



# PRONTO

Productivity, Non-Tariff  
Measures and Openness

# PRONTO

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## Abstract

We develop an international duopoly model where the firms/countries trade (export) their output in a third, world-market, while production generates pollution, affecting negatively households' welfare in the two countries. To control pollution, governments use the following instruments (i) an emission tax, the revenue from which is used to finance public pollution abatement; (ii) a revenue-recycling tax, refunded to the emitting firm contingent on specific actions such as environmentally friendly R&D; and (iii) an environmentally related standard. We examine the impacts of the aforementioned environmental policies and forms of distribution of the environmental tax revenues as Non-Tariff Measures (NTMs) by identifying which policy scheme is more environmentally efficient and export promoting in an imperfectly competitive international trade-cum-environment framework. Simulation results show that public abatement is export promoting, while revenue recycling and ERSs are more environmental friendly, but export reducing.

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# Intra (Inter) Regional Effects of Environmental Policies as NTMs in an Economic Union

## Some Simulation Results

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### Abstract

We develop an international duopoly model where the firms/countries trade (export) their output in a third, world-market, while production generates pollution, affecting negatively households' welfare in the two countries. To control pollution, governments use the following instruments (i) an emission tax, the revenue from which is used to finance public pollution abatement; (ii) a revenue-recycling tax, refunded to the emitting firm contingent on specific actions such as environmentally friendly R&D; and (iii) an environmentally related standard. We examine the impacts of the aforementioned environmental policies and forms of distribution of the environmental tax revenues as Non-Tariff Measures (NTMs) by identifying which policy scheme is more environmentally efficient and export promoting in an imperfectly competitive international trade-cum-environment framework. Simulation results show that public abatement is export promoting, while revenue recycling and ERSs are more environmental friendly, but export reducing.

**Keywords:** Environmental R&D, Emission taxation, Recycling tax revenues, Public Abatement, Environmental Related Standards, International Trade.

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# 1 Introduction

The recent literature has extensively studied the role environmental policies may play as strategic trade policy non-tariff measures (NTMs),<sup>1</sup> in an age where for long GATT/WTO regulations and directives (i) restrict and in many cases prohibit the use of price and quantities related trade barriers; and (ii) protect the natural environment from over-usage and illegal trade of certain types of natural resources, as the world as a whole gradually becomes more environmentally conscientious.<sup>2</sup> Thus, countries in the pursuit of national economic objectives (e.g., employment and even tax revenue enhancement), resort to the use of environmental taxes and environmentally related standards (ERS) as NTMs,<sup>3</sup> in order to protect domestic industries and sectors from foreign competition, to restrict imports, or to promote exports. The upswing of such policies can be that environmental taxes and standards in conjunction with increased environmental awareness, despite of possible trade impediments, may increase trade in environmentally friendlier products, and provide stronger incentives to invest in “greener” technologies, which in turn can have positive spillovers to the rest of the economy, facilitating sustainable economic growth and aiding development.

In the context of using environmental taxes and ERSs as NTMs, a natural question that arises is how governments use the collected tax revenues of the former measures. There are two notable uses of such tax revenues. The first is either subsidizing firms’ investments in environmental R&D technology or creating incentives that motivate firms to undertake ER&D programs, i.e., so-called revenue recycling. The second, is financing government own pollution abatement activities, i.e., so-called provision of public pollution abatement.

The revenue recycling scheme was first used by Swedish policy makers in 1992 when an environmental charge on nitrogen oxide (NO<sub>x</sub>) emissions was introduced. The revenue from the tax was refunded to the affected plants in proportion to the amount of energy produced.<sup>4</sup> Thus, producers with a relatively high emissions rate paid a net tax, while those with low emissions rates received a refund. The results indicated a 35% reduction in NO<sub>x</sub> emissions within 20 months after the implementation of the tax. However, there are also other countries that use such environmental

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<sup>1</sup>These include environmental taxes, standards, tradable and non-tradable emissions permits, and possibly other regulatory environmental measures.

<sup>2</sup>*Copeland and Taylor (2004)*, and *Copeland (2012)* provide an excellent survey of such trade and environment related issues.

<sup>3</sup>It is possible to define environmental related standards as product standards (the most important), process standards, trade in hazardous standards, trade reforms, criminal and civil law, etc.

<sup>4</sup>According to *Aidt (2010)* and *Sterner and Fredriksson (2005)*, emission taxation is more politically acceptable if the tax revenues are refunded to the regulated industry. Polluters pay a charge on pollution and the revenues are refunded to them in proportion to their output market share.

policies, the revenues from which are refunded in different ways.

France following the "polluter pays principle" introduced in 1985 a tax on production generated air pollution (TPPA) for sulphur dioxide (SO<sub>2</sub>) emissions,<sup>5</sup> the revenues from which were earmarked for subsidies to abatement investments or for research and development. Any firm paying the air pollution tax was eligible to apply for the subsidy. The subsidy was awarded based on the level of the additional fixed capital investment the firm invested to reduce emissions. However, results by *Millock et al. (2004)* indicate that the overall effectiveness of this revenue rebating scheme is negative, as the tax rate was set very low, providing no strong-enough incentives to firms to adopt effective abatement technologies.

Norway in January 2007, introduced a tax on the emissions of nitrogen oxides in order to meet the NO<sub>x</sub> emissions standards, as agreed under the Gothenburg protocol. At the time of introduction, the tax covered approximately 55 per cent of total Norwegian NO<sub>x</sub> emissions. In May 2008, the tax was transformed into a Fund for investments through an agreement between the Norwegian government and business organizations causing further declines in NO<sub>x</sub> emissions. Refunding was tied directly to actual abatement costs at the firm level (expenditure based refunding), while compensations were paid to certain affected industries inter alia freight ships, fishing vessels and aircrafts.

In January 2008, Switzerland introduced and enforced the Carbon Dioxide (CO<sub>2</sub>) incentive tax on all hydrocarbon fuels, such as coal, oil and natural gas, unless they are used for energy. The revenues from the tax were partly redistributed to companies in proportion to the total payroll of their employees, and another part to the Swiss public via health insurance programs. Other than that, 33% of the revenue was allocated to a 10-year building program for climate-friendly building renovations. The *International Energy Agency (IEA)* praises the design of Switzerland's CO<sub>2</sub> tax, underscoring that recycling of the tax revenues to all citizens and enterprises, is considered as a "sound fiscal practice".

The motivation for introducing public pollution abatement activities stems from two evidence-based observations. First, governments spend a considerable portion of their tax revenues for pollution and abatement control (PAC) activities. For example, *Linster et al. (2007)* establish that aside of private sector pollution abatement activity, governments and international organizations also undertake pollution abatement and control (PAC) policies.<sup>6</sup> Second, particularly in developed

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<sup>5</sup>In 1990 the tax was extended to encompass nitrogen oxides (NO<sub>x</sub>) and hydrochloric acid (HCl) and then in 1995 also emissions of volatile organic compounds (VOC).

<sup>6</sup>The authors report, among other things, that during 1990-2000 for most countries public expenditures accounted for about 40-60% of total PAC expenditures. Public PAC expenditures as a percentage of total PAC expenditures averaged 55 percent in Canada, Finland, France and Korea, 77 percent in Germany, 35 percent in Japan, and 40 percent in the US.

economies, (i) the effect of environmental factors is more profound than that of income growth on individual's well-being; and (ii) public spending for the provision of non-consumption public goods (e.g. ensuring environmental protection and improvement) is far more important for the well-being of their citizens, relative to public spending related to economic growth.<sup>7</sup>In this respect, several studies conclude that higher welfare gains occur with increased public expenditures on environmental improvements (e.g. cleaner air and water, increased amount of waste recycling), rather than, e.g., on educational goods (see for instance *Rehdanz, K. and Maddison, D. (2005)*, *Welsch, H. (2006)*, *Ng, Y. K. (2008)*, *Ong, Q. and Quah, E. (2014)*). Motivated by these considerations, a limited strand of the international trade and environment literature considers the simultaneous abatement of pollution by both the private and public sectors (see e.g., *Hatzipanayotou et al. (2005)*, *Hadjiyiannis et al. (2009)*, *Tsakiris et al. (2015)*). In this line of work, governments finance public pollution abatement activities either by lump-sum taxation or by revenues from environmental taxes, or by proceeds from the sales of tradable emissions permits. These studies, however, exploit the subject of public pollution abatement in the context of perfectly competitive trade models. To the best of our knowledge, this issue has not been raised yet in the framework of imperfectly competitive trade models.

Another strand of the literature considers environmental policies in the form of ERS and their effects on international trade, welfare and growth, in imperfect competitive markets. For instance, *Ulph (1996)* comparing the cases where both governments use the same policy instrument, either taxes or standards, points out that did the use of environmental standards leads to lower distortions to both environmental policy and R&D investment than the use of emission taxes. He also shows that when both governments impose standards, social welfare levels are increased significantly in both countries. *Barrett (1994)* examines the effects of standards as barriers to trade, suggesting that environmental protection standards can enhance innovation and competitiveness of some industries, but this result rests on specific assumptions.

In the present study, we assess the effect of three distinct environmental policies on pollution emissions, welfare and more importantly on trade flows (export promotion) and competition among countries to change their market share in world product markets. In particular, we consider (i) an emission tax, the revenue from which is used to finance public pollution abatement; (ii) a revenue-recycling tax, refunded to the emitting firm, contingent on specific actions, such as environmentally friendly R&D; and (iii) an environmentally related standard. Our model consists of

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<sup>7</sup>The argument being that as incomes grow and households can afford consumption of certain public expenditure items such as education, they prefer increased public spending in areas of limited private consumption spending, e.g., environmental quality.

distinct versions of an asymmetric international duopoly model, with two non-identical countries. To operationalize this, we assume that production-generated pollution in each country is local, and is abated differently. Firms in both countries have an incentive to invest in ER&D techniques to abate pollution (private abatement) in response either to emissions taxes or the abide by environmental standards which are imposed. In the first version of the model, one country accounts also for public pollution abatement, which is financed through the environmental tax revenues, whereas the second country follows a revenue-recycling policy according to which a part of the emission tax revenues is refunded to the emitting firm - the rest of these revenues being redistributed lump-sum to the consumers. In the second version, one government engages in public abatement while the second imposes an environmental standard. Finally, in the last version we consider that one government uses revenue recycling taxation and the other implements an environmental standard.

Furthermore, we compare our findings to the special cases in which both countries are symmetric in the sense that they abate and control pollution (non-cooperatively) in the same way. That is we examine the case when both countries engage in public abatement, the case when both countries use recycling of environmental tax revenues, and finally the case when both governments impose an environmental standard. In all cases considered, both governments commit ex ante to the environmental policies that are going to implement.

Our findings can be briefly summarized as follows. First, in all cases we consider, the governments face a trade-off between leaving trade flows unaffected and choosing policies that protect the environment, verifying the dual nature and behavior of NTMs. Second, public abatement is found to be export promoting: that is the country which adopts public abatement, ends up exporting more to the rest of the world. Third, revenue recycling can be thought of as a more environmentally-friendly policy: firms conduct more ER&D activities and as a consequence they emit less; though at the cost of lower output and exports. However, this type of intervention is not as efficient as ERSs in improving social welfare, providing evidence that NTMs may be welfare or trade promoting provided that certain conditions are met.<sup>8</sup>

Due to the complicated nature of our equilibrium conditions, it turns out that it is very hard to come up with closed-form solutions. So in order to obtain our results, we resort to numerical simulations. We make some plausible assumptions regarding basic parameter values and we solve the model numerically to obtain equilibrium values of taxes, ERSs, quantities of exports and so on. In order to evaluate the sensitivity of our results for the benchmark case, we simulate our model for different values of crucial parameters such as the cost of ER&D, the size of the world market

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<sup>8</sup>For instance, the exact magnitude of the effect depends on assumptions about the cost of ER&D, the market size outside the economic union, and the efficiency of the government that engages in public abatement.

as well as the efficiency of the government. As already mentioned above, the numerical results we obtain depend on the values of these parameters.

The rest of the paper is organized as follows. Section 2 presents the first scenario (public abatement vs revenue recycling), its main findings and numerical results. In Section 3 we discuss the second scenario (public abatement vs ERS) and in Section 4 the third one (revenue recycling vs ERS). Both sections are also accompanied by main results and numerical simulations. The concluding remarks are summarized in Section 5.

## 2 Public Abatement vs Revenue Recycling

We consider an asymmetric international duopoly model where each firm is located in a different country (1 and 2). Having the same production technology, both firms produce an identical and homogeneous good consumed in a third market, e.g. rest of the world (ROW). Inverse demand for the product is assumed to be linear of the form  $P = B - Q$ , where  $P$  is the market price,  $B > 0$  is a market size parameter and  $Q = q_1 + q_2$  is the total market output. Without loss of generality, we assume zero production costs.

In order to make the model reasonably simple, we assume that the only policy instruments available to each country's government are emission taxes. Emission taxes correct for pollution, the environmental externality that arises due to over-production.

Each firm has an incentive to invest in ER&D techniques to abate pollution (private abatement). Both firms use "end-of-pipe" technology for pollution abatement (following *Poyago-Theotoky (2007)*).<sup>9</sup> Each firm's total emissions after ER&D are expressed by

$$E_i(q_i, r_i) = (q_i - r_i), \quad i = 1, 2 \quad (1)$$

The adoption of ER&D entails a cost of the form  $\frac{1}{2}kr_i^2$ , with  $k > 0$ . Larger values of  $k$  imply that the ER&D technology used becomes less efficient.

The first country accounts also for public pollution abatement ( $g$ ) which is financed through the environmental tax revenues (following *Hadjjiannis et al. (2009)*). Thus, the government's (balanced) budget constraint is written as

$$g = t_1(q_1 - r_1) \quad (2)$$

The second country on the other hand, follows a revenue-recycling policy ( $t_2$ ) according to which a part of the emission tax revenues ( $\delta$ ) is refunded to the emitting firm whilst the rest of

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<sup>9</sup>Each firm's emissions per unit of output are assumed to be one.

these revenues is redistributed to the consumers in a lump-sum fashion. It is straightforward that when  $\delta = 1$  the firm gets a full refund which is equivalent of paying no tax so the condition  $0 < \delta < 1$  must hold.<sup>10</sup> We consider only the case of endogenous refunding. In other words, the firm in country 2 knows and recognizes that a share of its tax payments will be refunded to it proportionally to its output.

Emissions in the first country cause environmental damage of the form

$$D(E_1) = \frac{1}{2}\theta[(q_1 - r_1) - \alpha g]^2 \quad (3)$$

where  $\alpha$  is a parameter that captures the government's efficiency (for one unit) of public pollution abatement.

On the other hand, emissions in the second country cause environmental damage of the form

$$D(E_2) = \frac{1}{2}\theta[(q_2 - r_2)]^2 \quad (4)$$

where  $\theta > 0$  reflects the marginal damages from unabated emissions, which is assumed to be the same for both countries.

We consider a pre-commitment game played in 3 stages. In the first stage, both governments decide on the environmental policy by setting emission taxes  $t_1, t_2$  to maximize their social welfare levels while country 2 also chooses the share of tax revenues that is going to rebate. In the second stage, both firms determine the optimal ER&D levels  $r_1, r_2$ .<sup>11</sup> In the final stage, taking the governments' policy choices as given, the two firms decide non-cooperatively their output quantities  $q_1, q_2$  in order to maximize their profits. The sub-game perfect equilibrium of the game is solved using backward induction.

## 2.1 Pre-commitment Game

### 2.1.1 Output Competition

In the last stage both firms chose outputs to maximize their own profits, as follows:

$$\pi_1(q_1, q_2, r_1, t_1) = (B - q_1 - q_2)q_1 - t_1(q_1 - r_1) - \frac{1}{2}k(r_1)^2 \quad (5)$$

$$\pi_2(q_1, q_2, r_2, t_2, \delta) = (B - q_2 - q_1)q_2 - t_2(q_2 - r_2) - \left[\frac{1}{2}k(r_2)^2 - \delta t_2(q_2 - r_2)\right] \quad (6)$$

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<sup>10</sup>Following *Gersbach and Requate (2004)* we incorporate partial refunding of the tax revenues.

<sup>11</sup>In the present paper, we only consider the case where firms decide on their emission-reducing R&D non-cooperatively. Nevertheless, there are studies that point out that social welfare is higher in the case of an environmental R&D cartel compared to independent R&D when environmental damages are relatively low (*Poyago-Theotoky, 2007*).



where  $t_1, t_2$  are the taxes imposed per unit of emissions.

By differentiating with respect to  $q_1$  and  $q_2$  respectively we obtain the following first-order conditions:<sup>12</sup>

$$B - q_1 - q_2 - t_1 = q_1 \quad (7)$$

$$B - q_1 - q_2 - t_2(1 - \delta) = q_2 \quad (8)$$

Solving the system above, the Cournot-Nash equilibrium outputs are found to be:

$$q_1(r_1, r_2, t_1, t_2, \delta) = \frac{1}{3}[B - 2t_1 + t_2(1 - \delta)] \quad (9)$$

$$q_2(r_1, r_2, t_1, t_2, \delta) = \frac{1}{3}[B + t_1 - 2t_2(1 - \delta)] \quad (10)$$

Simple comparative statics show the following effects of environmental taxes and share of recycling on trade:

$$\frac{\partial q_i}{\partial t_i} < 0, \quad i = 1, 2 \quad (11)$$

$$\frac{\partial q_i}{\partial t_j} > 0, \quad i = 1, 2 \quad (12)$$

i.e. local competitiveness raises with low environmental regulation and when a tax from abroad is lowered, local output falls (and vice versa), which is the so-called *strategic* effect.

$$\frac{\partial q_1}{\partial \delta} < 0 \quad (13)$$

$$\frac{\partial q_2}{\partial \delta} > 0 \quad (14)$$

i.e. production and competitiveness in the first country declines for higher share of recycling whilst production and competitiveness in the second country increases for higher values of  $\delta$ . Nevertheless, outputs in both countries increase when the market size parameter  $B$  increases.

Therefore profits in equilibrium are:

$$\begin{aligned} \pi_1(r_1, r_2, t_1, t_2, \delta) = & \frac{1}{18}[-9kr_1^2 + 2(B^2 + 9r_1t_1 + (2t_1 + t_2(1 - \delta))^2 \\ & - 2B(2t_1 - t_2(1 - \delta)))] \end{aligned} \quad (15)$$

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<sup>12</sup>Note that both the second-order conditions ( $\frac{\partial^2 \pi_i}{\partial q_i^2} = -2 < 0$ ) and the stability condition ( $\Delta = 3 > 0$ ) hold throughout the paper. Furthermore, in order to ensure that  $q_i > 0$  the conditions  $t_1 < \frac{1}{2}[B + t_2(1 - \delta)]$  and  $t_2 < \frac{B + t_1}{2(1 - \delta)}$  must also be satisfied.

$$\pi_2(r_1, r_2, t_1, t_2, \delta) = \frac{1}{18}[-9kr_2^2 + 2B^2 + 2t_1^2 + 4B(t_1 - 2t_2(1 - \delta)) - 2t_2(-9r_2 + 4(t_1 - t_2(1 - \delta)))(1 - \delta)] \quad (16)$$

### 2.1.2 ER&D Selection

In this stage, both firms choose the optimal ER&D investment levels in order to maximize their profits as given by (15) and (16). The associated first-order conditions are:<sup>13</sup>

$$r_1 = \frac{t_1}{k} \quad (17)$$

$$r_2 = \frac{t_2(1 - \delta)}{k} \quad (18)$$

It is straightforward that the higher share of the emission tax revenues ( $\delta$ ) is being refunded to the emitting firm, the less is its associated impact on ER&D.

Substituting these into the profit functions, we obtain:

$$\pi_1(t_1, t_2, \delta) = \frac{(2B^2k + (9 + 8k)t_1^2 - 8kt_1t_2(1 - \delta) + 2kt_2^2(1 - \delta)^2)}{18k} + \frac{4Bk(-2t_1 + t_2(1 - \delta))}{18k} \quad (19)$$

$$\pi_2(t_1, t_2, \delta) = \frac{(2B^2k + 4Bk(t_1 - 2t_2(1 - \delta)) + 2k(t_1 + 2t_2(1 - \delta))^2)}{18k} + \frac{9t_2^2(1 - \delta)^2}{18k} \quad (20)$$

### 2.1.3 Optimal Taxes and Share of Recycling

In the first stage, each government chooses the emission tax that maximize its social welfare function, taking into account how the firm will react to its environmental policy. Moreover, the government in the second country decides also the share of the emission tax revenue that is going to rebate to the emitting firm.

The social welfare functions are defined as the sum of the firms' profits minus the environmental damages. The first country's social welfare function is

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<sup>13</sup>The second-order conditions ( $\partial^2\pi_i/\partial r_i^2 = k > 0$ ,  $i = 1, 2$ ), hold throughout the paper, so the conditions for interior solutions are satisfied.

$$\begin{aligned}
SW_1(q_1, q_2, r_1, r_2, t_1, t_2, \delta) &= (B - q_1 - q_2)q_1 - t_1(q_1 - r_1) - \frac{1}{2}k(r_1)^2 \\
&\quad - \frac{1}{2}\theta[(q_1 - r_1) - \alpha g]^2
\end{aligned} \tag{21}$$

with the government satisfying its budget constraint

$$g = t_1(q_1 - r_1) \tag{22}$$

The second country's social welfare function is

$$\begin{aligned}
SW_2(q_1, q_2, r_1, r_2, t_1, t_2, \delta) &= (B - q_2 - q_1)q_2 - t_2(q_2 - r_2) \\
&\quad - [\frac{1}{2}k(r_2)^2 - \delta t_2(q_2 - r_2)] \\
&\quad + (1 - \delta)t_2(q_2 - r_2) - \frac{1}{2}\theta[(q_2 - r_2)]^2
\end{aligned} \tag{23}$$

with the associated government's (balanced) budget constraint being satisfied

$$(1 - \delta)t_2(q_2 - r_2) = t_2(q_2 - r_2) + \delta t_2(q_2 - r_2) \tag{24}$$

Substituting  $q_1$ ,  $q_2$ ,  $r_1$  and  $r_2$ , from the equations (9), (10), (17) and (18) above, we obtain the levels of total welfare for both countries as functions of the environmental taxes  $t_1$ ,  $t_2$  and the share of recycling  $\delta$ . However, the associated first-order conditions ( $\partial SW_1/\partial t_1$ ,  $\partial SW_2/\partial t_2$  and  $\partial SW_2/\partial \delta$ ) cannot be solved analytically. We therefore proceed to obtain numerical results, in particular to obtain numerically the optimal values of  $t_1$ ,  $t_2$  and  $\delta$  given some values for the main parameters of the model. Our results are laid out in the following section.

## 2.2 Main Findings and Numerical Simulations

### 2.2.1 Main Results

In our work we evaluate how different environmental policies impact on polluting emissions, private ER&D expenditure to reduce these emissions and on international trade. In all cases we consider, the governments face a trade-off between leaving international trade flows unaffected and choosing policies that protect the environment. Supposing that the first country engages in public abatement, while the second one in revenue "recycling", our model's main results are the following:

**Result 1** Revenue “recycling” is perceived to be more effective than public abatement - in terms of welfare - for low ER&D cost and inefficiency of the first government to abate pollution.

**Result 2** Public abatement is considerably more effective than revenue “recycling” - in terms of welfare - given a large market size and inefficiency of the first government to abate pollution.

In order for the recycling policy to be effective in terms of ER&D and emission reduction, it must be also accompanied with a high tax. This finding is in line with *Sterner and Høglund (2006)* who demonstrate that significant abatement effects could be achieved if only a sufficiently high tax is charged. A real-world example along these lines is the Swedish charge on nitrogen oxides and its successful effects underpin this result. Moreover, the result we present, suggests that recycling of tax revenues creates strong incentives for firms to adopt cleaner technology in order to reduce their polluting emissions. Our results are also in line with *Coria and Mohlin (2013)* who point out that refunding can speed up the diffusion of abatement technology if firms do not strategically influence the size of the refund.<sup>14</sup>

Figures 1,2 and 3 verify the aforementioned results. In particular, Figure 1 refers to the case in which the only parameter that varies is the cost of ER&D ( $k$ ). Figure 2 depicts the results when the only parameter that changes is the market size ( $B$ ). Finally, figure 3 presents the results when the only parameter that changes is the first government’s efficiency to abate pollution ( $\alpha$ ) publicly. In the first two figures, there is a clear crossover of the welfare results indicating that the effectiveness of the environmental policy depends on the parameter values of our model.

### 2.2.2 Numerical Simulations

The main numerical findings are summarized in Table 1. Column (A) contains results for the case where the governments do not intervene at all, while the rest of the columns present results where the governments intervene to mitigate the effects of emissions on social welfare. We also compare these results with two benchmark cases. In the first case, both governments engage in public pollution abatement (col. E) while in the second one, both governments use tax-revenue recycling as their policies (col. F). This comparison indicates that when both countries “recycle” their tax revenues to their emitting firms, they manage to attain a high level of social welfare; however the sum of their exports to the rest of the world is larger when both countries engage in a public abatement scheme.

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<sup>14</sup>Note that in our model, optimal taxes as well as the share of the refund are endogenously determined by the governments in the first stage of the game and not by the firms and that the governments are pre-committed to these choices.

In order to assess the robustness of the results, we perform a number of experiments which allow us to explore the sensitivity of our numerical findings to the parameter values we have chosen. In all tables described below, we use a value of the parameter examined as a benchmark and express the changes as a percentage of this benchmark.

Table 2 reports the numerical results of our basic model in the case where we vary the cost of ER&D,  $k$ . As this parameter becomes larger, since the second government engages in recycling of tax revenues, it imposes a higher emissions tax and refunds a larger share of the revenues to the emitting firm, providing a strong incentive to invest in ER&D. Consequently ER&D activities undertaken by the second firm reduce the country's net total emissions substantially. On the other hand, public abatement provides the first country with higher levels of production and exports but leads to higher aggregate net emissions. Furthermore as investment in ER&D becomes more costly, ER&D activities decrease. Production and market share for the first firm increase whereas production levels for the second one decrease; nevertheless total exports to the rest of the world increase. As it is expected when the cost of ER&D ( $k$ ) increases, aggregate net emissions increase as well.

Table 3 reports the results when the varying parameter is the market size ( $B$ ). It is straightforward that when the market size increases, the optimal taxes, the ER&D activities, the production levels, the social welfare levels, total exports and the aggregate net emissions increase. Again, the first country is better off in terms of production and exports; however the second country gains in terms of ER&D and reduced emissions.

The numerical solutions of our model when the only parameter that varies is the first government's efficiency to abate pollution publicly ( $\alpha$ ) are reported in Table 4. It is straightforward that when the first government becomes more efficient, its production, exports and social welfare increase whilst its net emissions decline. Government in country 2 on the other hand, imposes a relatively high tax, refunding a significant share of the tax revenues to the emitting firm. As a result, firm in country 2 rises its expenditures in ER&D. Nevertheless, emissions are significantly higher than emissions in the first country. Finally production and social welfare decrease as the efficiency of the first government ( $\alpha$ ) increases.

### **3 Public Abatement vs Environmental Related Standard**

In this setting we assume that country one imposes a tax to finance public abatement whereas country two adopts an environmental related standard. Again, we consider a three-stage pre-commitment game. In the first stage, the first government chooses the emission tax ( $t_1$ ) that max-

imizes its total welfare while the second government selects the optimal environmental standard ( $s_2$ ). In the second stage, both firms determine the optimal ER&D levels  $r_1, r_2$ . In the final stage, taking the governments' policy choices as given, the two firms decide non-cooperatively their output quantities  $q_1, q_2$  in order to maximize their profits. The sub-game perfect equilibrium of the game is solved using backward induction.

### 3.1 Output Competition

The first firm's profit maximization problem is represented as follows:

$$\max_{q_1} \pi_1(q_1, q_2; r_1, t_1) = (B - q_1 - q_2)q_1 - t_1(q_1 - r_1) - \frac{1}{2}k(r_1)^2 \quad (25)$$

By differentiating (25) with respect to  $q_1$  we get the following first-order condition:

$$B - q_1 - q_2 - t_1 = q_1 \quad (26)$$

The second firm's profit maximization problem is represented as follows:

$$\begin{aligned} \max_{q_2} \pi_2(q_1, q_2; r_2, s_2) &= (B - q_2 - q_1)q_2 - \frac{1}{2}k(r_2)^2 \\ \text{s.t. } q_2 - r_2 &\leq s_2 \end{aligned} \quad (27)$$

The Lagrangian for (27) is  $L = (B - q_2 - q_1)q_2 - \frac{1}{2}k(r_2)^2 + \lambda(s_2 - q_2 + r_2)$ .<sup>15</sup>

According to the Kuhn-Tucker conditions we find that the optimal output for the second firm is as follows:

$$q_2 = \frac{B - q_1 + ks_2}{2k} \quad \text{if } r_2 = q_2 - s_2 \quad (28)$$

$$q_2 < \frac{B - q_1 + ks_2}{2k} \quad \text{if } r_2 > q_2 - s_2 \quad (29)$$

The optimal outputs for both firms<sup>16</sup> are found respectively as:

$$q_1 = \frac{B(1+k) - 2t_1 - k(s_2 + t_1)}{3 + 2k} \quad (30)$$

$$q_2 = \frac{B + 2ks_2 + t_1}{3 + 2k} \quad (31)$$

<sup>15</sup>According to the Kuhn-Tucker conditions, the optimal output has to satisfy the following constraints:  $\frac{\partial L}{\partial q_2} = B - q_1 - 2q_2 - \lambda = 0$ ,  $\frac{\partial L}{\partial \lambda} = s_2 - q_2 + r_2 \geq 0$ ,  $\lambda \geq 0$  and  $\lambda(\frac{\partial L}{\partial \lambda}) = 0$ . If  $\lambda > 0$  then  $\frac{\partial L}{\partial \lambda} = 0$  so  $s_2 = q_2 - r_2$  and  $B - q_1 - 2q_2 > 0$ . If  $\lambda = 0$  then  $\frac{\partial L}{\partial \lambda} > 0$ , thus  $s_2 > q_2 - r_2$  and  $B - q_1 - 2q_2 = 0$ .

<sup>16</sup>In order to ensure that  $q_1 > 0$  and  $q_2 > 0$ , the conditions  $t_1 < \frac{B+Bk-ks_2}{2+k}$  and  $s_2 > \frac{-B-t_1}{2k}$  must hold. The second-order conditions for the maximization problems are also satisfied i.e.  $\frac{\partial^2 \pi_1}{\partial q_1^2} = -2 < 0$  and  $\frac{\partial^2 \pi_2}{\partial q_2^2} = -(2+k) < 0$ .

A simple comparative static analysis show that

$$\frac{\partial q_1}{\partial t_1} < 0 \quad (32)$$

$$\frac{\partial q_1}{\partial s_2} < 0 \quad (33)$$

$$\frac{\partial q_2}{\partial s_2} > 0 \quad (34)$$

$$\frac{\partial q_2}{\partial t_1} > 0 \quad (35)$$

It is obvious that the exports and the competitiveness of the first (second) country can be stimulated when the emission tax is low (high). On the other hand, the second (first) country increases (decreases) its output and exports in the presence of an environmental standard.

Therefore profits in equilibrium are:

$$\begin{aligned} \pi_1(r_1, r_2, t_1, s_2) = & -\frac{kr_1^2}{2} + \frac{[B(2+k) - (3+2k)r_2]}{(3+2k)^2} \\ & - \frac{(3+k)s_2 + (2+k)t_1][B(1+k) - 2t_1 - k(s_2 + t_1)]}{(3+2k)^2} \\ & + \frac{t_1[-B(1+k) + 3r_1 + 2t_1 + k(2r_1 + s_2 + t_1)]}{3+2k} \end{aligned} \quad (36)$$

$$\pi_2(r_1, r_2, t_1, s_2) = -\frac{kr_2^2}{2} + (r_2 - s_2)\left[-r_2 - s_2 + \frac{B(2+k) + 2t_1 + k(s_2 + t_1)}{3+2k}\right] \quad (37)$$

### 3.2 ER&D Selection

In the second stage, both firms choose their ER&D activities to maximize their profit functions as given by (36) and (37):

Solving we obtain the optimal ER&D which are found as:

$$r_1 = \frac{t_1}{k} \quad (38)$$

$$r_2 = \frac{B - 3s_2 + t_1}{3 + 2k} \quad (39)$$

Comparative statics show that

$$\frac{\partial r_i}{\partial t_1} > 0, i = 1, 2 \quad (40)$$

i.e. an increase in the environmental tax imposed by the first country can motivate both firms to invest more in ER&D activities to abate pollution.

$$\frac{\partial r_2}{\partial s_2} < 0 \quad (41)$$

i.e. the adoption of a stricter environmental standard may discourage the second country's firm to expand its ER&D activities.

### 3.3 Optimal Tax and ERS

In the first stage, the first government chooses the emission tax that maximizes its social welfare, taking into account how the firm will react to its environmental policy whereas the second one chooses an environmental related standard. The social welfare functions are defined as the sum of the firms' profits minus the environmental damages.

The first country's social welfare function is

$$SW_1(q_1, q_2, r_1, r_2, t_1, s_2) = (B - q_1 - q_2)q_1 - t_1(q_1 - r_1) - \frac{1}{2}k(r_1)^2 - \frac{1}{2}\theta[(q_1 - r_1) - \alpha g]^2 \quad (42)$$

with the government satisfying its budget constraint

$$g = t_1(q_1 - r_1) \quad (43)$$

The second country's social welfare function is

$$SW_2(q_1, q_2, r_1, r_2, t_1, s_2) = (B - q_2 - q_1)q_2 - \frac{1}{2}k(r_2)^2 - \frac{1}{2}\theta[(q_2 - r_2)]^2 \quad (44)$$

Substituting  $q_1$ ,  $q_2$ ,  $r_1$  and  $r_2$ , from the equations (30), (31), (38) and (39) above, we obtain the lev-

els of total welfare for both countries as functions of the environmental tax  $t_1$  and the environmental standard  $s_2$ . However, the associated first-order conditions ( $\partial SW_1/\partial t_1$  and  $\partial SW_2/\partial s_2$ ) cannot be solved analytically simultaneously. We therefore proceed to obtain numerical results, in particular to obtain numerically the optimal values of  $t_1$  and  $s_2$  given some values for the main parameters of the model. Our main findings are discussed in the section below.



### 3.4 Main Findings and Numerical Simulations

#### 3.4.1 Main Results

When the first country engages in public abatement and the second one imposes an environmental related standard, our model's main results are the following:

**Result 3** *Environmental standards promote social welfare more than public abatement for low ER&D cost and inefficiency of the first government to abate pollution publicly.*

**Result 4** *With respect to social welfare, public abatement is considered more effective than environmental standards for large market size and inefficiency of the first government to abate pollution.*

#### 3.4.2 Numerical Simulations

The main numerical findings are summarized in Table 1. Column (C) presents the results for the case where the first government engages in public abatement whereas the second one uses an environmental standard. We can also compare these results with two benchmark cases. In the first case, both governments engage in public pollution abatement (col. E), while in the second one, both governments impose environmental standards (col. G). This comparison indicates that environmental policy that takes the form of environmental standards, leads to the maximum levels of social welfare that can be attained. Meanwhile, environmental standards provide both countries with strong incentives to invest in ER&D to abate polluting emissions. The significant reduced levels of net emissions underpin these findings.

In order to assess the robustness of the results we have discussed in the previous subsection, we perform a number of experiments which allow us to explore the sensitivity of our numerical findings to the parameter values we have chosen. Table 2 reports the numerical results of our basic model in the case where we vary the cost of ER&D,  $k$ .

## 4 Revenue Recycling vs Environmental Related Standard

In this case we assume that country one imposes a revenue-recycling tax ( $t_2$ ) so that a part of the emission tax revenues ( $\delta$ ) is refunded to the emitting firm. The rest of the tax revenues is redistributed to the consumers in a lump-sum fashion. On the contrary, country two adopts an environmental related standard. Again, we consider a three-stage pre-commitment game. In the first

stage, the first government chooses the emission tax ( $t_1$ ) and the share of recycling ( $\delta$ ) that maximize its total welfare whereas the second government selects the optimal environmental standard ( $s_2$ ). In the second stage, both firms determine the optimal ER&D levels  $r_1, r_2$ . In the final stage, taking the governments' policy choices as given, the two firms decide non-cooperatively their output quantities  $q_1, q_2$  in order to maximize their profits. The sub-game perfect equilibrium of the game is solved using backward induction.

#### 4.1 Output Competition

The firms' profit maximization problems are represented as follows:

$$\max_{q_1} \pi_1(q_1, q_2; r_1, t_1, \delta) = (B - q_1 - q_2)q_1 - t_1(q_1 - r_1) - \left[\frac{1}{2}k(r_1)^2 - \delta t_1(q_1 - r_1)\right] \quad (45)$$

By differentiating (25) with respect to  $q_1$  we get the following first-order condition:

$$B - q_1 - q_2 - t_1(1 - \delta) = q_1$$

The second firm's profit maximization problem is represented as follows:

$$\begin{aligned} \max_{q_2} \pi_2(q_1, q_2; r_2, s_2) &= (B - q_2 - q_1)q_2 - \frac{1}{2}k(r_2)^2 \\ \text{s.t. } q_2 - r_2 &\leq s_2 \end{aligned} \quad (46)$$

The Lagrangian for (27) is  $L = (B - q_2 - q_1)q_2 - \frac{1}{2}k(r_2)^2 + \lambda(s_2 - q_2 + r_2)$ .<sup>17</sup>

According to the Kuhn-Tucker conditions we find that the optimal output for the second firm is as follows:

$$q_2 = \frac{B - q_1 + ks_2}{2k} \quad \text{if } r_2 = q_2 - s_2 \quad (47)$$

$$q_2 < \frac{B - q_1 + ks_2}{2k} \quad \text{if } r_2 > q_2 - s_2 \quad (48)$$

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<sup>17</sup>According to the Kuhn-Tucker conditions, the optimal output has to satisfy the following constraints:  $\frac{\partial L}{\partial q_2} = B - q_1 - 2q_2 - \lambda = 0$ ,  $\frac{\partial L}{\partial \lambda} = s_2 - q_2 + r_2 \geq 0$ ,  $\lambda \geq 0$  and  $\lambda(\frac{\partial L}{\partial \lambda}) = 0$ . If  $\lambda > 0$  then  $\frac{\partial L}{\partial \lambda} = 0$  so  $s_2 = q_2 - r_2$  and  $B - q_1 - 2q_2 > 0$ . If  $\lambda = 0$  then  $\frac{\partial L}{\partial \lambda} > 0$ , thus  $s_2 > q_2 - r_2$  and  $B - q_1 - 2q_2 = 0$ .

The optimal outputs for both firms<sup>18</sup> are found respectively as:

$$q_1 = \frac{B(1+k) - 2t_1 + (2+k)t_1\delta - k(s_2 + t_1)}{3+2k} \quad (49)$$

$$q_2 = \frac{B + t_1(1-\delta) + 2ks_2}{3+2k} \quad (50)$$

A simple comparative static analysis show that

$$\frac{\partial q_1}{\partial t_1} < 0 \quad (51)$$

$$\frac{\partial q_1}{\partial s_2} < 0 \quad (52)$$

$$\frac{\partial q_1}{\partial \delta} > 0 \quad (53)$$

$$\frac{\partial q_2}{\partial s_2} > 0 \quad (54)$$

$$\frac{\partial q_2}{\partial t_1} > 0 \quad (55)$$

$$\frac{\partial q_2}{\partial \delta} < 0 \quad (56)$$

It is obvious that the exports and the competitiveness of the first (second) country can be stimulated when the emission tax is low (high). On the other hand, the second (first) country increases (decreases) its output and exports in the presence of an environmental standard.

Therefore profits in equilibrium are:

$$\begin{aligned} \pi_1(r_1, r_2, t_1, s_2, \delta) = & -\frac{kr_1^2}{2} + \frac{t_1[-B(1+k) + 3r_1 + 2t_1 + k(2r_1 + s_2 + t_1) - (2+k)t_1\delta]}{(3+2k)} \\ & + \frac{[B(2+k) - 3(r_2 + s_2) + 2t_1 - k(2r_2 + s_2 + t_1)(-1 + \delta) - 2t_1\delta]}{(3+2k)^2} \\ & + \frac{[B(1+k) - 2t_1 - k(s_2 + t_1) + (2+k)t_1\delta]}{(3+2k)^2} \\ & + t_1\delta[-r_1 + \frac{B(1+k) - 2t_1 - k(s_2 + t_1) + (2+k)t_1\delta}{3+2k}] \end{aligned} \quad (57)$$

$$\pi_2(r_1, r_2, t_1, s_2, \delta) = -\frac{kr_2^2}{2} + (r_2 - s_2)[-r_2 - s_2 + \frac{B(2+k) + 2t_1 - (2+k)t_1\delta}{3+2k}] \quad (58)$$

<sup>18</sup>In order to ensure that  $q_1 > 0$  and  $q_2 > 0$ , the conditions  $t_1 < \frac{B+Bk-ks_2}{2+k}$  and  $s_2 > \frac{-B-t_1}{2k}$  must hold. The second-order conditions for the maximization problems are also satisfied i.e.  $\frac{\partial^2 \pi_1}{\partial q_1^2} = -2 < 0$  and  $\frac{\partial^2 \pi_2}{\partial q_2^2} = -(2+k) < 0$ .

## 4.2 ER&D Selection

In the second stage, both firms choose their ER&D activities to maximize their profit functions as given by (57) and (58):

Solving we obtain the optimal ER&D which are found as:

$$r_1 = \frac{t_1(1 - \delta)}{k} \quad (59)$$

$$r_2 = \frac{B - 3s_2 + t_1(1 - \delta)}{3 + 2k} \quad (60)$$

Comparative statics show that

$$\frac{\partial r_i}{\partial t_1} > 0, i = 1, 2 \quad (61)$$

i.e. an increase in the environmental tax imposed by the first country can motivate both firms to invest more in ER&D activities to abate pollution.

$$\frac{\partial r_i}{\partial \delta} < 0, i = 1, 2 \quad (62)$$

in other words, the higher share of the emission tax revenues ( $\delta$ ) is being refunded to the emitting firm, the less is its associated impact on environmental innovation.

$$\frac{\partial r_2}{\partial s_2} < 0 \quad (63)$$

i.e. the adoption of a stricter environmental standard may discourage the second country's firm to expand its ER&D activities.

## 4.3 Optimal Tax, share of recycling and ERS

In the first stage, the first government chooses the emission tax and the share of revenue recycling that maximizes its social welfare, taking into account how the firm will react to its environmental policy whereas the second one chooses an environmental related standard. The social welfare functions are defined as the sum of the firms' profits minus the environmental damages.

The first country's social welfare function is

$$SW_1(q_1, q_2, r_1, r_2, t_1, \delta, s_2) = (B - q_1 - q_2)q_1 - \frac{1}{2}k(r_1)^2 - \frac{1}{2}\theta[(q_1 - r_1)]^2 \quad (64)$$

with the government satisfying its (balanced) budget constraint

$$(1 - \delta)t_1(q_1 - r_1) = t_1(q_1 - r_1) + \delta t_1(q_1 - r_1) \quad (65)$$

The second country's social welfare function is

$$\begin{aligned} SW_2(q_1, q_2, r_1, r_2, t_1, \delta, s_2) = & (B - q_2 - q_1)q_2 \\ & - \frac{1}{2}k(r_2)^2 - \frac{1}{2}\theta[(q_2 - r_2)]^2 \end{aligned} \quad (66)$$

Substituting  $q_1$ ,  $q_2$ ,  $r_1$  and  $r_2$ , from the equations (49), (50), (59) and (60) above, we obtain the levels of total welfare for both countries as functions of the environmental tax  $t_1$ , the share of revenue recycling  $\delta$  and the environmental standard  $s_2$ .

Solving for the optimal environmental standard we get

$$s_2 = \frac{2k(2+k)[B + t_1(1-\delta)]}{k(9+4k) + (3+2k)^2\theta}$$

However, the associated first-order conditions ( $\partial SW_1/\partial t_1$ ,  $\partial SW_1/\partial \delta$  and  $\partial SW_2/\partial s_2$ ) cannot be solved analytically altogether. We therefore proceed to obtain numerical results, in particular to obtain numerically the optimal values of  $t_1$ ,  $\delta$  and  $s_2$  given some values for the main parameters of the model. The results are discussed in the following section..

## 4.4 Main Findings and Numerical Simulations

### 4.4.1 Main Results

When the first country imposes a revenue recycling tax, while the second one imposes an environmental related standard, our model's main result is the following:

**Result 5** *Environmental standards always promote social welfare independently of the parameter values of our model.*

In this case the two governments face a significant trade-off between promoting international trade and protecting the environment. Revenue recycling policy, provides the first firm with stronger incentives to undertake green R&D and thus reduce its net emissions. However, this type of intervention is not as efficient as an environmental standard in improving social welfare. A comparison of these different forms of regulation suggests that the implementation of environmental standards

is considered highly effective as the second country gains a largest market share and is better off in terms of social welfare, no matter what the parameter values of our model are. Figures 7 and 8 confirm this result.

#### **4.4.2 Numerical Simulations**

We also compare the results with the benchmark cases where both governments use either a tax-revenue recycling or environmental standards. The relevant results are summarized in columns (F) and (G) of Table 1. Environmental standards are perceived to be considerable more effective than revenue recycling, providing both firms with strong incentives to invest in ER&D. Subsequently, both firms end up with significantly reduced net polluting emissions. Another important conclusion emerge from this analysis is that when governments impose environmental standards attain the maximum level of improvement of their social welfare.

In order to assess the robustness of the results , we perform a number of simulations which allow us to explore the sensitivity of our numerical findings to the parameter values we have chosen. Tables 8 and 9 summarize the results when we vary the parameter values of our model. An increase in the ER&D cost, raise the output of the second producer and cut the output of the rival, other parameters being equal.

## **5 Concluding Remarks**

The present study performs a comparison of differing environmental policies to modeling pollution abatement and evaluates how they affect trade flows, social welfare, and private ER&D expenditure to reduce polluting emissions. Our approach provides interesting new insights about the impacts that non tariff based instruments could have on international trade and competition among countries in order to increase their market shares in world markets and can be a useful implement for analysis within the EU's different countries as well as between the EU and the rest of the world.

More ofthen than not, governments face a trade-off between promoting international trade and protecting the environment. If public abatement is not efficient in terms of social welfare, then it is considered optimal to do revenue recycling. With low ER&D cost and high market size values, the country that engages in public abatement is always better off in terms of exports and social welfare, whereas the country that selects the recycling of tax revenues creates strong incentives for the firm to invest more in ER&D and ends up with lower net emissions; though at the cost of lower output and exports.

Public abatement can be considered as a better policy instrument than environmental standards - in terms of welfare -given a large market size and inefficiency of the first government to abate pollution publicly. Nevertheless, environmental standards always promote social welfare independently of the parameter values of our model when compared to the revenue recycling policy.

In general, a recycling policy requires a relatively high tax to attain significant results in emissions reduction and ER&D innovation. In contrast, the policy of public abatement is found to be export promoting as when both countries abate pollution publicly, the sum of their exports to the rest of the world is higher than in any other case, however environmental standards increase significantly both countries' social welfare levels.

Further issues to be addressed in future research include the introduction of transboundary pollution and its implications and the use of ER&D spillover effects. The time-consistency game scenario and its results are other applications under consideration as well.

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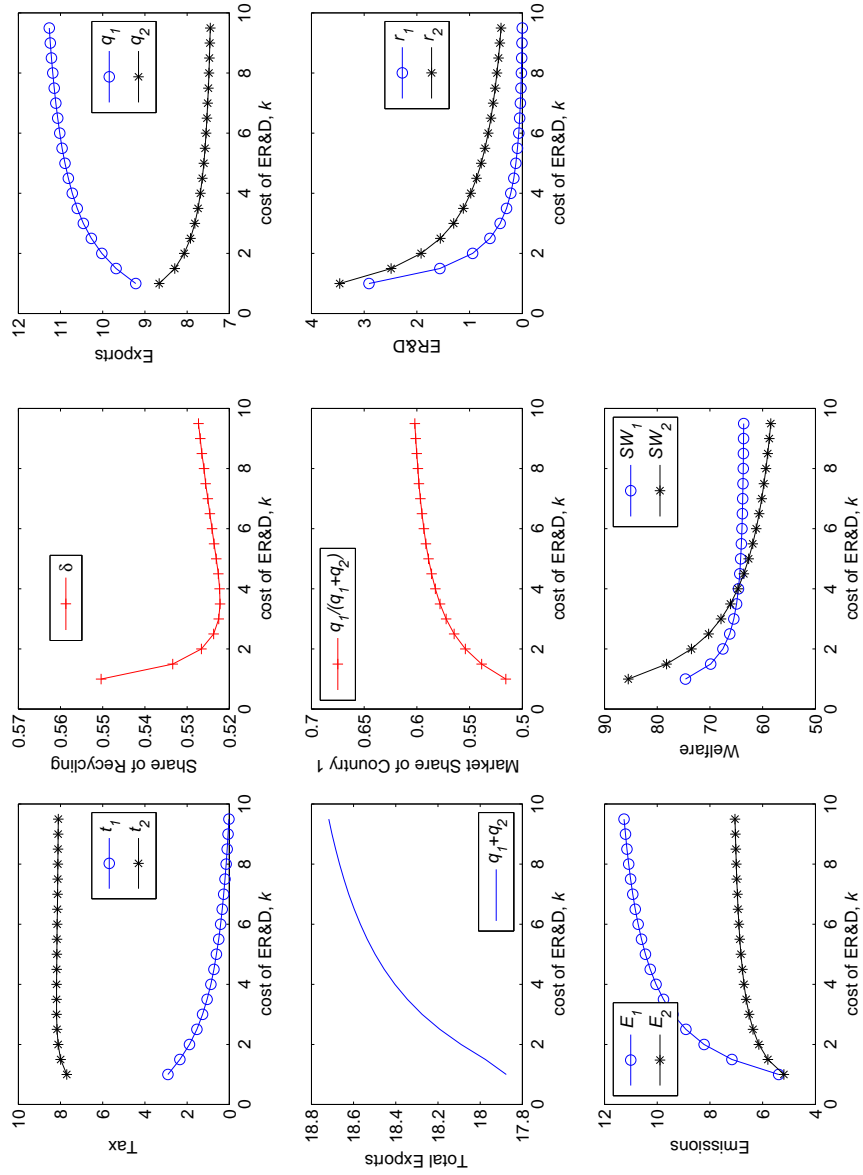


Figure 1: Public Abatement vs Recycling - varying the cost of ER&D ( $k$ )

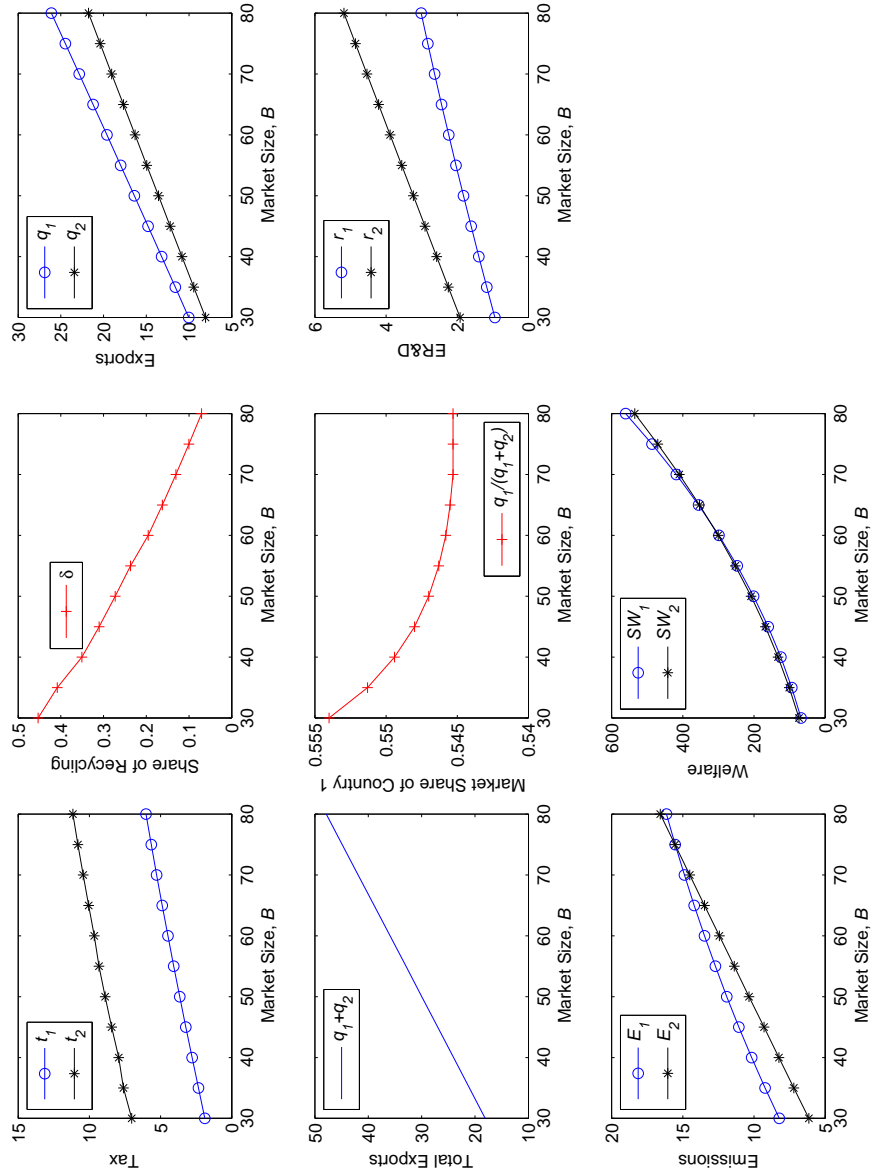


Figure 2: Public Abatement vs Recycling - varying the market size (B)

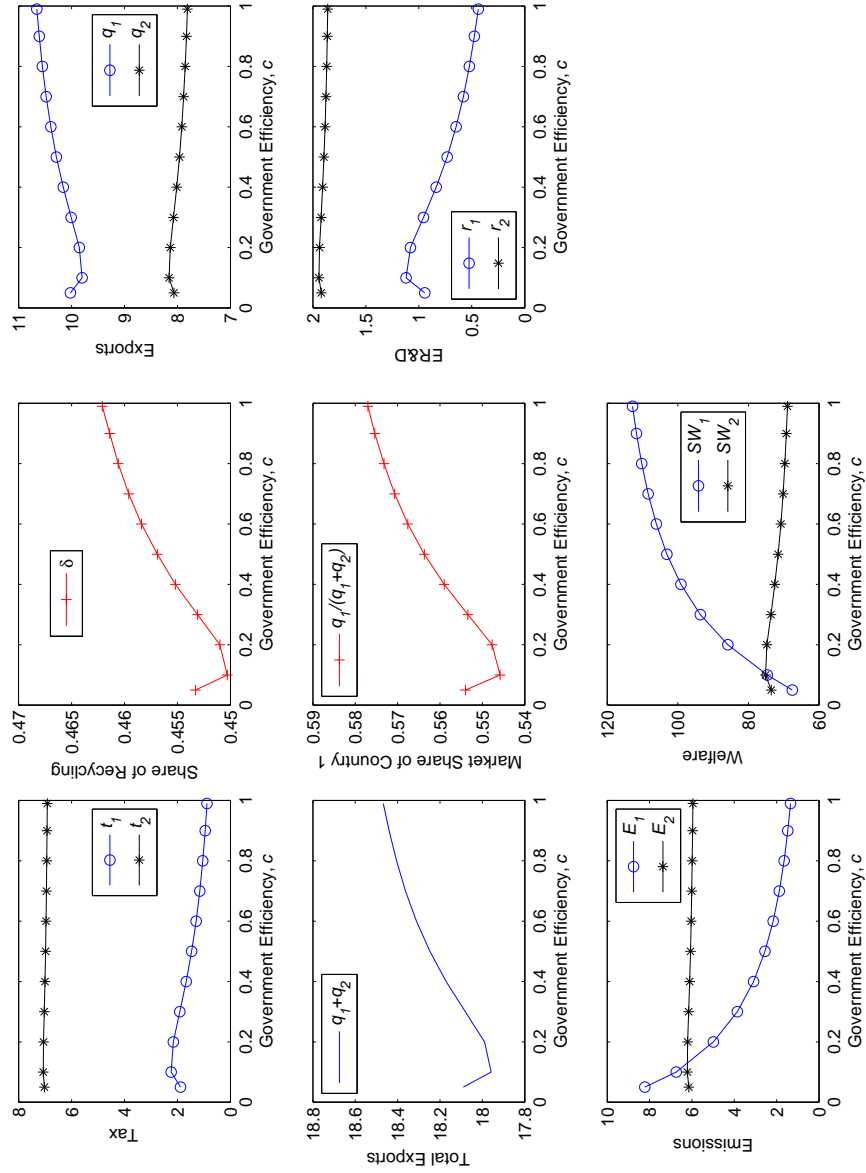


Figure 3: Public Abatement vs Recycling - varying the government's efficiency ( $\alpha$ )

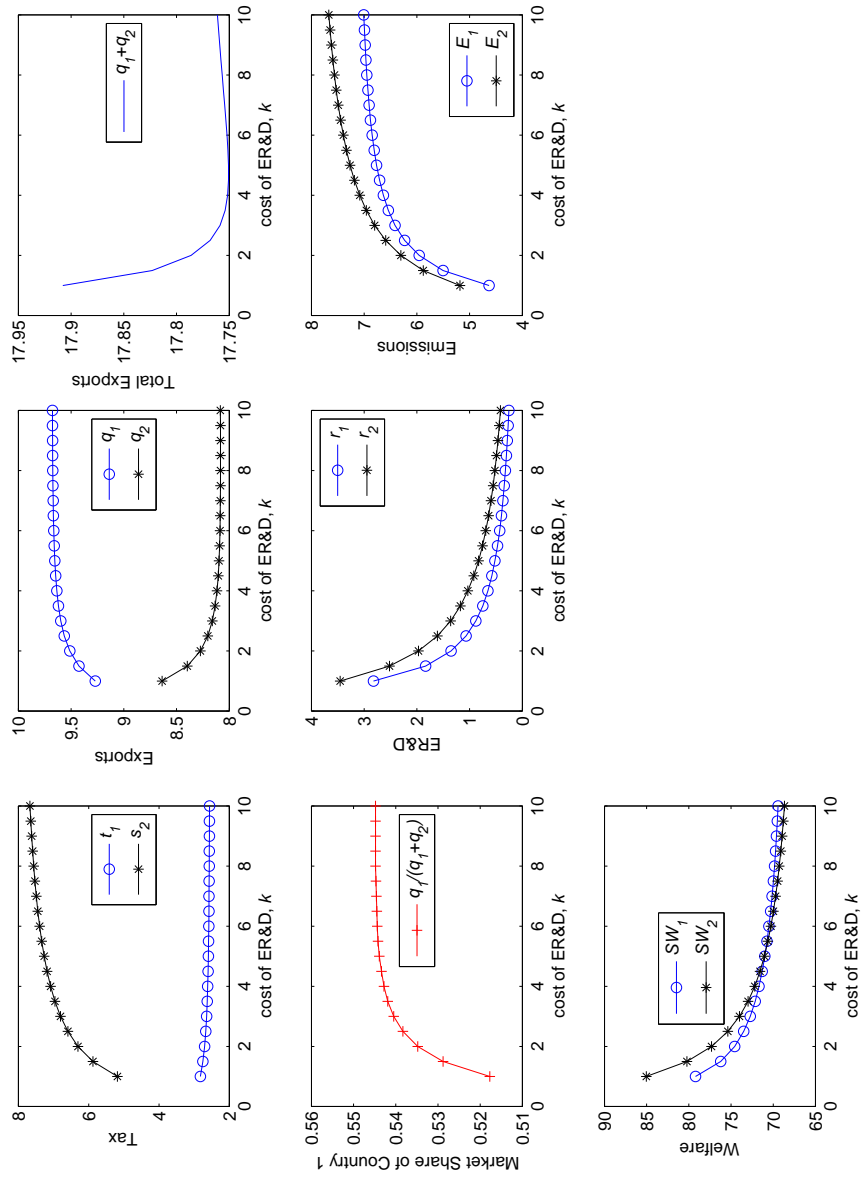


Figure 4: Public Abatement vs ERS - varying the cost of ER&D (k)

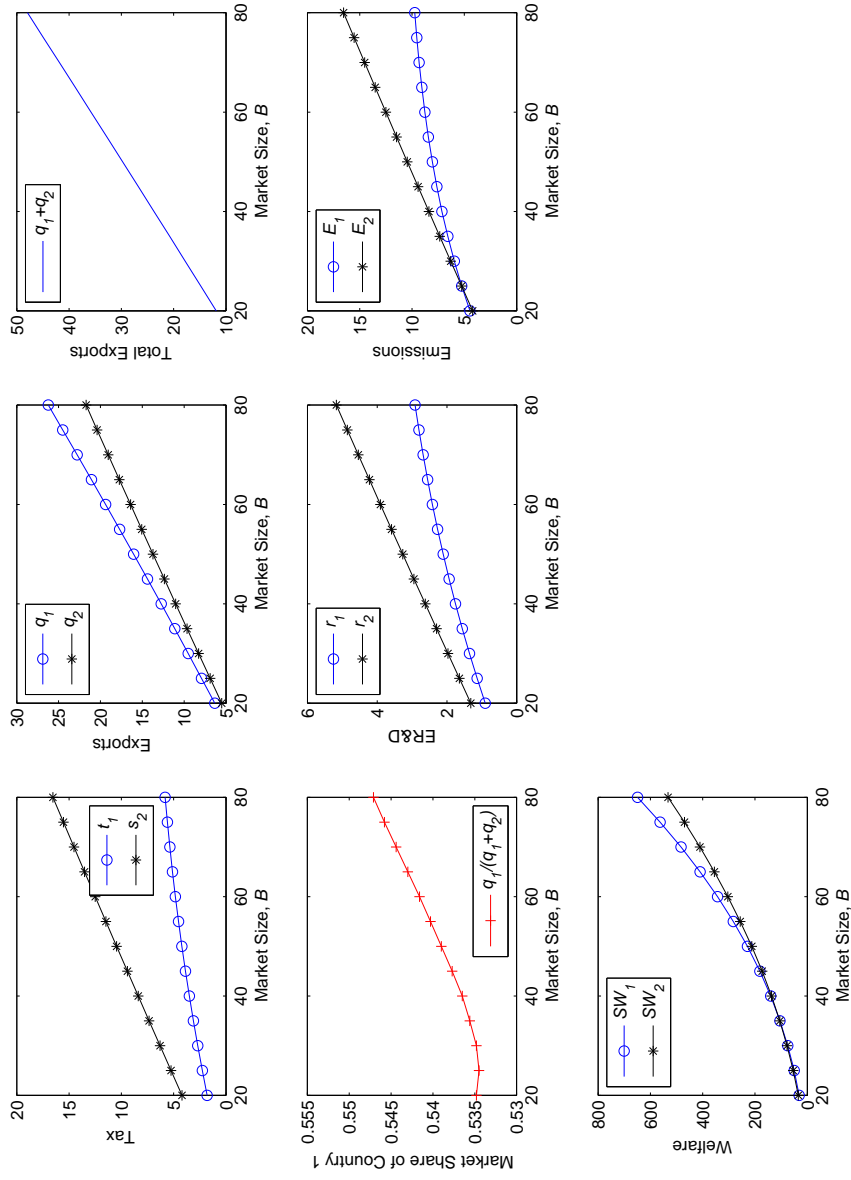


Figure 5: Public Abatement vs ERS - varying the market size ( $B$ )

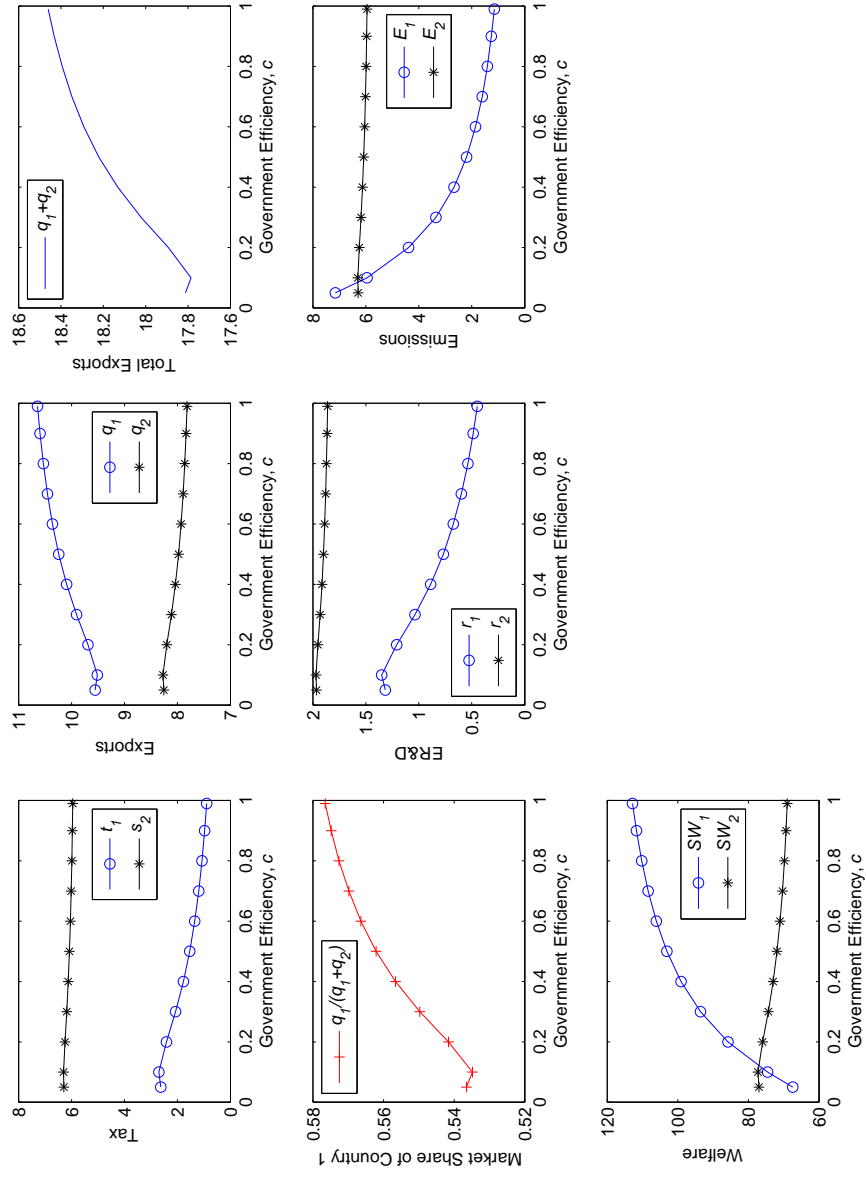


Figure 6: Public Abatement vs ERS - varying the government's efficiency ( $\alpha$ )



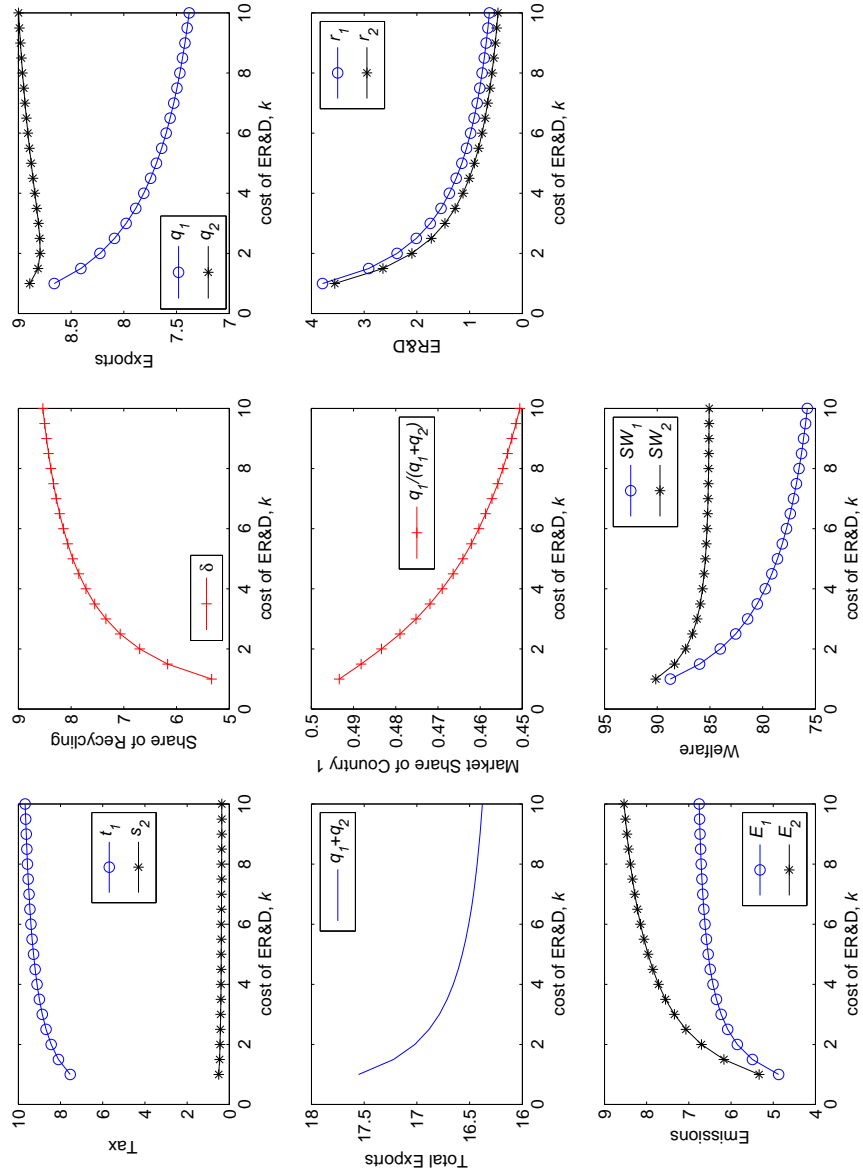


Figure 7: Recycling vs ERS - varying the cost of ER&D ( $k$ )

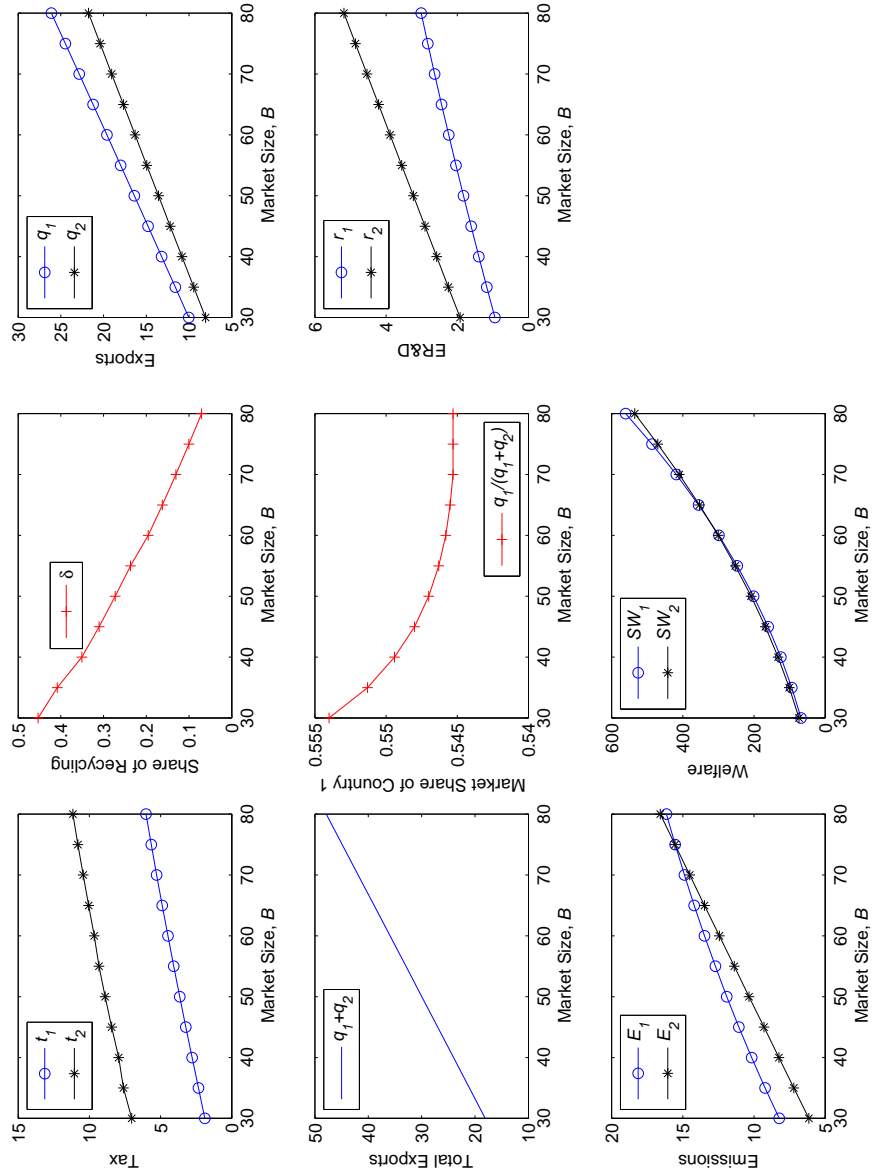


Figure 8: Recycling vs ERS - varying the market size (B)

## Appendix-Tables

Table 1: Main Results — Comparing Different Models

Variable	No Regulation (A)	Abatem. vs Recycl. (B)	Abatem. vs ERS (C)	Recycl. vs ERS (D)	Both Abatem. (E)	Both Recycl. (F)	Both ERS (G)
$t_1$	-	1.887	2.632	8.444	1.716	6.410	
$t_2$	-	7.028			1.716	6.410	
$\delta$	-	0.453		0.437		0.359	
$s_2$	-		6.290	6.699			5.963
$r_1$	0	0.943	1.316	2.376	0.858	1.055	2.422
$r_2$	0	1.921	1.966	2.093	0.858	1.055	2.422
$q_1$	10	10.022	9.555	8.227	9.428	8.630	8.385
$q_2$	10	8.068	8.256	8.793	9.428	8.630	8.385
$q_1+q_2$	20	18.09	17.81	17.020	18.856	17.260	16.770
$q_1/(q_1+q_2)$	0.5	0.554	0.536	0.483	0.500	0.500	0.500
$SW_1$	50	67.538	67.445	84.025	58.934	84.106	87.288
$SW_2$	50	73.503	76.979	87.310	58.934	84.106	87.288
$E_1$	10	8.222	7.155	5.850	7.834	6.575	5.963
$E_2$	10	6.147	6.290	6.699	7.834	6.575	5.963

Notes for Table 1: In all numerical experiments we assume that the demand parameter  $B = 30$ , the cost of ER&D  $k = 2$ , the inefficiency of the government engaging in abatement takes the value  $\alpha = 0.05$  and the damage parameter in the social welfare function  $\theta$  takes the value 1. Column (A) reports the results when no government intervenes to correct the pollution externality. Column (B) reports our results country 1 engages in public abatement, while country 2 employs revenue recycling (case 1). Column (C) shows the results when the first government uses public abatement whilst the second one uses an ERS (case 2). Column (D) refers to the case where the first government follows a revenue recycling policy while the second one imposes an ERS (case 3). Column (E) shows results when both governments engage in public abatement, column (F) reports results when when both governments use tax revenue recycling as their instrument while column (G) shows results when both governments impose ERS.

Table 2: Numerical Results — Varying the Cost of ER&D,  $k$

$k$	$t_1$	$t_2$	$\delta$	$r_1$	$r_2$	$q_1$	$q_2$	$q_1+q_2$	$q_1/(q_1+q_2)$	$SW_1$	$SW_2$	$E_1$	$E_2$
2.5	-18.50%	0.61%	-0.55%	-34.80%	-19.01%	2.48%	-1.83%	0.56%	1.91%	-1.92%	-4.43%	8.41%	3.53%
3	-32.88%	0.86%	-0.78%	-55.25%	-32.18%	4.35%	-3.11%	1.02%	3.29%	-3.08%	-7.64%	14.33%	5.97%
3.5	-44.32%	0.93%	-0.84%	-68.18%	-41.79%	5.80%	-4.05%	1.41%	4.33%	-3.83%	-10.07%	18.73%	7.75%
4	-53.62%	0.91%	-0.82%	-76.81%	-49.09%	6.96%	-4.76%	1.74%	5.14%	-4.35%	-11.97%	22.13%	9.09%
4.5	-61.32%	0.84%	-0.76%	-82.81%	-54.81%	7.91%	-5.31%	2.01%	5.78%	-4.71%	-13.50%	24.84%	10.15%
5	-67.80%	0.74%	-0.66%	-87.12%	-59.40%	8.70%	-5.76%	2.25%	6.31%	-4.98%	-14.76%	27.05%	11.00%
5.5	-73.33%	0.64%	-0.57%	-90.30%	-63.17%	9.37%	-6.12%	2.46%	6.74%	-5.19%	-15.81%	28.88%	11.70%
6	-78.11%	0.53%	-0.47%	-92.70%	-66.31%	9.94%	-6.43%	2.64%	7.11%	-5.35%	-16.70%	30.42%	12.29%
6.5	-82.26%	0.42%	-0.38%	-94.54%	-68.97%	10.43%	-6.68%	2.80%	7.43%	-5.47%	-17.47%	31.75%	12.78%
7	-85.92%	0.31%	-0.28%	-95.98%	-71.25%	10.87%	-6.90%	2.94%	7.70%	-5.57%	-18.13%	32.89%	13.21%
7.5	-89.16%	0.21%	-0.19%	-97.11%	-73.22%	11.25%	-7.09%	3.07%	7.93%	-5.65%	-18.71%	33.89%	13.58%
8	-92.06%	0.12%	-0.11%	-98.01%	-74.94%	11.59%	-7.25%	3.18%	8.14%	-5.71%	-19.23%	34.77%	13.90%
8.5	-94.65%	0.02%	-0.02%	-98.74%	-76.46%	11.89%	-7.40%	3.29%	8.33%	-5.77%	-19.69%	35.56%	14.19%
9	-97.00%	-0.06%	0.06%	-99.33%	-77.81%	12.16%	-7.52%	3.38%	8.49%	-5.82%	-20.10%	36.25%	14.44%
9.5	-99.12%	-0.15%	0.13%	-99.81%	-79.01%	12.41%	-7.64%	3.47%	8.64%	-5.85%	-20.47%	36.88%	14.67%

Notes for Table 2: The table reports the numerical solutions of our model in the case where country 1 engages in public abatement and country 2 in revenue recycling, when we vary the cost of environmental R&D,  $k$ . We use the values of column (B) of Table 1 as a benchmark and then we compute all the other values as percentages of this benchmark.

Table 3: Numerical Results — Varying the Demand Parameter,  $B$

$B$	$t_1$	$t_2$	$\delta$	$r_1$	$r_2$	$q_1$	$q_2$	$q_1+q_2$	$q_1/(q_1+q_2)$	$SW_1$	$SW_2$	$E_1$	$E_2$
35	23.91%	8.21%	-9.91%	23.91%	17.10%	15.81%	17.10%	16.38%	-0.49%	38.61%	37.11%	12.11%	17.10%
40	47.48%	12.94%	-22.66%	47.48%	34.17%	31.67%	34.17%	32.78%	-0.84%	84.25%	80.02%	23.59%	34.17%
45	70.64%	19.90%	-31.50%	70.64%	51.22%	47.57%	51.22%	49.20%	-1.09%	137.19%	128.68%	34.48%	51.22%
50	93.37%	26.47%	-39.84%	93.36%	68.25%	63.52%	68.25%	65.63%	-1.27%	197.65%	183.07%	44.81%	68.25%
55	115.61%	32.70%	-47.74%	115.60%	85.24%	79.53%	85.24%	82.08%	-1.40%	265.85%	243.15%	54.60%	85.24%
60	137.36%	37.38%	-56.89%	137.35%	102.21%	95.59%	102.21%	98.55%	-1.49%	342.00%	308.89%	63.88%	102.21%
65	158.59%	43.01%	-64.17%	158.58%	119.15%	111.72%	119.15%	115.03%	-1.54%	426.29%	380.26%	72.67%	119.15%
70	179.30%	48.43%	-71.19%	179.30%	136.05%	127.91%	136.05%	131.54%	-1.57%	518.89%	457.21%	80.99%	136.05%
75	199.49%	53.65%	-77.92%	199.48%	152.93%	144.16%	152.93%	148.07%	-1.58%	619.97%	539.73%	88.86%	152.93%
80	219.14%	58.68%	-84.43%	219.13%	169.77%	160.48%	169.77%	164.62%	-1.57%	729.68%	627.77%	96.30%	169.77%

Notes for Table 3: The table reports the numerical solutions of our model in the case where country 1 engages in public abatement and country 2 in revenue recycling, when we vary the international demand parameter,  $B$ . We use the values of column (B) of Table 1 as a benchmark and then we compute all the other values as percentages of this benchmark.

Table 4: Numerical Results — Varying the Government Efficiency,  $\alpha$

$\alpha$	$t_1$	$t_2$	$\delta$	$r_1$	$r_2$	$q_1$	$q_2$	$q_1 + q_2$	$q_1 / (q_1 + q_2)$	$SW_1$	$SW_2$	$E_1$	$E_2$
0.1	18.68%	0.55%	-0.66%	18.68%	1.11%	-2.20%	1.11%	-0.73%	-1.49%	10.50%	2.22%	-18.06%	1.11%
0.2	14.35%	0.42%	-0.51%	14.35%	0.85%	-1.69%	0.85%	-0.56%	-1.14%	27.05%	1.71%	-39.35%	0.85%
0.3	1.37%	0.04%	-0.04%	1.37%	0.08%	-0.16%	0.08%	-0.05%	-0.11%	38.60%	0.16%	-53.10%	0.08%
0.4	-11.41%	-0.34%	0.42%	-11.41%	-0.67%	1.35%	-0.67%	0.44%	0.90%	46.74%	-1.35%	-62.44%	-0.68%
0.5	-22.33%	-0.66%	0.79%	-22.33%	-1.32%	2.63%	-1.32%	0.87%	1.75%	52.64%	-2.63%	-68.97%	-1.32%
0.6	-31.30%	-0.93%	1.13%	-31.29%	-1.85%	3.69%	-1.85%	1.22%	2.44%	57.07%	-3.67%	-73.69%	-1.85%
0.7	-38.62%	-1.15%	1.39%	-38.62%	-2.28%	4.56%	-2.29%	1.51%	3.01%	60.49%	-4.52%	-77.22%	-2.29%
0.8	-44.66%	-1.33%	1.61%	-44.66%	-2.64%	5.27%	-2.64%	1.74%	3.47%	63.20%	-5.22%	-79.95%	-2.64%
0.9	-49.68%	-1.48%	1.79%	-49.67%	-2.94%	5.86%	-2.94%	1.94%	3.85%	65.40%	-5.79%	-82.10%	-2.94%
0.99	-52.96%	-1.60%	1.94%	-53.51%	-3.17%	6.31%	-3.17%	2.08%	4.14%	67.05%	-6.23%	-83.69%	-3.17%

Notes for Table 4: The table reports the numerical solutions of our model in the case where country 1 engages in public abatement and country 2 in revenue recycling, when we vary the government efficiency parameter,  $\alpha$ . We use the values of column (B) of Table 1 as a benchmark and then we compute all the other values as percentages of this benchmark.

Table 5: Numerical Results — Varying the Cost of ER&D,  $k$

$k$	$t_1$	$s_2$	$r_1$	$r_2$	$q_1$	$q_2$	$q_1+q_2$	$q_1/(q_1+q_2)$	$SW_1$	$SW_2$	$E_1$	$E_2$
2.5	-1.26%	4.57%	-21.01%	-18.20%	0.55%	-0.85%	-0.10%	0.65%	-1.44%	-2.50%	4.60%	4.57%
3	-2.14%	7.88%	-34.76%	-30.96%	0.90%	-1.37%	-0.15%	1.05%	-2.47%	-4.28%	7.65%	7.88%
3.5	-2.78%	10.39%	-44.45%	-40.36%	1.13%	-1.69%	-0.18%	1.31%	-3.25%	-5.59%	9.79%	10.39%
4	-3.26%	12.37%	-51.63%	-47.56%	1.29%	-1.90%	-0.20%	1.49%	-3.87%	-6.61%	11.37%	12.37%
4.5	-3.63%	13.96%	-57.17%	-53.25%	1.40%	-2.04%	-0.20%	1.61%	-4.37%	-7.42%	12.59%	13.96%
5	-3.92%	15.27%	-61.57%	-57.84%	1.49%	-2.14%	-0.20%	1.69%	-4.79%	-8.08%	13.54%	15.27%
5.5	-4.16%	16.37%	-65.15%	-61.63%	1.55%	-2.20%	-0.20%	1.75%	-5.15%	-8.63%	14.31%	16.37%
6	-4.35%	17.31%	-68.12%	-64.81%	1.59%	-2.24%	-0.19%	1.79%	-5.45%	-9.09%	14.95%	17.31%
6.5	-4.51%	18.11%	-70.62%	-67.51%	1.63%	-2.27%	-0.19%	1.82%	-5.71%	-9.48%	15.48%	18.11%
7	-4.65%	18.82%	-72.76%	-69.82%	1.65%	-2.29%	-0.18%	1.84%	-5.95%	-9.82%	15.93%	18.82%
7.5	-4.76%	19.43%	-74.60%	-71.84%	1.68%	-2.30%	-0.17%	1.85%	-6.15%	-10.12%	16.31%	19.43%
8	-4.86%	19.98%	-76.22%	-73.60%	1.69%	-2.30%	-0.17%	1.86%	-6.33%	-10.38%	16.64%	19.98%
8.5	-4.95%	20.47%	-77.63%	-75.16%	1.70%	-2.30%	-0.16%	1.87%	-6.50%	-10.61%	16.93%	20.47%
9	-5.02%	20.91%	-78.89%	-76.55%	1.71%	-2.30%	-0.15%	1.87%	-6.65%	-10.81%	17.19%	20.91%
9.5	-5.09%	21.30%	-80.02%	-77.79%	1.72%	-2.29%	-0.15%	1.87%	-6.78%	-11.00%	17.42%	21.30%
10	-5.15%	21.65%	-81.03%	-78.91%	1.73%	-2.28%	-0.14%	1.86%	-6.90%	-11.16%	17.62%	21.65%

Notes for Table 5: The table reports the numerical solutions of our model in the case where country 1 engages in public abatement and country 2 imposes an ERS, when we vary the cost of environmental R&D,  $k$ . We use the values of column (C) of Table 1 as a benchmark and then we compute all the other values as percentages of this benchmark.

Table 6: Numerical Results — Varying the Demand Parameter,  $B$

$B$	$t_1$	$s_2$	$r_1$	$r_2$	$q_1$	$q_2$	$q_1+q_2$	$q_1/(q_1+q_2)$	$SW_1$	$SW_2$	$E_1$	$E_2$
20	-33.34%	-33.33%	-33.34%	-33.33%	-33.33%	-33.33%	-33.33%	0.00%	-58.33%	-55.56%	-25.10%	-33.33%
25	-16.23%	-16.63%	-16.23%	-16.63%	-16.74%	-16.63%	-16.69%	-0.06%	-32.67%	-30.50%	-11.83%	-16.63%
35	15.34%	16.56%	15.34%	16.56%	16.90%	16.56%	16.74%	0.14%	40.03%	35.86%	10.51%	16.56%
40	29.78%	33.04%	29.78%	33.04%	33.96%	33.04%	33.53%	0.32%	87.74%	77.00%	19.81%	33.04%
45	43.31%	49.45%	43.33%	49.45%	51.19%	49.45%	50.38%	0.54%	143.39%	123.35%	28.03%	49.45%
50	56.01%	65.79%	56.01%	65.79%	68.56%	65.79%	67.27%	0.77%	207.21%	174.85%	35.27%	65.79%
55	67.84%	82.05%	67.84%	82.05%	86.09%	82.05%	84.21%	1.02%	279.38%	231.44%	41.63%	82.05%
60	78.86%	98.26%	78.86%	98.25%	103.76%	98.25%	101.20%	1.27%	360.08%	293.05%	47.21%	98.25%
65	89.10%	114.39%	89.10%	114.39%	121.57%	114.39%	118.23%	1.53%	449.44%	359.63%	52.11%	114.39%
70	98.61%	130.47%	98.61%	130.47%	139.51%	130.46%	135.30%	1.79%	547.57%	431.14%	56.40%	130.47%
75	107.43%	146.48%	107.43%	146.48%	157.57%	146.48%	152.42%	2.04%	654.57%	507.54%	60.17%	146.48%
80	115.60%	162.45%	115.60%	162.45%	175.75%	162.45%	169.56%	2.30%	770.51%	588.79%	63.47%	162.45%

Notes for Table 6: The table reports the numerical solutions of our model in the case where country 1 engages in public abatement and country 2 imposes an ERS, when we vary the international demand parameter,  $B$ . We use the values of column (C) of Table 1 as a benchmark and then we compute all the other values as percentages of this benchmark.



Table 7: Numerical Results — Varying the Government Efficiency,  $c$

$\alpha$	$t_1$	$s_2$	$r_1$	$r_2$	$q_1$	$q_2$	$q_1+q_2$	$q_1/(q_1+q_2)$	$SW_1$	$SW_2$	$E_1$	$E_2$
0.1	2.61%	0.21%	2.61%	0.21%	-0.45%	0.21%	-0.14%	-0.31%	10.56%	0.42%	-16.74%	0.21%
0.2	-8%	-1%	-8%	-1%	1%	-1%	0%	1%	27%	-1%	-39%	-1%
0.3	-21.26%	-1.72%	-21.26%	-1.72%	3.67%	-1.72%	1.17%	2.47%	38.75%	-3.40%	-53.12%	-1.72%
0.4	-32.55%	-2.63%	-32.55%	-2.63%	5.62%	-2.63%	1.80%	3.75%	46.92%	-5.18%	-62.73%	-2.63%
0.5	-41.62%	-3.36%	-41.62%	-3.36%	7.18%	-3.36%	2.30%	4.78%	52.84%	-6.60%	-69.34%	-3.36%
0.6	-48.82%	-3.94%	-48.82%	-3.94%	8.43%	-3.94%	2.69%	5.58%	57.28%	-7.72%	-74.06%	-3.94%
0.7	-54.57%	-4.40%	-54.57%	-4.40%	9.42%	-4.40%	3.01%	6.22%	60.70%	-8.61%	-77.57%	-4.40%
0.8	-59.22%	-4.78%	-59.22%	-4.78%	10.22%	-4.78%	3.27%	6.73%	63.42%	-9.33%	-80.27%	-4.78%
0.9	-63.05%	-5.09%	-63.05%	-5.09%	10.88%	-5.09%	3.48%	7.15%	65.62%	-9.91%	-82.40%	-5.09%
0.99	-65.95%	-5.32%	-65.95%	-5.32%	11.38%	-5.32%	3.64%	7.47%	67.28%	-10.36%	-83.97%	-5.32%

Notes for Table 7: The table reports the numerical solutions of our model in the case where country 1 engages in public abatement and country 2 imposes an ERS, when we vary the government efficiency parameter,  $\alpha$ . We use the values of column (C) of Table 1 as a benchmark and then we compute all the other values as percentages of this benchmark.

Table 8: Numerical Results — Varying the Cost of ER&D,  $k$

$k$	$t_1$	$\delta$	$s_2$	$r_1$	$r_2$	$q_1$	$q_2$	$q_1+q_2$	$q_1/(q_1+q_2)$	$SW_1$	$SW_2$	$E_1$	$E_2$
2.5	2.84%	-3.64%	5.51%	-15.39%	-17.47%	-1.68%	0.03%	-0.80%	-0.89%	-1.74%	-0.75%	3.89%	5.51%
3	4.95%	-6.36%	9.57%	-26.57%	-29.87%	-3.03%	0.18%	-1.37%	-1.68%	-3.10%	-1.25%	6.54%	9.57%
3.5	6.59%	-8.49%	12.71%	-35.08%	-39.11%	-4.13%	0.37%	-1.81%	-2.37%	-4.19%	-1.59%	8.44%	12.71%
4	7.91%	-10.18%	15.20%	-41.78%	-46.24%	-5.06%	0.57%	-2.15%	-2.97%	-5.08%	-1.84%	9.86%	15.20%
4.5	8.99%	-11.58%	17.24%	-47.21%	-51.90%	-5.84%	0.78%	-2.42%	-3.50%	-5.83%	-2.02%	10.96%	17.24%
5	9.90%	-12.75%	18.93%	-51.69%	-56.50%	-6.52%	0.97%	-2.65%	-3.98%	-6.46%	-2.15%	11.83%	18.93%
5.5	10.68%	-13.75%	20.36%	-55.46%	-60.32%	-7.11%	1.15%	-2.84%	-4.40%	-7.01%	-2.25%	12.53%	20.36%
6	11.34%	-14.60%	21.59%	-58.67%	-63.52%	-7.63%	1.33%	-3.01%	-4.77%	-7.48%	-2.33%	13.10%	21.59%
6.5	11.93%	-15.35%	22.66%	-61.45%	-66.26%	-8.10%	1.49%	-3.15%	-5.11%	-7.90%	-2.39%	13.58%	22.66%
7	12.44%	-16.02%	23.59%	-63.88%	-68.61%	-8.51%	1.63%	-3.27%	-5.42%	-8.27%	-2.43%	13.98%	23.59%
7.5	12.90%	-16.61%	24.41%	-66.01%	-70.67%	-8.88%	1.77%	-3.38%	-5.70%	-8.60%	-2.47%	14.33%	24.41%
8	13.31%	-17.14%	25.14%	-67.90%	-72.47%	-9.22%	1.90%	-3.47%	-5.95%	-8.90%	-2.50%	14.63%	25.14%
8.5	13.67%	-17.60%	25.80%	-69.60%	-74.07%	-9.52%	2.02%	-3.56%	-6.18%	-9.17%	-2.52%	14.89%	25.80%
9	14.00%	-18.03%	26.39%	-71.12%	-75.49%	-9.80%	2.13%	-3.64%	-6.39%	-9.41%	-2.54%	15.11%	26.39%
9.5	14.31%	-18.42%	26.92%	-72.49%	-76.77%	-10.05%	2.23%	-3.70%	-6.59%	-9.63%	-2.56%	15.32%	26.92%
10	14.59%	-18.79%	27.41%	-73.74%	-77.92%	-10.28%	2.33%	-3.77%	-6.77%	-9.83%	-2.57%	15.50%	27.41%

Notes for Table 8: The table reports the numerical solutions of our model in the case when the country 1 uses revenue recycling and country 2 an ERS, while the only parameter that varies is the cost of ER&D,  $k$ . We use the values of column (D) of Table 1 as a benchmark and then we compute all the other values as percentages of this benchmark.

Table 9: Numerical Simulations — Varying the Demand Parameter,  $B$

$B$	$t_1$	$\delta$	$s_2$	$r_1$	$r_2$	$q_1$	$q_2$	$q_1+q_2$	$q_1/(q_1+q_2)$	$SW_1$	$SW_2$	$E_1$	$E_2$
20	-18.35%	31.17%	-33.33%	-33.33%	-33.33%	-33.33%	-33.33%	-33.33%	0.00%	-55.56%	-55.56%	-33.33%	-33.33%
25	-8.71%	14.84%	-16.67%	-16.67%	-16.67%	-16.67%	-16.67%	-16.67%	0.00%	-30.56%	-30.56%	-16.67%	-16.67%
35	8.01%	-13.60%	16.67%	16.67%	16.67%	16.67%	16.67%	16.67%	0.00%	36.11%	36.11%	16.67%	16.67%
40	15.47%	-26.28%	33.33%	33.33%	33.33%	33.33%	33.33%	33.33%	0.00%	77.78%	77.78%	33.33%	33.33%
45	22.47%	-38.15%	50.00%	50.00%	50.00%	50.00%	50.00%	50.00%	0.00%	125.00%	125.00%	50.00%	50.00%
50	31.76%	-44.98%	66.67%	66.67%	66.67%	66.67%	66.67%	66.67%	0.00%	177.78%	177.78%	66.67%	66.67%
55	38.19%	-55.48%	83.33%	83.33%	83.33%	83.33%	83.33%	83.33%	0.00%	236.11%	236.11%	83.33%	83.33%
60	44.34%	-65.49%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	0.00%	300.00%	300.00%	100.00%	100.00%
65	50.23%	-75.09%	116.67%	116.67%	116.67%	116.67%	116.67%	116.67%	0.00%	369.44%	369.44%	116.67%	116.67%
70	55.90%	-84.35%	133.33%	133.33%	133.33%	133.33%	133.33%	133.33%	0.00%	444.45%	444.44%	133.33%	133.33%
75	61.38%	-93.28%	150.00%	150.00%	150.00%	150.00%	150.00%	150.00%	0.00%	525.00%	525.00%	150.00%	150.00%

Notes for Table 9: The table reports the numerical solutions of our model in the case when the country 1 uses revenue recycling and country 2 an ERS, while the only parameter that varies is the market size parameter,  $B$ . We use the values of column (D) of Table 1 as a benchmark and then we compute all the other values as percentages of this benchmark.