < e_f$.

It is easily seen from (63) and (64) that for the domestic firm as well, its critical R&D cost level is lower if the foreign firm does R&D:

$$R_h^1 < R_h^2 \tag{65}$$

It is unclear in general whether R_h^1 in (63) and R_h^2 in (64) are larger or smaller than R_f^1 in (60) and R_f^2 in (61), respectively. Both comparisons depend on whether F_h^{nf} is larger or smaller than $F_f^{nh} - F_f^{fh}$. In Appendix 4 we show that for most admissible parameter values:

$$F_h^{nf} > F_f^{nh} - F_f^{fh} \tag{66}$$

which is what we shall assume from now on. Combining (66) with (60), (61), (63) and (64) yields:

$$R_f^1 < R_h^1, \qquad R_f^2 < R_h^2 \tag{67}$$

Thus the domestic firm's R&D incentive is larger than the foreign firm's incentive. This is what one might expect, for two reasons. First, the domestic government discriminates against the foreign firm, because it cares about the domestic upstream firm's profits, but not about the foreign upstream firm's profits. Secondly, the foreign firm has a better pollution abatement technology to start with as compared to the domestic upstream firm. However, while the domestic firm's R&D incentive is usually larger than the foreign firm's incentive, this is not always the case.

Nash equilibria

Combining (67) with (62) and (65) yields:

$$R_f^1 < R_h^1 < R_h^2, \qquad R_f^1 < R_f^2 < R_h^2 \tag{68}$$

It then follows that there are Nash equilibria (R&D, R&D) when $R < R_f^1$, (R&D, No R&D) when $R_f^1 < R < R_h^2$ and (No R&D, No R&D) when $R > R_h^2$. If $R_h^1 < R_f^2$, then there is an additional Nash Equilibrium equilibrium namely (No R&D, R&D) when $R_h^1 < R < R_f^2$. In order to avoid the complication of multiple equilibria, we shall assume that $R_h^1 > R_f^2$. From (63) and (61), this inequality holds if and only if:

$$p < p^* \equiv 1 - \frac{F_f^{nh} - F_f^{fh}}{F_h^{nf}} \tag{69}$$

The RHS of (69) is positive by (66) and less than one because of our assumption, introduced in subsection 4.2.1, that F_f^{jh} is decreasing in e_j, $j = f, n$.

Figure **??** illustrates the different combinations of Nash equlibria depending on the R&D cost R.

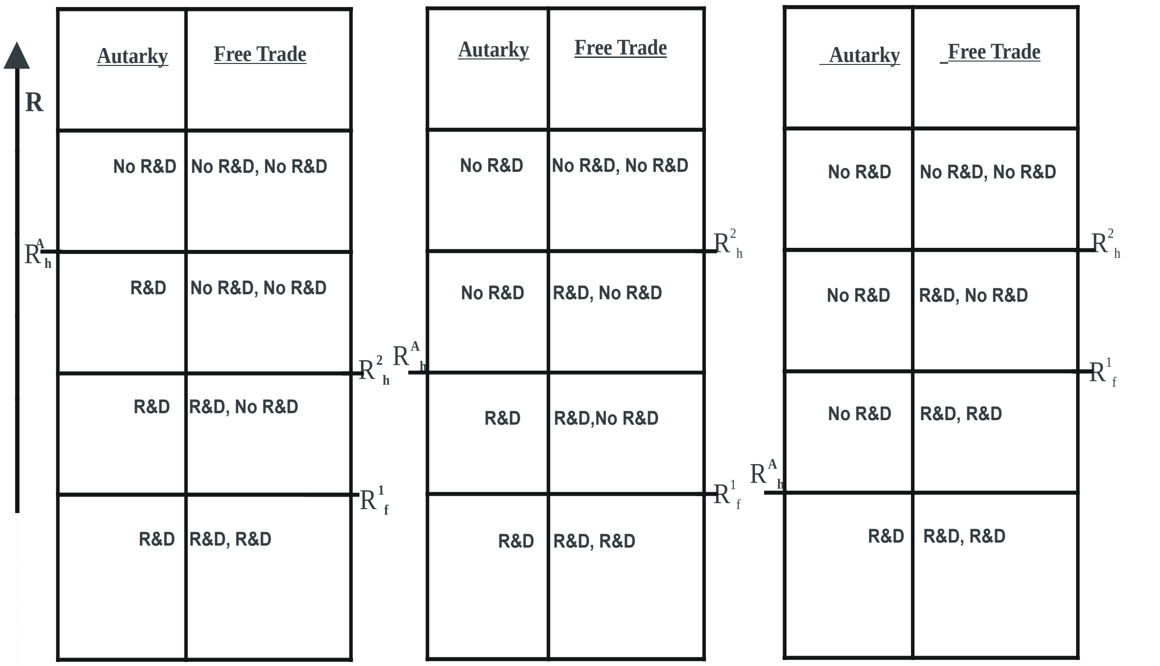

Figure 5: The different possible combinations of Nash Equilibria depending on the R&D cost R.

5.3 Domestic firm's R&D incentive

We know from subsection 5.2 that the domestic firm will do R&D in the free trade Nash equilibrium if and only if $R < R_h^2 = pF_h^{nf}$. We have to compare this threshold level R_h^2 to the threshold level $R_h^A = p\left(F_h^{n0} - F_h^{h0}\right)$ under autarky from subsection 5.1. We see that free trade gives the domestic firm a larger incentive to invest in R&D if and only if $F_h^{nf} < F_h^{n0} - F_h^{h0}$. Substituting (26) for $i = h, n$ and (48), the domestic firm's R&D incentive is larger under free trade if and only if:

$$e_f > \bar{e}_f \equiv \frac{e_h e_n \left(\lambda e_n^2 + 1\right)\left(\lambda e_h^2 + 1\right) - \sqrt{Z}}{\left(\lambda e_h^2 + 1\right)\left(\lambda e_n^2 - 1\right) e_h} \tag{70}$$

where

$$\begin{aligned} Z \equiv\ & e_n^6 \left(2e_h^2\lambda^3 - e_h^4\lambda^4 + 4e_h^2\lambda^2 - 2\lambda^2 e_h - \lambda^2 + 2\lambda^4 e_h^5\right) + \\ & + e_n^4 \left(-2\lambda + 5e_h^2\lambda^2 - 4\lambda e_h + 4\lambda^3 e_h^5 + \lambda^4 e_h^6 + 8e_h^2\lambda\right) + \\ & + e_n^2 \left(-1 + 2\lambda^2 e_h^5 - 5e_h^4\lambda^2 + 4e_h^2 - 2e_h - 2\lambda^3 e_h^6\right) - e_h^2 \left(2\lambda^2 e_n^5 - 1 - 2e_n\right)\left(e_h^2\lambda + 1\right)^2 \end{aligned}$$

We see that the foreign firm's technology needs to be sufficiently "bad" ($e_f > \bar{e}_f$ in (70)) for the domestic firm's R&D incentive to increase with free trade. This is because the worse is e_f, the larger the fee that the domestic firm can command in case it succeeds in R&D and the foreign firm does not.

In Appendix 5 we show that the critical value of e_f in (70) is increasing in e_h. Thus, free trade worsens the domestic firm's R&D incentive if it has a very inefficient existing technology. The reason is that the domestic firm then has a large R&D incentive under autarky, in order to improve upon its existing bad technology. However, under free trade the domestic firm will not be able to sell its bad technology anyway, so that the value of e_h is irrelevant to its R&D incentive.

6 Pollution, Consumer Surplus & Welfare Comparison

In this section, we compare the expected welfare under Autarky and under Free trade scenario for the different equilibriums. For this we first find out the total welfare, pollution and consumer surplus under Autarky and Under Free trade for the different R&D decison outcomes.

6.1 Pollution

6.1.1 No R&D in autarky; (No R&D, No R&D) with trade

For future reference, it will be useful here to consider the more general case where under free trade the foreign firm supplies the technology e_j, where $j \in \{f, n\}$

Comparing emissions under Autarky (28) those under Free Trade (38), it is clear that $E^{jh} = E^{h0}$ for $e_j = e_f$. Moreover, E^{jh} is decreasing in e_j for $e_j = e_h$. From (38) we find:

$$\frac{dE^{jh}}{de_j} = \frac{-\lambda e_j^6 - 2\lambda e_j^5 e_h + 3\lambda e_j^4 e_h^2 + 3e_j^4 - 3e_j^2 e_h^2 - 4e_j e_h^3 + 2e_h^4}{\left(\lambda e_j^4 + 3e_j^2 - 2e_h^2\right)^2}$$

Setting $e_j = e_h$ yields:

$$\frac{dE^{jh}}{de_j}|_{e_j=e_h} = \frac{-2e_h^4}{(\lambda e_h^4 + e_h^2)^2} < 0$$

Thus, when reducing e_j below e_h, E^{jh} initially rises above E^{h0}. However, for low enough e_j, E^{jh} will start declining again. There are three solutions to $E^{jh} = E^{h0}$ from

(28) and (38): $e_j = e_f$ and:

$$e_j = \frac{1 + \lambda e_h^2 \pm \sqrt{\lambda^2 e_h^4 - 6\lambda e_h^2 + 1}}{2\lambda e_h} \tag{71}$$

There are only real solutions to (71) when $\lambda^2 e_h^4 - 6\lambda e_h^2 + 1 \geq 0$, which is satisfied for:

$$\lambda \leq \frac{1}{e_h^2}\left(3 - 2\sqrt{2}\right) \text{ and } \lambda \geq \frac{1}{e_h^2}\left(3 + 2\sqrt{2}\right)$$

The first inequality is irrelevant by (21). The second inequality is ruled out by our restriction (18).

Thus we can conclude that the pollution is lower under Autarky as compared to that under Free trade.

6.1.2 R&D in autarky; (No R&D, No R&D) with trade

In autarky, emissions are E^{n0} if R&D is successful and E^{h0} if it is not. E^{i0} for $i = h, n$ is given by (28). With trade, emissions are E^{fh} from (38) with $j = f$. Thus:

$$D^{NN} - D^R = \frac{1}{2}\lambda(E^{fh})^2 - \frac{1}{2}\lambda\left[p\left(E^{n0}\right)^2 + (1-p)\left(E^{h0}\right)^2\right] \tag{72}$$

Solving for p, we see that the pollution damage under free trade is greater than under autarky for

$$p \equiv p_E < \frac{(E^{fh})^2 - \left(E^{h0}\right)^2}{\left(E^{n0}\right)^2 - \left(E^{h0}\right)^2}$$

When p_E exceeds the maximum value of p^* from (69), environmental damage under free trade will be greater than under autarky. When $p_E < p^*$, damage will be greater under free trade when $p < p_E$ and greater under autarky when $p_E < p < p^*$. However the latter case occurs for a very limited range of parameters only. Setting p at its maximum value p^* from (69) for instance, and e_n at its minimum value (because (72) is increasing in e_n), we find $D^R > D^{NN}$ for the following set of parameter values:

- when $\lambda = 4,\ e_n = 0.72,\ e_h = 0.8$, for $0.798 < e_f < 0.8$
- when $\lambda = 7,\ e_n = 0.57,\ e_h = 0.82$, for $0.81 < e_f < 0.82$

- when $\lambda = 8, \ e_n = 0.54, \ e_h = 0.85$, for $0.79 < e_f < 0.85$

Thus for most parameter values within the feasible range, expected pollution damage is higher under Free Trade than under Autarky.

6.1.3 R&D in autarky; (R&D, No R&D) with trade

In autarky, emissions are E^{n0} if R&D is successful and E^{h0} if it is not. E^{i0} for $i = h, n$ is given by (28). With trade, emissions are E^{nf} from (50) if the domestic firm's R&D is successful and E^{fh} from (38) with $j = f$ if it is not. Since $E^{n0} = E^{nf}$, we have:

$$D^{RN} - D^{R} = \frac{1}{2}\lambda\left(1-p\right)\left[\left(E^{fh}\right)^2 - \left(E^{h0}\right)^2\right]$$

We have already shown in subsection 6.1.1 that $E^{fh} > E^{h0}$. Thus we find, again, that pollution is higher under free trade than in autarky.

6.1.4 R&D in autarky; (R&D, R&D) with trade

In autarky, emissions are E^{n0} if R&D is successful and E^{h0} if it is not. E^{i0} for $i = h, n$ is given by (28). With trade, emissions are E^{nn} from (57) if R&D by both firms is successful, E^{nf} from (50) if only the domestic firm is successful, E^{nh} from (38) with $j = n$ if only the foreign firm is successful, and E^{fh} from (38) with $j = f$ if neither is successful. Thus we have:

$$D^{RR} - D^{R} =$$
$$\frac{1}{2}\lambda\left[p^2\left(E^{nn}\right)^2 + p\left(1-p\right)\left(E^{nf}\right)^2 + p\left(1-p\right)\left(E^{nh}\right)^2 + \left(1-p\right)^2\left(E^{fh}\right)^2 - p\left(E^{n0}\right)^2 - \left(1-p\right)\left(E^{h0}\right)^2\right]$$

Since $E^{nn} = E^{nf} = E^{n0}$, this simplifies to:

$$D^{RR} - D^{R} = \frac{1}{2}\lambda(1-p)\left[p\left(E^{nh}\right)^2 + (1-p)\left(E^{fh}\right)^2 - \left(E^{h0}\right)^2\right]$$

In subsection 6.1.1 we have seen that $E^{jh} > E^{h0}$ for $j = f, n$. Thus, $D^{RR} - D^{R} > 0$: Expected pollution damage is larger with trade than in autarky.

6.1.5 No R&D in autarky; (R&D, No R&D) with trade

In autarky, emissions are E^{h0} from (28) with $i = h$. With trade, emissions are E^{nf} from (50) if the domestic firm's R&D is successful and E^{fh} from (38) with $j = f$ if it is not. In subsection 6.1.1 we have seen that $E^{fh} > E^{h0}$. We know that $E^{nf} = E^{n0}$ and in subsection 6.1.2 we have seen that $E^{n0} > E^{h0}$. Thus, in this case as well, expected pollution damage under Free trade is greater than under Autarky.

6.1.6 No R&D in autarky; (R&D, R&D) with trade

In autarky, emissions are E^{h0} from (28) with $i = h$. With trade, emissions are E^{nn} from (57) if R&D by both firms is successful, E^{nf} from (50) if only the domestic firm is successful, E^{nh} from (38) with $j = n$ if only the foreign firm is successful, and E^{fh} from (38) with $j = f$ if neither is successful. We know from subsection 6.1.1 that $E^{jh} > E^{h0}$ with $j = f, n$, and from subsection 6.1.2 that $E^{nn} = E^{nf} > E^{h0}$. Therefore we can conclude that expected polltution damage under Free trade is always greater than the damage under Autarky.

6.1.7 Discussion

We can conclude that for all Nash Equilibria except {R&D in autarky;(No R&D, No R&D) with trade} the expected pollution damage is greater under free trade. The reason for this is that, under free trade, the domestic downstream has increased access to cleaner or better pollution abatement technology. When the downstream firm has the efficient technology available, it would tend to produce more as the environmental tax would be lower with the better technology. In the case of {R&D in autarky;(No R&D, No R&D) with trade} ,neither firm does R&D under free trade and the domestic firm does R&D under Autarky. The pollution damage would be higher under autarky when the probability of finding the new technology p is very high. This implies that when the domestic firm succeeds in R&D, the downstream firm uses the most efficient technology e_n under autarky and would therefore tend to produce the highest. When the domestic firm is not sucessful in finding the better technology under Autarky, the expected pollution damage would be higher under Free trade as the most efficient technology available would be that supplied by the foreign upstream firm (e_f) under free trade and therefore the downstream firm will produce the highest.

This result is very much in line with the rebound effect from the literature which is commonly used in energy conservation, innovation theory and green marketing to refer to increases in demand that are caused by the introduction of more efficient technologies. This increase in consumption reduces the conservation effect of the improved technology on total energy use. Binswanger (2001) surveys some empirical evidences of the rebound effect, notably that of a study by Biesiot and Noorman (1999),who calculates the energy saving options of Dutch households due to better insulation, energy efficient dwelling and due to improvements in energy efficiency in transport. He found that by all these options, the total energy use of households could be potentially reduced by 30%, but, due to the rebound effect, the net energy consumprion increased by around 5 - 50% of the initial level of consumption. implying that energy saving technologies may lead to a reduction in energy consumption, but that part of the saving potential is lost because of the induced increase in service demand.

Similar to this in our analysis also, we see that with the availability of a efficient or cleaner pollution abatement technology would result in an increase in the expected pollution damage due to the rebound effect.

6.2 Consumer Surplus

6.2.1 No R&D in autarky; (No R&D, No R&D) with trade

For future reference, it will be useful here to consider the more general case where under free trade the foreign firm supplies the technology e_j,where $j \in \{f, n\}$.

Comparing the consumer surplus (2) under Autarky and Free trade from the respective output levels (22) and (32):

$$C^{jh} - C^{h0} = \frac{1}{2}\left[\left(q_h^{h0}\right)^2 - \left(q_j^{jh}\right)^2\right]$$

We have seen in subsection 6.1.1 that $E^{jh} = e^j q_j^{jh} > E^{h0} = e^h q_h^{h0}$. Since $e^j < e^h$, this implies that $q_j^{jh} > q_h^{h0}$ and therefore $C^{h0} < C^{jh}$. Thus we can conclude that the consumer surplus is lower under Autarky as compared to that under Free trade.

6.2.2 R&D in autarky; (No R&D, No R&D) with trade

In autarky, consumer surplus is C^{n0} if R&D is successful and C^{h0} if it is not. C^{i0} for $i = h, n$ is given by (27). With trade, consumer surplus is C^{fh} from (37) with $j = f$. Thus:

$$C^{NN} - C^{R} = \frac{1}{2}(q_f^{fh})^2 - \frac{1}{2}\left[p\left(q_n^{n0}\right)^2 + (1-p)\left(q_h^{h0}\right)^2\right] \tag{73}$$

Solving for p, we see that the consumer surplus under free trade is greater than under autarky for:

$$p < p_c \equiv \frac{(q_f^{fh})^2 - \left(q_h^{h0}\right)^2}{\left(q_n^{n0}\right)^2 - \left(q_h^{h0}\right)^2}$$

When p_c exceeds the maximum value of p^* from (69), consumer surplus under free trade will be greater than under autarky. When $p_c < p^*$, consumer surplus will be greater under free trade when $p < p_c$ and greater under autarky when $p_c < p < p^*$. However the latter case occurs for a very limited range of parameters only. Setting p at its maximum value p^* from (69) for instance, and e_n at its minimum value (because (73) is increasing in e_n), we find $C^R > C^{NN}$ for the following set of parameter values:

- when $\lambda = 4,\ e_n = 0.72,\ e_h = 0.8$, for $0.798 < e_f < 0.8$
- when $\lambda = 7,\ e_n = 0.57,\ e_h = 0.82$, for $0.81 < e_f < 0.82$
- when $\lambda = 8,\ e_n = 0.54,\ e_h = 0.85$, for $0.79 < e_f < 0.85$

Thus we can conclude that for most parameter values within the feasible range, expected consumer surplus is higher under Free trade than under Autarky.

6.2.3 R&D in autarky; (R&D, No R&D) with trade

In autarky, consumer surplus is C^{n0} if R&D is successful and C^{h0} if it is not. C^{i0} for $i = h, n$ is given by (27). With trade, consumer surplus is C^{nf} from (49) if the domestic firm's R&D is successful and C^{fh} from (37) with $j = f$ if it is not. Since $C^{nf} = C^{n0}$, we have:

$$C^{RN} - C^{R} = \frac{1}{2}(1-p)\left[\left(q_f^{fh}\right)^2 - \left(q_h^{h0}\right)^2\right]$$

We have already shown in subsection 6.2.1 that $q_j^{jh} > q_h^{h0}$. Thus we find again that the expected consumer surplus is higher under free trade than in autarky.

6.2.4 R&D in autarky; (R&D, R&D) with trade

In autarky, consumer surplus is C^{n0} if R&D is successful and C^{h0} if it is not. C^{i0} for $i = h, n$ is given by (27). With trade, consumer surplus is C^{nn} from (56) if R&D by both firms is successful, C^{nf} from (49) if only the domestic firm is successful, C^{nh} from (37) with $j = n$ if only the foreign firm is successful, and C^{fh} from (37) with $j = f$ if neither firm is successful. Thus we have:

$$C^{RR} - C^{R} =$$

$$\frac{1}{2}\left[p^2 \left(q^{nn}\right)^2 + p\left(1-p\right)\left(q_f^{nh}\right)^2 + p\left(1-p\right)\left(q_h^{nf}\right)^2 + \left(1-p\right)^2\left(q_f^{fh}\right)^2 - p\left(q_h^{n0}\right)^2 - \left(1-p\right)\left(q_h^{h0}\right)^2\right]$$

Since $C^{nn} = C^{nf} = C^{n0}$, this simplifies to:

$$C^{RR} - C^{R} = \frac{1}{2}\left(1-p\right)\left[p\left(q_n^{nh}\right)^2 + \left(1-p\right)\left(q_f^{fh}\right)^2 - \left(q_h^{h0}\right)^2\right]$$

In subsection 6.2.1, we have seen that $q_j^{jh} > q_h^{h0}$ for $j = f, n$.Thus $C^{RR} - C^{R} > 0$. Thus we see that the expected Consumer Surplus is greater under Free Trade than in Autarky.

6.2.5 No R&D in autarky; (R&D, No R&D) with trade

In autarky, consumer surplus is C^{h0} from (27) with $i = h$. With trade, consumer surplus is C^{nf} from (49) if only the domestic firm is successful, and C^{fh} from (37) with $j = f$ if it is not. In subsection 6.2.1, we have seen that $C^{jh} > C^{h0}$. We know that $C^{nf} = C^{n0}$ and in subsection 6.2.2, we have seen that $C^{n0} > C^{h0}$. Thus, in this case, as well, expected pollution damage under free trade is greater than under Autarky.

6.2.6 No R&D in autarky; (R&D, R&D) with trade

In autarky, consumer surplus is C^{h0} from (27) with $i = h$. With trade, consumer surplus are C^{nn} from (56) if R&D by both firms is successful, C^{nf} from (49) if only the domestic firm is successful, C^{nh} from (37) with $j = n$ if only the foreign firm is successful, and C^{fh} from (37) with $j = f$ if neither firm is successful. We know from subsection 6.2.1, that $C^{jh} > C^{h0}$ with $j = f, n$ and from subsection 6.2.2 that $C^{nn} = C^{nf} > C^{h0}$. Therefore we can conclude that expected consumer surplus under free trade is always greater than the damage under autarky.

6.2.7 Discussion

Thus we can conclude that for all Nash Equilibria except [R&D in autarky; (No R&D, No R&D) with trade] case the expected consumer surplus is greater under free trade. The reason for this is same as the one cited for the increase in the expected pollution damage. By liberalizing the trade in the pollution abatement technology sector, the domestic downstream has increased access to better or cleaner technology and therefore tend to produce more and therefore will result in the increase in consumer surplus.

In the case of [R&D in autarky; (No R&D, No R&D) with trade] Nash equilibrium, the expected consumer surplus could be greater under Autarky for very high probability of sucess in finding the new technology p. This is because in this equilibrium, neither firms do R&D under free trade and under Autarky the domestic firm does R&D. So the consumer surplus would be higher under those values where the domestic firm suceeds in finding the better technology as the downstream firm would tend to produce the highest when the most efficient technology is avaialable. When the domestic firm is not sucessful in finding the better technology, the consumer surplus would be higher under Free trade as the most efficient technology available would be that supplied by the foreign upstream firm e_f under free trade and the downstream would produce the highest.

6.3 Welfare

6.3.1 No R&D in autarky; (No R&D, No R&D) with trade

For future reference, it will be useful here to consider the more general case where under free trade the foreign firm supplies the technology $e_{j,}$ where $j \in \{f, n\}$

Comparing the welfare under Autarky (29) with $i = h$ and under free trade (39), it is clear that $W^{h0} = W^{jh}$ for $e_j = e_{h.}$ From (39) we find:

$$\frac{dW^{jh}}{de_j} = \frac{-7e_j e_h^2 + 2e_j^3 + 3e_j^2 e_h - 2\lambda e_j^5 - 2\lambda e_j e_h^4 + 6\lambda e_j^2 e_h^3 - 2\lambda e_j^3 e_h^2 + \lambda^2 e_j^6 e_h - \lambda^2 e_j^5 e_h^2}{2\left(3e_j^2 - 2e_h^2 + \lambda e_j^4\right)^2}$$

Setting $e_j = e_h$:

$$\frac{dW^{jh}}{de_j}|_{e_j=e_h} = \frac{-e_h^3}{\left(\lambda e_h^4 + e_h^2\right)^2} < 0$$

Thus when reducing e_j below e_h, W^{jh} rises above W^{h0}. However, for low enough e_j, W^{jh} will start declining again. From (39) and (29), we find there are three solutions for $W^{jh} = W^{h0}$: $e_j = e_h$ and (for $e_j \neq e_h$):

$$\lambda = \frac{(e_h - e_j)\left(e_j^2 + 4e_h e_j + e_h^2\right) \pm \sqrt{(e_j - e_h)(e_h + e_j)E}}{2e_j^2 e_h^2 (e_h - e_j)}$$

which only has a real-valued solution if $E \leq 0$. However,

$$E \equiv \frac{1}{a^2} - \frac{6}{a} + 8 + 6a + a^2$$

with $a \equiv \frac{e_j}{e_h}$, is positive for all $a \in [0, 1]$. It follows that $W^{jh} > W^{h0}$.

Thus we can conclude that welfare under free trade is greater than under autarky.

6.3.2 R&D in autarky; (No R&D, No R&D) with trade

In autarky, welfare is $W^{n0} - R$ if R&D by the domestic firm is successful and $W^{h0} - R$ if it is not. W^{i0} for $i = h, n$ is given by (29). With trade, welfare is W^{jh} from (39) with $j = f$. Thus:

$$W^{NN} - W^{R} = W^{fh} - pW^{n0} - (1 - p)W^{h0} + R \tag{74}$$

Solving for p, we see that for welfare under free trade to be higher than under autarky:

$$p < p^w \equiv \frac{W^{fh} - W^{h0} + R}{W^{n0} - W^{h0}} \tag{75}$$

When p^w exceeds the maximum value of p^* from (69), the expected welfare under free trade will be greater than under autarky. When $p^w < p^*$, expected welfare will be greater under free trade when $p < p^w$ and greater under autarky when $p^w < p < p^*$. It can be shown that p^w can be positive for the lowest possible value of R (R_h^2 from (64)) and it can be below p^* for the highest possible value of R (R_h^A from (59)).

Thus we see that in this equilibrium, welfare could be higher under free trade or under autarky.

6.3.3 R&D in autarky; (R&D, No R&D) with trade

In autarky, welfare is $W^{n0} - R$ if R&D by the domestic firm is successful and $W^{h0} - R$ if it is not. W^{i0} for $i = h, n$ is given by (29). With trade, welfare is $W^{nj} - R$ from (42) if the domestic firm's R&D is successful and $W^{fh} - R$ from (30) with $j = f$ if it is not. Thus:

$$W^{RN} - W^{R} = pW^{nf} + (1-p)\,W^{fh} - \left[pW^{n0} + (1-p)\,W^{h0}\right] = (1-p)\left[W^{fh} - W^{h0}\right] \tag{76}$$

The second equality follows from $W^{n0} = W^{nf}$.

We know from subsection 6.3.1 that $W^{fh} > W^{h0}$. Thus we conclude that expected welfare is higher under free trade than under autarky.

6.3.4 R&D in autarky; (R&D, R&D) with trade

In autarky, welfare is $W^{n0} - R$ if R&D by the domestic firm is successful and $W^{h0} - R$ if it is not. W^{i0} for $i = h, n$ is given by (29). With trade, welfare is $W^{nf} - R$ from (42) if only the domestic firm's R&D is successful and $W^{fh} - R$ from (30) with $j = f$ if neither is successful, $W^{nn} - R$ from (58) if R&D by both firms is successful and $W^{nh} - R$ from (30) with $j = f$ if only the foreign firm is successful. Thus we have:

$$W^{RR} - W^{R} = p^2 W^{nn} + p\,(1-p)\,W^{nf} + p\,(1-p)\,W^{nh} + (1-p)^2\,W^{fh} - pW^{n0} - (1-p)\,W^{h0}$$

Since $W^{n0} = W^{nn} = W^{nf}$, this can be simplified to:

$$W^{RR} - W^{R} = (1-p)\left[pW^{nh} + (1-p)W^{fh} - W^{h0}\right]$$

In subsection 6.3.1, we have seen that $W^{nh}, W^{fh} > W^{h0}$. Thus $W^{RR} - W^{R} > 0$. Thus the expected welfare under Free trade is greater than Autarky.

6.3.5 No R&D in autarky; (R&D, No R&D) with trade

In autarky, welfare is W^{h0} from (29) with $i = h$.With trade, welfare is $W^{nf} - R$ from (42) if the domestic firm's R&D is successful and $W^{fh} - R$ from (30) with $j = f$ if it is not.

Comparing welfare under autarky with expected welfare under free trade, we will see that:

$$W^{RN} - W^{N} = pW^{nf} + (1-p)W^{fh} - R - W^{h0} > p\left(W^{nf} - F_h^{nf} - W^{h0}\right) + (1-p)\left(W^{fh} - W^{h0}\right) > 0 \tag{77}$$

The first inequality follows from $R < R_h^2$ in (64). The second inequality follows from the fact that $W^{nf} - F_h^{nf} - W^{h0} > 0$ as shown in Appendix 6 and $W^{fh} > W^{h0}$ as shown in subsection 6.3.1. Thus we see that the welfare under free trade is greater than under autarky.

6.3.6 No R&D in autarky; (R&D, R&D) with trade

In autarky, welfare is W^{h0} from (29) with $i = h$. With trade, welfare is W^{nf} from (42) if only the domestic firm's R&D is successful and W^{fh} from (30) with $j = f$ if neither is successful, $W^{nn} = W^{nf}$ from (42) and (58) if R&D by both firms is successful and W^{nh} from (30) with $j = f$ if only the foreign firm is successful. Thus we have

$$\begin{aligned} W^{RR} - W^{N} &= pW^{nf} + p(1-p)W^{nh} + (1-p)^2 W^{fh} - W^{h0} - R > \\ &> p\left(W^{nf} - F_h^{nf} - W^{h0}\right) + p(1-p)\left(W^{nh} - W^{h0}\right) + (1-p)^2\left(W^{fh} - W^{h0}\right) > 0 \end{aligned}$$

The first inequality follows from $R < R_f^1 < R_h^2$ by (68), with R_h^2 given by (64). The second inequality follows from the fact that $W^{nf} - F_h^{nf} - W^{h0} > 0$ as shown in Appendix 6 and $W^{jh} > W^{h0}$, $j = f, n$, as shown in subsection 6.3.1. Thus we see that the welfare under free trade is greater than under autarky.

6.3.7 Discussion

Thus we can conclude that the domestic country is better of with trade liberalisation in all the possible Nash equilibria but for [R&D in autarky; (No R&D, No R&D) with trade] case.The welfare is higher because, with free trade, the chances of having a better or cleaner technology for the downstream firm is higher and therefore the production level increases resulting in increase in the consumer surplus, tax revenue and the pollution damage[2]. The increase in the consumer surplus and tax revenue is greater than the welfare loss resulting from the increase in the pollution damage. Thus, though the pollution damage increases, the domestic country is better off with the liberalization of the pollution abatement technology. In the case of [R&D in autarky; (No R&D, No R&D) with trade], the welfare could be higher or lower depending on

[2]Following the discussion in subsections 6.1 and 6.2, we see that the both pollution and consumer surplus is higher under free trade for most feasible range of values.

the probability of success for the domestic firm in finding the new technology. If the probability is very high (low), then under autarky, the welfare is higher (lower) than free trade.

7 Conclusion and Policy Implication

From the analysis we see that the R&D incentive of the domestic firm as a result of trade liberalization can go either way depending on the initial level of abatement technology that its rival has. If the foreign firm initially has a very efficient technology as compared to the domestic firm's technology (i.e. a very low value of e_f), then the domestic firm's incentive decreases with the implementation of trade liberalization. This is because as e_f tends closer to e_n,the license fee that the domestic firm can charge, if it suceeds in R&D, will diminish. This is because the license fee it can charge is the difference between the profits of the downstream firm when it uses the most efficient technology (e_n) and the second best available technology (e_f). However under autarky, the domestic firm has a large R&D incentive, as the license fee it can charge is the difference between the profits of the downstream firm when it uses the most efficient technology (e_n) and no abatement technology. This will be much higher than the license fee it can get when it supplies the inefficient technology (e_h).

From the welfare point of view, we see that generally the expected pollution damage and expected consumer surplus will be higher when the downstream uses the most efficient technology (mostly under Free trade) and this is due to the rebound effect of having an efficient or cleaner technology. The net expected welfare is also generally higher under free trade than under autarky and this is because the increase in the consumer surplus and the tax revenue is greater than the welfare loss from the increase in the pollution damage resulting from the increased production.

As a policy implication, the result of this paper suggests that it is in the best interest for countries to liberalize its pollution abatement sector industry to countries which are very similar in terms of the available technology. If a country with a very inefficient technology liberalises its R&D sector with a country with a very highly efficient technology, then the domestic firm in the liberalizing country will not have nay incentive to do R&D. In other words, with trade liberalization, for the R&D incentive to increase, the difference between the exisitng domestic and foreign country's firm's technology should be smaller.

In the context of the ongoing WTO negotiations, where the environmental goods and services sector is a key element for negotitatios, the policy recommendation of this paper is that countries should adopt a preferential trade liberalization policy where, they have to choose which countries to open up their pollution abatement R&D sector to. Developing countries should be very cautious when liberalizing their pollution abatement sector and they should first liberalize trade with those countries with slightly better technology so that it will induce their R&D development and subsequently adopt full liberalization. This will make them competent to developed countries technology and the subsequent liberalization would result in fostering their R&D quest for a better pollution abatment technology. From the environmental pollution damage point of view, the paper suggests that trade liberalization will result in an increase in the damage and the important policy concern that this paper poses to relevant countries is whether it is conducive and sustainable to liberalize trade to have a higher welfare at the expense of environmental degradation?

It is worth mentioning that if the government's true motive is only to reduce the environmental damage by trade liberalization, it might be better off by using a pollution damage constrained welfare function, as it would be able to liberalize and attain a lower pollution damage. It would be itneresting to see whether using such a constrained welfare function might result in an increase in the total social welfare We intend to take this and other related issues in our future research.

8 Appendix

Appendix 1. Conditions for $q_2^s > 0$ in autarky

Rename $e_i = x$ and set $q_0^{i0} = 0$ and $dq_0^{i0}/dx = 0$ in (24). This yields, respectively:

$$\begin{aligned} \frac{\lambda x^3 - \lambda x^2 + x + 1}{x(\lambda x^2 + 1)} &= 0 \\ -\lambda^2 x^4 + 4\lambda x^2 + 1 &= 0 \end{aligned}$$

The only positive solution for λ is $\lambda = \frac{5}{2}\sqrt{5} + \frac{11}{2}$. Therefore $q_0^{i0} > 0$ if and only if inequality (16) holds.

Appendix 2. Conditions for $q_2^s > 0$ under free trade

To find the corresponding value of λ for the minimum value of q_2^s and the Rename $e_j = x$ and set $q_h^{jh} = 0$ and $dq_h^{jh}/dx = 0$ in (34) and (46). This yields, respectively:

$$\begin{aligned} \frac{3x - e_h + x^3\lambda - \lambda x^2 e_h}{\lambda x^4 + 3x^2 - 2e_h^2} &= 0 \\ x^6\lambda^2 - 8x^3 e_h \lambda + 6x^2 e_h^2 \lambda + 3x^2 - 12x e_h + 2e_h^2 &= 0 \end{aligned}$$

The only positive solution for λ is $\lambda = \frac{1}{2(e_h)^2}\left(3\sqrt{5} + 5\right)$. Therefore $q_h^{jh} > 0$ if and only if inequality (17) holds.

Appendix 3. The condition for F_f^{jh} to be decreasing in e_j is stricter than the condition for F_h^{nf} to be decreasing in e_n.

In (48), rename $e_n = x,\ e_f = z$ and define $V_h^{nf} \equiv F_h^{nf}$, so that:

$$V_h^{nf} = \left[\frac{1}{\lambda x^2 + 1}\right]^2 - \left[\frac{(\lambda x^3 - z\lambda x^2 + x + z)}{2x\left(\lambda x^2 + 1\right)}\right]^2$$

In (36), rename $e_j = x,\ e_h = y$, so that:

$$F_f^{jh} = \left[\frac{(x^2 + xy - y^2)}{\lambda x^4 + 3x^2 - 2y^2}\right]^2 - \left[\frac{1}{2}x\frac{(3x - y + x^3\lambda - \lambda x^2 y)}{\lambda x^4 + 3x^2 - 2y^2}\right]^2$$

Differentiating F_h^{nf} with respect to x yields:

$$\frac{\partial F_h^{nf}}{\partial x} = \frac{1}{2x^3\left(\lambda x^2 + 1\right)^3}\left(-x^7 z\lambda^3 + x^6 z^2\lambda^3 + 3x^5 z\lambda^2 - 5x^4 z^2\lambda^2 - 8x^4\lambda + 5x^3 z\lambda + 3x^2 z^2\lambda + xz + z^2\right) \tag{78}$$

Differentiating F_f^{jh} with $y = z$ with respect to x yields:

$$\frac{\partial F_f^{jh}}{\partial x} = -\frac{Z}{2\left(\lambda x^4 + 3x^2 - 2z^2\right)^3} \tag{79}$$

with

$$\begin{aligned} Z \equiv\ & x^{10}z\lambda^3 - x^9z^2\lambda^3 + 3x^8z\lambda^2 - 9x^7z^2\lambda^2 + 8x^7\lambda + 14x^6z^3\lambda^2 + 23x^6z\lambda - 6x^5z^4\lambda^2 - 51x^5z^2\lambda \\ & +12x^4z^3\lambda + 21x^4z + 8x^3z^4\lambda - 35x^3z^2 + 6x^2z^3 + 14xz^4 - 8z^5 \end{aligned} \tag{80}$$

We see from (78) that F_h^{nf} is at its maximum for:

$$x^7z\lambda^3 - x^6z^2\lambda^3 = 3x^5z\lambda^2 - 5x^4z^2\lambda^2 - 8x^4\lambda + 5x^3z\lambda + 3x^2z^2\lambda + xz + z^2 \tag{81}$$

Now we can replace the two first terms on the RHS of (80) by the RHS of (81) multiplied by x^3. Substituting into (79) and simplifying yields:

$$\frac{\partial F_f^{jh}}{\partial x} = \frac{z(z-x)\left[3x^7\lambda^2 - 4x^6z\lambda^2 + 3x^5z^2\lambda^2 + 14x^5\lambda - 10x^4z\lambda - 4x^3z^2\lambda + 11x^3 - 6x^2z - 3xz^2 + 4z^3\right]}{\left(\lambda x^4 + 3x^2 - 2z^2\right)^3} \tag{82}$$

We know that $z > x$. The sign of (82) then depends on the expression between sqaure brackets. Setting this equal to zero and solving for λ yields:

$$\lambda = \frac{5xz + 2z^2 - 7x^2 \pm \sqrt{x^3z^5D}}{-4x^3z + 3x^2z^2 + 3x^4} \tag{83}$$

which only has a real-valued solution if $D \geq 0$. However,

$$D \equiv -8b^4 - 12 + 29b + 14b^2 - 51b^3 + 16b^5$$

with $b \equiv \frac{x}{z}$, is negative for all $b \in [0, 1]$. It follows that F_f^{jh} is either always increasing or always decreasing in x when F_h^{nf} is at its maximum. The comparison of Figures 3 and 4 already shows some examples with F_f^{jh} increasing in x when F_h^{nf} is at its maximum. This must then always be the case.

Appendix 4. $F_h^{nf} > F_f^{nh} - F_f^{fh}$ holds for most parameter values

Define $G \equiv (F_h^{nf} - F_f^{nh} + F_f^{fh})$. It is easily seen that $G = 0$ for $e_f = e_n$ and $G > 0$ for $e_f = e_h$. It can be shown that G can only be negative if it is decreasing in e_f at $e_f = e_n$. Renaming $e_n = x,\ e_h = z$, we find from (48) and (36):

$$\left.\frac{dG}{de_f}\right|_{e_f = x} = \frac{z - x}{2x\left(\lambda x^2 + 1\right)^2\left(\lambda x^4 + 3x^2 - 2z^2\right)^3}\Gamma \tag{84}$$

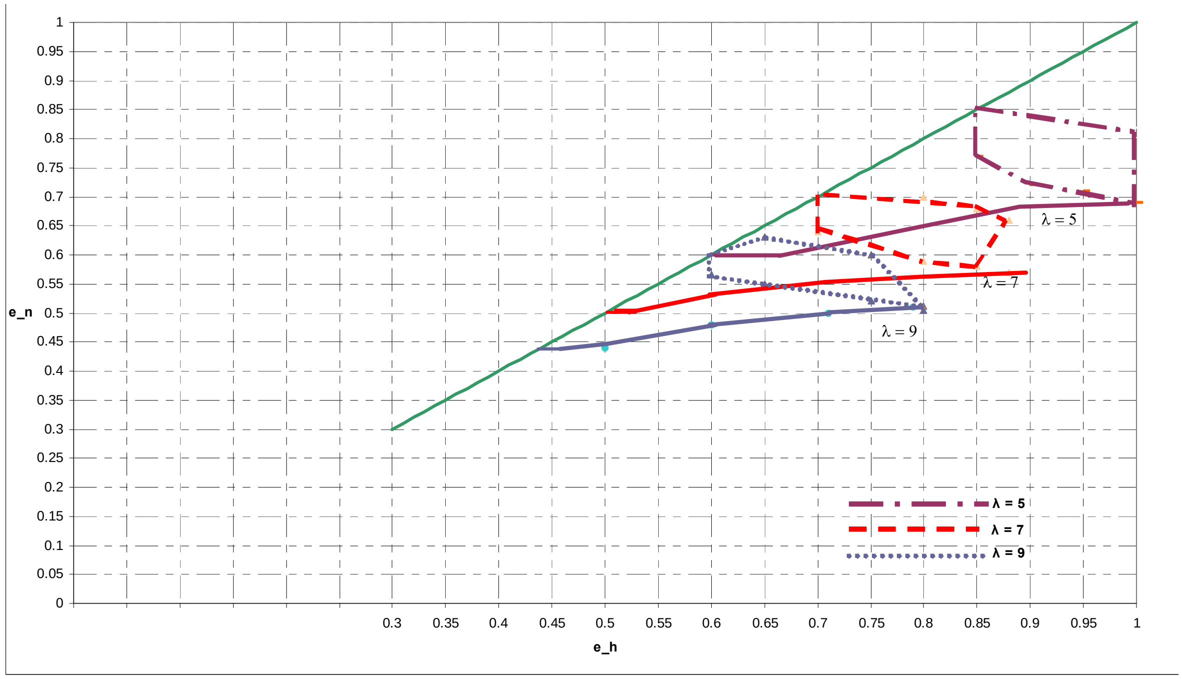

Figure 6: Values of $e_h,\ e_n$ and λ for which (66) does not hold.

with

$$\begin{aligned}\Gamma \equiv\ & x^{14}z\lambda^5 - 2x^{13}\lambda^4 + 3x^{12}z\lambda^4 - 8x^{11}z^2\lambda^4 - 8x^{11}\lambda^3 + 6x^{10}z^3\lambda^4 + 22x^{10}z\lambda^3 - 36x^9z^2\lambda^3 - 20x^9\lambda^2 \\ & +4x^8z^3\lambda^3 + 50x^8z\lambda^2 - 36x^7z^2\lambda^2 + 8x^7\lambda + 8x^6z^3\lambda^2 + 73x^6z\lambda + 8x^5z^4\lambda^2 - 12x^5z^2\lambda + 54x^5 \\ & +12x^4z^3\lambda + 75x^4z - 68x^3z^2 - 16x^2z^5\lambda - 62x^2z^3 + 24xz^4 + 16z^5\end{aligned}$$

The sign of the RHS of (84) is then the sign of Γ. We numerically determined the values of $x,\ z$ and λ for which $\Gamma = 0$ and entered them into Figure 6. We found that Γ can only be positive for $\lambda > 3$.

Appendix 5

Renaming $e_n = z,\ e_h = x$ and differentiating $\bar{e}_f$ in (70) with respect to e_h, we get:

$$\frac{d\bar{e}_f}{dz} = \frac{\left(x^2\lambda+1\right)^2\left(8z^4\lambda - 3z^2\lambda - 5z^3\lambda - z + 5z^4\lambda^2 - 3z^5\lambda^2 - z^6\lambda^3 + z^7\lambda^3 - 1\right)x^2}{\left(x^2\lambda-1\right)\left(z^2\lambda+1\right)^2 z^2\sqrt{K}} \tag{85}$$

with

$$K \equiv z^2 - x^2 + 2xz^2 - 2x^2z - 2x^4\lambda + 2z^4\lambda + 4xz^4\lambda - 4x^4z\lambda + 4x^2z^2 - x^6\lambda^2 + z^6\lambda^2 + 8x^4z^2\lambda$$
$$+2xz^6\lambda^2 - 2x^6z\lambda^2 - 5x^2z^4\lambda^2 + 5x^4z^2\lambda^2 + 2x^2z^5\lambda^2 - 2x^5z^2\lambda^2 + 4x^6z^2\lambda^2 - 2x^2z^6\lambda^3$$
$$+2x^6z^2\lambda^3 + 4x^4z^5\lambda^3 - 4x^5z^4\lambda^3 + x^4z^6\lambda^4 - x^6z^4\lambda^4 - 2x^5z^6\lambda^4 + 2x^6z^5\lambda^4$$

The sign of $d\bar{e}_f/dz$ depends on the second term between brackets in the numerator on the RHS of (85)

Differentiating (26), w.r.t e_i, we get the first derivative as:

$$f'(e_i) = \frac{1 + e_i - 8\lambda e_i^4 + 3\lambda e_i^2 + 5\lambda e_i^3 + 3\lambda^2 e_i^5 - 5\lambda^2 e_i^4 - \lambda^3 e_i^7 + \lambda^3 e_i^6}{2\left(\lambda {e_i}^2 + 1\right)^3 {e_i}^3} \tag{86}$$

We see that the term in the second bracker in (85) is the negative of the term in (86). In our analysis, since we restrict the technology such that the license fee is decreasing in the technology (as it is a sufficient condition for $F_f^{n0} > F_f^{f0}$). Thus the numerator of the (86) is negative 0. Thus it can be seen that the numerator on the R.H.S of (85) is positive for all the feasible valus of e_h where the license fee is decreasing which is the restriction we impose in our model.

Appendix 6: Proof that $W^{RN} - W^N > 0$

Renaming $e_n = x, e_f = y, e_h = z$:

$$W^{nf} - F_h^{nf} = \frac{1}{2}\frac{1}{x^2\lambda + 1} - \frac{1}{\left(\lambda x^2 + 1\right)^2} + \frac{\left(\lambda x^3 - y\lambda x^2 + x + y\right)^2}{4x^2\left(\lambda x^2 + 1\right)^2}$$

We know that the license fee F_h^{nf} is increasing in y.

$$\frac{d}{dy}\left(W^{nf} - F_h^{nf}\right) = -\frac{1}{2x^2}\frac{x^2\lambda - 1}{\left(\lambda x^2 + 1\right)^2}\left(\lambda x^3 - y\lambda x^2 + x + y\right) < 0$$

Therefore $W^{nf} - F_h^{nf}$ will be decreasing in y, so setting $y = x$ and simplifying:

Therefore the minimum value is when $y = z$:

This is decreasing in y.So minimum value is when $y = z$

Setting $y = z$ and simplifying we get $W^{nf} - F_h^{nf}$:

$$\frac{1}{2}\frac{x^2\lambda - 1}{\left(x^2\lambda + 1\right)^2} + \frac{\left(\lambda x^3 - z\lambda x^2 + x + z\right)^2}{4x^2\left(\lambda x^2 + 1\right)^2} \tag{87}$$

Differentiating (87) with respect to x, we get:

$$-\frac{\left(-x^7z\lambda^3+x^6z^2\lambda^3+2x^6\lambda^2+3x^5z\lambda^2-5x^4z^2\lambda^2-6x^4\lambda+5x^3z\lambda+3x^2z^2\lambda+xz+z^2\right)}{2x^3\left(\lambda x^2+1\right)^3}$$

The sign of the above expression depends on the sign of the term inside the bracket which is quadriatic with uniqe maximum.

When z is the lowest, i.e. when $z=x$, the numerator becomes:

$$2\lambda x^4+2x^2>0$$

When plotting the expression for the maximum value of z, i.e. $z=1$ for several labdas we that it is always positive,

Thus we see that (87) is decreasing in x,so the minimum value of $W^{nf}-F_h^{nf}$ is when $x=z$

Setting $x=z$ yields:

$$W^{nf}-F_h^{nf}=\frac{1}{2\left(z^2\lambda+1\right)}=W^{h0}$$

Thus we can conclude that $W^{RN}>W^N$.

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