MEMORANDUM

No 21/2006

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ISSN: 0809-8786

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University of Oslo

This series is published by the
University of Oslo
Department of Economics

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28 September 2006

Climate agreements: emission quotas versus technology policies[a]

Rolf Golombek[b] and Michael Hoel[c]

Abstract

The Kyoto Agreement is the result of international negotiations over many years. However, because of a number of weaknesses, different sorts of climate agreement have been suggested: for example, coordinated R&D activities that reduce abatement costs for all firms. We will compare an agreement focusing only on emissions (a Kyoto type of agreement) with an agreement focusing only on technology, assuming that the costs of abatement are affected by R&D in all firms through technology spillovers. In an emissions agreement, emissions should be restricted to the extent that the carbon price exceeds the Pigovian level. For sufficiently low technology spillovers, an emissions agreement is more efficient than a technology agreement specifying an R&D subsidy to be imposed on all firms in all countries. The opposite may hold if technology spillovers are sufficiently large. Finally, an alternative technology agreement specifying R&D expenditure in each country is more efficient than an agreement specifying an R&D subsidy.

Keywords: climate policy, international climate agreements, R&D policy, technology spillovers

JEL classification: H23, O30, Q20, Q28, Q48

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[a] This article was written during our participation in the ‘Environmental economics: policy instruments, technology development and international cooperation’ project at the Centre for Advanced Study (CAS) at the Norwegian Academy of Science and Letters in Oslo in 2005–6. We are grateful for many useful comments and suggestions from the participants in this group, and in particular from Cathrine Hagem. CAS’s financial, administrative and professional support is much appreciated. The support of the Research Council of Norway, under the RENERGI programme, is also gratefully acknowledged.

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1. Introduction

The Kyoto Protocol is the result of international negotiations over many years. If honoured, it will reduce emissions during the period 2008–12 compared to ‘business-as-usual’ (BAU) emissions. There are, however, many weaknesses with the agreement. The most important is limited coverage: although most countries in the world have ratified the agreement, the Kyoto Protocol imposes concrete emission limits on fewer than 40 countries. This group of countries is responsible for only about a third of global emissions of greenhouse gases (GHG) in 2003 (calculations based on United Nations data). Second, the restrictions imposed by the agreement are weak: the difference between the sum of BAU emissions and the sum of emissions under the Kyoto Agreement is quite small (about 1 per cent of global GHG emissions: see, for example, Hagem and Holtsmark, 2001). Third, it is not clear whether there will be any follow-up to the Kyoto Agreement after 2012. And even if there is, it is not clear whether it will include more countries and/or give the signatories stricter emission limits (fewer quotas) than the present agreement.

Given the weaknesses and uncertainties relating to the ‘Kyoto track’, several economists and others have asked whether different types of agreement might be designed to support large reductions of GHG emissions. One idea that has been proposed is to focus not directly on emissions but instead on policies affecting emissions. An obvious candidate would be a common carbon tax, as discussed by, for example, Cooper (1998), Wiener (1999), Victor (2001) and Victor and Coben (2005). Another idea would be to also focus on technology improvements in order to reduce abatement costs, thus increasing countries’ willingness to undertake significant emission reductions. For example, it might be beneficial to supplement a Kyoto type of agreement with elements relating to technology development. This will be the case if technology development is related to the R&D undertaken by each country and there are technology spillovers across countries: that is, each country’s technology depends not only on its own R&D investments but also on R&D by other countries. Even with no explicit agreement on emissions, an agreement leading to increased R&D, and thus to lower abatement costs, may result in a reduction in emissions. This is the background for proposals by, for example, Barrett (2003, Section 15.13) for a climate agreement focusing mainly on technology development. In the present paper we give a more detailed analysis of agreements focusing on technology development, henceforth termed technology agreements. In addition, we compare Kyoto types of agreement (quota agreements) with technology agreements.

As mentioned above, the process leading to the Kyoto Agreement indicates that most countries are reluctant to sign an international quota agreement. One reason is that, under quota agreements, some sectors will bear a disproportionately high share of total abatement costs. Workers and owners in such sectors will often be successful in lobbying against stringent abatement measures, thus making it difficult to reach an international agreement that substantially reduces emissions. In contrast, the costs of technology development will typically be more evenly shared by everyone in the economy, as these costs will be borne by all tax payers (to finance public R&D or to give tax breaks/subsidies to private firms undertaking R&D). Some sectors of the economy (producing ‘knowledge’) will even gain from such technology development and might thus engage in lobbying for a technology agreement.

While a technology-based agreement may have fewer problems with lobbying than a traditional quota agreement, there may be other types of problem in establishing a technology agreement. For example, while emissions are well defined and relatively easily monitored, the same is not true for R&D activities. If a country is required by international agreement to spend more on R&D than it would naturally chose to do, it would be relatively easy for that country to underspend on R&D but report other expenditure as R&D-based.

An alternative to specifying R&D expenditure in an agreement could be to state which policies signatories should use to influence R&D investments by private firms. It seems likely that it is easier to monitor whether countries are using the specified policies than monitor R&D expenditure. However, agreements specifying policies of this type are not without problems: policies aimed at influencing R&D investment by private firms are often an integral part of a country’s tax system and are also related to other domestic instruments, at both national and local (for example, municipality) levels. As tax systems and other policies vary significantly across countries, in practice it will hardly be feasible for a country (or some international agency) to verify all aspects of other countries’ R&D policies. Suppose an international climate agreement dictates policy instruments that affect R&D investment in all signatory countries. Each country will have some level of R&D investment that is individually rational for the country itself but, due to the spillover externality typically, will differ from what an international agreement aims at. Given the policies imposed by the international agreement, each country will have an incentive to try to set various non-verifiable domestic policy instruments so that the country achieves its individually rational level of R&D investment.

Whatever type of climate agreement one tries to establish, it is of vital interest to achieve broad participation and to significantly influence the behaviour of the signatories (as compared with the case of no cooperation). It is well known from the literature that free-riding may undermine the possibility of reaching broad participation in an emissions-based agreement. If a country stays outside an agreement, it can enjoy (almost) the same benefits of reduced emissions as if it participates in the agreement, while not bearing any of the costs of reducing emissions.

The issue of free-riding, together with the possibility of creating stable coalitions, has been discussed extensively during the last couple of decades in the context of emissions-based agreements (see, for example, Barrett (2003) for a thorough discussion of this and related matters). The literature on coalition stability and free-rider incentives in the context of technology agreements is much smaller. Two important contributions are Barrett (2006) and Buchner and Carraro (2005). From these contributions it is not obvious which type of agreement – emissions-based or technology-based – is most likely to be successful in the sense of being less vulnerable to free-riding. The conclusion of Barrett (2006) is that it may be just as difficult to reach a technology agreement as it is to reach an emissions-based agreement. On the other hand, Buchner and Carraro (2005) find that the grand coalition may be stable under the technology agreement they consider. There seem to be two important assumptions behind this optimistic conclusion. First, signatories can prevent non-signatories from obtaining knowledge that signatories have got through their R&D. Second, the knowledge created is beneficial in the sense that it not only lowers abatement costs but also gives a country increased output in the absence of any abatement.

The preceding discussion suggests that factors like free-riding incentives, burden sharing, lobbying and spillovers from the climate agreement are important in determining whether countries manage to agree on establishing a climate agreement, what type of agreement is established (if any) and the number of countries signing the agreement. The purpose of the present paper is not to examine these issues. Rather we take it for granted that a climate agreement is established with full participation. Our concern is to compare two types of agreement. The first is an agreement focusing only on emissions and the second is an agreement focusing only on technology development. In addition, we compare these two agreements to standard benchmark outcomes: namely, no cooperation and the first-best cooperative outcome.

We examine the four cases within a simple model in which technology development is R&D-driven and there are technology spillovers among countries. Regarding technology agreements, we mainly consider an agreement that specifies a policy that all countries must use to influence R&D (see preceding discussion). In the formal model used, this policy is simply a particular subsidy rate for R&D expenditure, although such a subsidy will in practice usually be an integral part of the tax systems of the countries. We also briefly consider an agreement that directly specifies R&D expenditure in each country.

The main assumptions used throughout are presented in Section 2. Firms choose R&D expenditure in order to maximize profits. R&D is beneficial not only to the particular firm but to all other firms through technology spillovers. For each firm, the choice of R&D expenditure depends on the R&D subsidy, which under a quota agreement is determined by each government in order to maximize the welfare of the country, whereas the group of all countries determines a common subsidy rate under a technology agreement.

The benchmark cases of no cooperation and first-best cooperation are analysed in Sections 3 and 4. Second-best climate agreements are considered in Sections 5–9. In Section 6 we derive some properties from an agreement focusing only on emissions reduction. Under this agreement the group of all countries determines emissions reduction in each country, taking into account how the individual countries and firms will respond to the agreement in the next stages of the game. We show that an ideally designed agreement of this type should restrict emissions so much that the carbon price (tax or quota price) should be higher than the Pigovian level (see also Golombek and Hoel, 2006). The interpretation is that since cross-country technology spillovers are not internalized in the agreement, countries should be given an extra incentive to undertake R&D. This is accomplished through a price of carbon that is higher than it would have been had these technology spillovers been internalized.

A technology agreement specifying an R&D subsidy is considered in Section 7. We show that the optimal subsidy will be higher than without any cooperation, but it may be higher or lower than the subsidy in the first-best outcome, depending on the size of third-order derivatives of the abatement cost function. Under this type of agreement, each country chooses its own abatement level. We show that abatement is chosen so that the price of carbon is lower than the price under no cooperation. A comparison of this type of agreement with a quota agreement is given in Section 8. We show that for sufficiently low technology spillovers, a second-best quota agreement is more efficient (that is, it gives each country a higher welfare level) than a second-best technology agreement. The opposite may hold if technology spillovers are sufficiently large.

Section 9 gives a brief analysis of an agreement specifying R&D expenditure in each country. We show that with such an agreement, R&D investments should be set so that the (explicit or implicit) subsidy to R&D expenditure is larger than in the first-best optimum. Moreover, an agreement specifying R&D expenditure is (if feasible) more efficient than an agreement specifying an R&D subsidy. Finally, Section 10 concludes.

2. Emissions and technology

In order to keep the analysis as simple as possible, we use a static framework, thus ignoring, for example, the fact that GHG emissions are stock pollutants. Moreover, all types of uncertainty – like the rate of return on R&D investments - are disregarded. Finally, all countries are assumed identical, and all firms within each country are also identical. While this of course is a drastic simplification, we believe the analysis nevertheless gives insight that is relevant in the real world.

We assume there are m identical firms in each of n identical countries. All firms invest in R&D and, to simplify, we disregard patents. We assume that the technology level of a particular domestic firm depends on its own R&D investments (X) and the amount of R&D investments by other firms in that country (x), as well as investments in R&D by all firms abroad (x^*).[1]

While technology spillovers allow other firms to benefit from a firm's R&D investment, technology diffusion is not perfect. For any firm, only part ($0 < \gamma < 1$) of other firms' R&D investment is beneficial. To simplify the analysis, it is assumed that the technology spillovers are the same between firms in the same country and between firms in different countries.[2] The technology level of a representative domestic firm (Y) is thus given by

$$Y = X + \gamma\left[(m-1)x + (n-1)mx^*\right] \tag{1}$$

In (1) we have assumed an additive structure of technology spillovers: that is, the technology level of a firm depends on the sum all firms' R&D investment, corrected by the technology diffusion parameter γ. Hence R&D investment, corrected by the technology diffusion parameter, is a perfect substitute.[3]

The technology level of a particular foreign firm (Y^*) is determined – seen from the domestic country – in a similar way to (1):

$$Y^* = X^* + \gamma\left[mx + (m-1+m(n-2))x^*\right] \tag{2}$$

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[1] With identical firms, R&D investment will be equal in all firms in equilibrium. However, in order to find the equilibrium it is expedient to distinguish between the levels of R&D investment in a particular domestic firm, in other domestic firms and in foreign firms.

[2] Our main results would not be changed if instead we had assumed that the spillover parameter γ was different between firms in the same country and between other firms.

[3] The modelling assumption of linear spillovers goes back at least to Spence (1984). An alternative view is found in Cohen and Levinthal (1989), where it is argued that the ability of a firm to learn from other firms may depend on its own R&D effort. Graevenitz (2002) discusses the policy implications of different modelling assumptions, whereas Golombek and Hoel (2004) apply the ideas of Cohen and Levinthal on climate policy.

In (2) the first term is R&D investment in the particular foreign firm, while the terms in the square brackets are the spillover effect from the 'domestic' firms plus the spillover effects from all other firms.

For the subsequent analysis, it is useful to have an equilibrium relationship between R&D investment and technology levels. From (1), (2) and the equilibrium conditions $X = x$, $X^* = x^*$, $Y = y$ and $Y^* = y^*$ we obtain

$$x = hy + (H - h)y^* \tag{3}$$

where the constants *h* and *H* are given by

$$h = \frac{1 + (nm - m - 1)\gamma}{1 + (nm - 2)\gamma - (nm - 1)\gamma^2} \tag{4}$$

$$H = \frac{1}{1 + (nm - 1)\gamma} \tag{5}$$

It is straightforward to show that $0 < H < h$ and $H < 1$.[4]

Note that in an equilibrium with $y = y^*$ (3) reduces to

$$x = Hy \tag{6}$$

Firms are identical, and each firm's income is increasing – up to a limit – in its own emissions. Put differently, each firm has an emission level that would follow from its production decisions if these decisions were made without considering the environmental impact of the emissions. This is often called the firm's BAU emission level and we denote it by $b(y)$. Reducing emissions below the business-as-usual level is costly: that is, it reduces the firm's income.

We formalize the cost of reducing emissions by the income function $R(e, y)$, which we assume is concave and differentiable with non-negative first derivatives. Moreover, we assume that the maximal income obtainable is independent of the technology level: that is, we are focusing on technology development that reduces abatement costs, not 'regular' technology improvements increasing the maximal output the economy can produce. Formally, we assume that $\max_e R(e, y) = \bar{R}$, where $\bar{R}$ is independent of *y*. The lowest possible emission level satisfying $R(e, y) = \bar{R}$ is the business-as-usual emission level $b(y)$.

From this definition and the concavity of *R*, it follows that $R_e(e, y) > 0$ for $e < b(y)$. We also assume that when $e < b(y)$, technology development reduces both total and marginal abatement costs: that is, $R_y > 0$ and $R_{ey} < 0$ for $e < b(y)$. As technology improves, the slope of the curve *R* thus becomes flatter. This is illustrated in Figure 1, where the solid line represents the old technology, y^0, and the dashed line represents the new technology, ($y^1 > y^0$). In this figure the business-as-usual emission level is reduced from e^0 to e^1 as technology improves from y^0 to y^1.

In the subsequent analysis, we assume that emissions in each country are set either through the international agreement or by the government of the country. The latter applies if there is no climate agreement (Section 3) or if the climate agreement does not regulate emissions (Section 7). With identical firms, emission levels are equal to $1/m$ of the country emission level. The only variable chosen by each firm is the level of its R&D investment. The cost of R&D investment is normalized to one. However, we assume that the domestic government subsidizes R&D investment by the rate σ (and the governments abroad subsidize R&D investment by the rate σ^*).[5] A particular domestic firm maximizes its profits by choosing R&D investments (*X*) to maximize

$$R(E, Y) - (1 - \sigma)X \tag{7}$$

where the second term is net R&D expenditure and the technology level *Y* is given by (1). All domestic firms solve a similar problem, and they will thus choose the same

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[4] $h < 1$ if $\gamma < \frac{m-1}{nm-1}$, which is approximately equal to $\frac{1}{n}$ if *m* is 'large'.

[5] In our simple model, where all R&D investment reduces abatement costs, subsidizing R&D is an obvious policy to encourage such investment. In a more complex setting, where some types of R&D investment might increase BAU emissions, and it is difficult for the regulator to distinguish between

values in equilibrium ($Y = y$). The first-order conditions for this problem are thus given by

$$R_y(e, y) = 1 - \sigma \tag{8}$$

According to (8), marginal costs of R&D investment ($1-\sigma$) should equal marginal benefit of these investments (R_y).

It follows from (8) that y is a function of e and σ:

$$y = y(e, \sigma) \tag{9}$$

From the properties of the income function it follows that

$$y_e(e,\sigma) = -\frac{R_{ey}}{R_{yy}} < 0 \quad \text{and} \quad y_\sigma(e,\sigma) = -\frac{1}{R_{yy}} > 0 \tag{10}$$

Foreign firms also minimize their total costs, hence the technology level of foreign firms y^* depends on e^* and σ^*. On the other hand, as both y and y^* depend on R&D investments in all countries – see (1) and (2) – R&D investment in any firm depends on e, e^*, σ and σ^*. So, if the domestic government changes its R&D subsidy, R&D investment will be affected in all domestic and foreign firms, and the technology level of domestic firms will change. Similarly, a change in the foreign R&D subsidy will affect R&D investment in all domestic and foreign firms, as well as the technology level of foreign firms, but will have no impact on the technology level of domestic firms.

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different types of R&D investment, subsidizing R&D might not be a good policy. See, for example,

3. No international agreement

In the absence of international cooperation, each country chooses its own carbon emissions and technology subsidy (σ) taking emissions (e*) and technology subsidies ($\sigma *$) of other countries as given. From the discussion after (9) and (10) it follows that this is equivalent to choosing y when $y*$ is given.

Total net benefits of a country are given by its income minus its R&D expenditure and environmental costs. In equilibrium all domestic firms must have the same emission levels (e), as well as identical amounts of R&D investment (x). Hence, total net benefits[6] are given by

$$R(e,y)-x-\delta[e+(n-1)e*] \tag{11}$$

where for each country the environmental damage is assumed to be proportional to the sum of total emissions $[e+(n-1)e^{*}]$. The marginal environmental cost for each country is δ.[7]

Inserting (3) and maximizing (11) with respect to e and y gives

$$R_e(e,y)=\delta \tag{12}$$

and

$$R_y(e,y)=h \tag{13}$$

Equation (12) is the standard result: that is, without international cooperation marginal costs of abatement should equal the country's own marginal benefit of abatement. Rewriting (13) as $R_y h^{-1}=1$ gives us a straightforward interpretation: the marginal benefits of R&D investment when domestic spillovers are taken into account ($R_y h^{-1}$) should equal marginal costs of R&D investment. Using (8) together with (13), we see that the technology subsidy in the non-cooperative equilibrium (N) is given by

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Lund (1994) for a detailed discussion.

[6] To simplify notation, we divide each country's net benefits by the number of firms, since this is exogenous and identical for all countries.

$$\sigma^N = 1 - h \tag{14}$$

Note in particular that this equation implies that the subsidy is independent of the income function (*R*) and the environmental damage cost (δ). This reflects the additive structure of (1).

The case without any agreement is given at *N* in Figure 2. It is easily verified that the properties of the function *R* imply that the curves defined by $R_e(e, y) = \delta$ and $R_y(e, y) = h$ – corresponding to equations (12) and (13) – are downward-sloping in the (*e,y*) diagram and that $R_e(e, y) = \delta$ is steeper than $R_y(e, y) = h$. At the intersection point *N* of these two curves both equations (12) and (13) hold, so that this point gives the equilibrium in the absence of any agreement.

4. The first-best social optimum

In the first-best optimum all firms must have the same emission level, as well as identical amounts of R&D investment (x). Hence, in this case, total net benefits per country are given – using (6) – by

$$R(e, y) - Hy - \delta ne \tag{15}$$

Maximizing (15) with respect to abatement *e* and R&D investment *x* gives

$$R_e(e, y) = n\delta \tag{16}$$

and

$$R_y(e, y) = H \tag{17}$$

Equation (16) is the standard requirement that marginal costs of abatement should equal the sum of marginal environmental costs for all countries: that is, the Pigovian level. Equation (17) is similar to what we found for the non-cooperative case, except that now *all* spillovers are taken into account when calculating the marginal benefits

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[7] None of our main results would change if, instead of the linear damage function, we use a convex environmental damage function.

of R&D ($R_y H^{-1}$), and not only domestic spillovers, as in the non-cooperative case. Using (8) together with (17), we see that the technology subsidy in the first-best optimum (F) is given by

$$\sigma^F = 1 - H \tag{18}$$

The first-best optimum is given at F in Figure 2. Like the curves defined by $R_e(e,y) = \delta$ and $R_y(e,y) = h$, the curves defined by $R_e(e,y) = n\delta$ and $R_y(e,y) = H$ – corresponding to equations (16) and(17) – are downward-sloping, and $R_e(e,y) = n\delta$ is steeper than $R_y(e,y) = H$. At the intersection point F of these two curves both equations (16) and (17) hold, so this point gives the first-best optimum.

Since $n\delta > \delta$, the curve $R_e(e,y) = n\delta$ must lie to the left of the curve $R_e(e,y) = \delta$, and since $H < h$, the curve $R_y(e,y) = H$ must lie above the curve $R_y(e,y) = h$. It thus follows that emissions are lower and R&D investment is higher in the first-best optimum than in the case of no cooperation.

In Figure 2 we have drawn two iso-welfare curves (curves along which net benefits are constant). Along each such line net benefits – given by (15) – are constant, and net benefits are higher the closer the line is to the maximum point, *F*. From the first-order conditions (16) and (17), it also follows that the iso-welfare curves are horizontal at the intersections with $R_e(e,y) = n\delta$ and vertical at the intersections with $R_y(e,y) = H$. They must therefore also be upward-sloping at *N*. In the subsequent sections we make use of these properties of the iso-welfare curves.

5. Second-best agreements

We now turn to second-best international climate agreements, which regulate *either* emissions *or* technology policies, but not both. Both types of agreement are designed so that total net benefits, given by (15), are as large as possible. The difference between the two agreements is the constraints given by the countries' responses to the agreement.

In a quota agreement, the emission levels (for all countries and thus for all firms) are set in the agreement. Countries respond to this agreement by choosing their technology policies (that is, their technology subsidies) in a non-cooperate manner. This leads to a particular technology level, which will depend on the emission level set in the agreement:

$$y = y^Q(e) \tag{19}$$

The properties of the function in (19), and the implications for the maximization of (15), are discussed in Section 6.

In a technology agreement, the technology subsidies (for all countries and thus for all firms) are set in the agreement. Countries respond to this agreement by choosing their emission levels in a non-cooperate manner. This leads to a particular emission level, which will depend on the technology subsidy set in the agreement:

$$e = e^T(\sigma) \tag{20}$$

The properties of the function in (20), and the implications for the maximization of (15), are discussed in Section 7.

6. A quota agreement

Consider an agreement that specifies emissions for each country and thus also for each firm. Each country will, in this case, want to choose σ, and thus y from (9), to maximize (11) subject to (3), taking e, e^* and σ^*, and thus y^* from (9), as given. This maximization problem has $R_y(e, y) = h$ as its first-order condition: that is, the same condition as we derived for the case of no international agreement. From the first-order condition of the firms' profit maximization problem (8) we thus have the following proposition:

Proposition 1: Countries will choose the same R&D subsidy under a quota agreement as they would without international agreement.

The result above implies that the function $y^Q(e)$ in (19) is implicitly defined by $R_y(e,y)=h$, so that

$$\frac{dy^Q(e)}{de} = -\frac{R_{ye}}{R_{yy}} < 0 \tag{21}$$

We next consider the optimal design of a quota agreement, given that each country responds to the agreement as explained above. The optimal quota agreement is the emission level (e) that maximizes (15) subject to (19). This gives

$$R_e(e,y) - n\delta + \left[R_y(e,y) - H\right]\frac{dy^Q(e)}{de} = 0 \tag{22}$$

From $R_y(e,y)=h$ and $H<h$ it follows that the term in square brackets is positive. Combining (21) and (22) therefore implies that the emission level is set so high in the optimal agreement that

$$R_e(e,y) > n\delta \tag{23}$$

This result may be expressed as follows:

Proposition 2: The abatement level in a second-best quota agreement is set so that the marginal abatement cost exceeds the sum of the marginal environmental costs.

The (second-best) optimal quota agreement is given by *Q* in Figure 3, which replicates the relevant parts of Figure 2. In designing the agreement, one is constrained by the countries' responses to be on the line $R_y(e,y)=h$. The highest sum of net benefits is given where an iso-welfare curve for net benefits is tangent to this line. Since such iso-welfare curves are horizontal at the curve $R_e(e,y)=n\delta$, and $R_y(e,y)=h$ is downward-sloping, this tangency point must be to the left of the curve $R_e(e,y)=n\delta$. All points to the left of the curve $R_e(e,y)=n\delta$, and thus in particular the point *Q*, satisfy the inequality in (23).

7. A technology agreement

Consider an agreement that specifies the technology subsidy, σ, to be used in all countries. Each country will, in this case, want to choose *e*, and thus *y* from (9), to maximize (11) subject to (3), taking e^* and σ^*, and thus y^* from (9), as given. The first-order condition is

$$R_e(e,y(e,\sigma))-\delta+\left[R_y(e,y(e,\sigma))-h\right]y_e(e,\sigma)=0 \tag{24}$$

which implicitly defines the function $e=e^T(\sigma)$ in (20). In Appendix 1 we derive

$$\frac{de^T(\sigma)}{d\sigma}=\frac{(R_y-h)y_{e\sigma}}{P} \tag{25}$$

where *P* is a positive term. We also show that $y_{e\sigma}$ cannot be signed without making further assumptions about the function *R*.[8]

We now consider the optimal design of a technology agreement, given that each country responds to the agreement as explained above. The optimal technology agreement is found by inserting $e=e^T(\sigma)$ and $y=y(e^T(\sigma),\sigma)$ into (15) and maximizing with respect to the subsidy rate. This gives

$$\left[(R_e-n\delta)+(R_y-H)y_e\right]\frac{de^T(\sigma)}{d\sigma}+(R_y-H)y_\sigma=0 \tag{26}$$

Combining this with (24) yields

$$R_y-H=\frac{(n-1)\delta-(h-H)y_e}{y_\sigma}\frac{de^T(\sigma)}{d\sigma} \tag{27}$$

Using (10) and remembering that $h>H$, it is clear that the first fraction in (27) is positive. The sign of the second fraction in (27) is ambiguous – compare the

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[8] $y_{e\sigma}$ has the same sign as $R_{ey}R_{yyy}-R_{yy}R_{eyy}$.

discussion after (25) – and it therefore follows that the sign of $R_y - H$ is ambiguous. Three possible cases are illustrated in Figures 4–6. In all figures we have drawn the curve for $e^T(\sigma)$ – defined by (24) – in addition to the relevant parts of Figure 2. The curve for $e^T(\sigma)$ goes through the point *N* – defined by (12) and (13). Moreover, we see from (25) that this curve is vertical at the point *N*, since $R_y = h$ here. Since $y_e < 0$, it also follows from (24) that the part of the curve that lies above (13) (that is, $R_y < h$) also lies to the right of (12) (that is, $R_e < \delta$). In this part of the diagram it follows from (25) that the curve for $e^T(\sigma)$ is positively sloped if $y_{e\sigma} < 0$, and negatively sloped if $y_{e\sigma} > 0$. Similarly, the part of the curve that lies below (13) (that is, $R_y > h$) also lies to the left of (12) (that is, $R_e > \delta$). In this part of the diagram the curve for $e^T(\sigma)$ is negatively sloped if $y_{e\sigma} < 0$ and positively sloped if $y_{e\sigma} > 0$.

Whatever the sign of $y_{e\sigma}$, the second-best optimum must imply that $R_y(e, y) < h$. The reason for this is that the iso-welfare curves are upward-sloping at *N*, while $e^T(\sigma)$ is vertical at *N*. The second-best optimum must therefore be somewhere on $e^T(\sigma)$ above the curve $R_y(e, y) = h$: that is, somewhere where $R_y(e, y) < h$. From the discussion above we know that $R_e < \delta$ when $R_y(e, y) < h$. We thus have the following Proposition:

Proposition 3: In the second-best optimal technology agreement, each country chooses its emission level so that the marginal abatement cost is lower than it would be without any agreement.

Before interpreting this result, we derive what the optimal R&D subsidy is in a second-best technology agreement. The result $R_y(e, y) < h$, together with (25) and (27), implies that $R(e, y) - H$ must have the opposite sign to $y_{e\sigma}$ and $R(e, y) = H$ if $y_{e\sigma} = 0$. If $y_{e\sigma} = 0$ the R&D subsidy is thus equal to the first-best subsidy – given by (18). This case is illustrated in Figure 4, where the curve $e^T(\sigma)$ – defined by (24) – is vertical since $y_{e\sigma} = 0$. In designing the agreement, the group of all countries is constrained by the countries' response to be on the curve $e^T(\sigma)$. The second-best agreement is the point on this curve with the highest sum of net benefits (welfare). Because the iso-welfare curves are vertical along the curve for $R_y(e,y)=H$, the second-best technology agreement is given by the point T in Figure 4: that is, at the intersection of $R_y(e,y)=H$ and $e^T(\sigma)$. It is clear from Figure 4 that, in this case, emissions are higher and R&D lower than in the first-best optimum.

The case when $y_{e\sigma}>0$ is illustrated in Figure 5. Here we have $R_y<H$, implying that the R&D subsidy is higher than the first-best subsidy – given by (18). It follows from Figure 5 that, compared with the first-best optimum, emissions or R&D investment or both must be higher.

The case $y_{e\sigma}<0$ is illustrated in Figure 6. Here we have $R_y>H$, implying that the R&D subsidy is lower than the first-best subsidy – given by (18) – but higher than the subsidy for the case of no agreement (since $R_y(e,y)<h$). From Figure 6 we see that emissions are higher and R&D investment is lower than in the first-best outcome. In this case, emissions are also higher than they were in the absence of an agreement. Yet, the welfare level is of course higher with the agreement than without, due to R&D investment being higher.

The results in Figures 4–6 may be summarized as follows:

Proposition 4: In the second-best optimal technology agreement, the R&D subsidy is higher than what it would have been without any agreement. The subsidy is also higher, lower or equal to the first-best subsidy depending on whether $R_{ey}R_{yyy}-R_{yy}R_{eyy}$ *is positive, negative or zero.*

We now give an interpretation of Proposition 3. Since the R&D subsidy in a technology agreement is higher than what a country would have chosen without any agreement, the R&D investment of the country is distorted away from the country's individually rational choice. We know that R&D investment is lower the higher the country's emissions – $y_e(e,\sigma)<0$ from (10). Hence, the distortion is reduced by increasing emissions beyond the level the country would had chosen in the absence of any agreement. The individually rational response of a country facing an R&D subsidy higher than its individually rational subsidy level is thus to choose higher emissions than the level equating marginal abatement costs with the country's marginal environmental costs.

8. A comparison of the two second-best agreements

Comparing the quota and technology agreements, most results regarding emission levels and R&D expenditure are ambiguous. The only general result from Figures 4–6 is that the equilibrium point *T* cannot lie south-west of the equilibrium point *Q*. We thus have the following relatively weak proposition:

Proposition 5: A second-best technology agreement has higher emissions and/or higher R&D expenditures than a second-best quota agreement.

With suitable assumptions about the income function *R*, we can of course obtain sharper results. If, for example, $R_{ey}R_{yyy} - R_{yy}R_{eyy} \leq 0$, implying $y_{e\sigma} \leq 0$, it is easy to confirm from Figures 4 and 6 that *T* must lie to the right of *Q*: that is, that emissions are higher with a technology agreement than with a quota agreement. Without this assumption, we cannot rule out the possibility of *T* lying to the left of *Q*, which can occur if the curves $R_e = \delta$ and $e^T(\sigma)$ bend backwards sufficiently strongly.

The most interesting comparison between the two types of agreement is with regard to welfare levels. From Figures 4–6 it is not obvious whether the iso-welfare curve going through *Q* is closer to the first-best outcome, *F*, than the iso-welfare curve going through *T*. Both are in fact possible. To see this, consider first the limiting case of no technology spillovers. In this case, the first-best agreement does not specify any R&D subsidies for countries to use. There should be no R&D subsidy in this case, and this is also the individually rational choice of each country. The first-best agreement is thus a pure quota agreement. A technology agreement will, in this case, have a lower welfare level than the quota agreement.

To see the possibility of a technology agreement giving a higher welfare level than a quota agreement, consider a situation in which technology spillovers are so large that H is 'small'. In this case, the first-best optimum may imply such large R&D investment that the socially optimal emission level is zero. An outcome of this sort is characterized by

$$R_e(0, y) \le n\delta \tag{28}$$

and

$$R_y(0, y) = H \tag{29}$$

instead of (16) and (17). Denote the value of y defined by (29) by y^0. If (24) holds with $\le$ when $(e, y) = (0, y^0)$ and $\sigma = 1 - H$ are inserted – that is, if

$$R_e(0, y^0) - \delta + \left[H - h\right] y_e(0, 1 - H) \le 0, \tag{30}$$

the first-best outcome can be achieved through a pure technology agreement with an R&D subsidy equal to 1-H. Notice that a first-best outcome with zero emissions cannot always be sustained by a pure technology agreement. No matter how high the spillovers, the term $R_e(0, y^0) - \delta$ in (30) may be non-negative; the whole expression on the left hand side of (30) will then be positive. In Appendix 2 we present a numerical example in which the first-best outcome with zero emissions can be implemented through a technology agreement.

Can the first-best solution given by (28) and (29) be implemented through a second-best quota agreement? A second-best quota agreement with a corner solution ($e = 0$) is given by (13) and (22) with < instead of = in (22). Such an agreement must differ from the first-best solution, as under the second-best quota agreement we have $R_y(0, y) = h$, whereas $R_y(0, y) = H$ under the first-best optimum. Since $h > H$, under the second-best quota agreement R&D investment will be too low.

We can summarize these results as follows:

Proposition 6: If technology spillovers are sufficiently low, a second-best quota agreement will give a higher welfare level than a second-best technology agreement. If technology spillovers are sufficiently large, a technology agreement may give a higher welfare level than a second-best quota agreement.

9. An alternative technology agreement

As mentioned in the Introduction, we believe it is more likely that a technology-based agreement will focus on policies influencing R&D instead of directly on R&D expenditure. It is nevertheless of interest to consider briefly a technology agreement that focuses directly on R&D expenditure instead of on R&D policies.

A technology agreement focusing directly on R&D expenditure will – within our model – mean that R&D expenditure in each country (x) is determined directly in the agreement. This implies that also the value of y for each country will be exogenous once the agreement is in force. The optimal response of each country is thus to choose its own emissions to maximize its net benefits given by (11), taking x, y and e^* as given. This results in the first-order condition $R_e(e,y)=\delta$. We thus have an important difference from the case where the agreement specifies the R&D subsidy to be used in each participating country. Instead of Proposition 3 we now get

Proposition 7: In a technology agreement that specifies R&D expenditure for each signatory, each country chooses its emission level so that its marginal abatement cost is equal to its own marginal environmental cost (that is, the same rule as it would use without any agreement).

The reason for the difference from Proposition 3 follows from the discussion at the end of Section 7. When an agreement specifies an R&D subsidy, each country can affect its own R&D investment through its choice of emissions. If the agreement

specifies R&D investment directly, countries don't have this possibility. In the latter case, countries therefore have no incentive to deviate from the standard rule that marginal abatement costs equal marginal environmental costs.
A second-best technology agreement of the present type is the choice of *x*, and thus *y*, that maximizes net benefits given by (15) subject to the constraint $R_e(e,y)=\delta$. Straightforward calculations reveal that the outcome must satisfy

$$R_y(e,y)-H=-(n-1)\delta\frac{R_{ey}}{R_{ee}}<0 \tag{31}$$

In words:

Proposition 8: In a second-best optimal technology agreement that specifies R&D investment in each country, R&D investment should be set so that the (explicit or implicit) subsidy to R&D expenditure should be larger than in the first-best optimum.

The second-best agreement of this type is illustrated in Figure 7. In designing the agreement, the group of all countries is constrained by the countries' response to be on the curve $R_e(e,y)=\delta$. Since this curve is downward-sloping in the (e,y) diagram and the iso-welfare curves are vertical at their intersections with the curve $R_y(e,y)=H$, the second-best optimum must be at a point, $\tilde{\mathrm{T}}$, above the latter curve, as derived formally in (31).

In Section 7 we discussed the case of a technology agreement that specified the R&D subsidy to be used in all countries. Here, the second-best optimum was on the curve $e^T(\sigma)$. We showed that the curve $e^T(\sigma)$ lies to the right of the curve $R_e(e,y)=\delta$ (above the curve $R_y(e,y)=h$). Moreover, all iso-welfare curves between *F* and the iso-welfare curve that is tangent to the curve $e^T(\sigma)$ have a higher welfare level than the latter iso-welfare curve. We therefore have the following Proposition:

Proposition 9: A second-best agreement that specifies R&D investment in each country gives a higher welfare level than a second-best technology agreement that specifies an R&D subsidy.

Proposition 9 is illustrated in Figure 7 for the case $y_{e\sigma} = 0$, but holds whatever value $y_{e\sigma}$ has. The intuition behind the result is related to Propositions 3 and 5. For any given equilibrium level of R&D expenditure, each country has lower emissions when R&D expenditure is determined directly in the technology agreement than when an R&D subsidy is specified. Since emissions in both cases are higher than what is implied by the first-best rule of marginal abatement costs equalizing the sum of the countries' marginal environmental costs, the agreement that gives the lowest emissions also gives the highest welfare level.

10. Concluding remarks

In the present paper we have examined alternatives to emission-based international climate agreements. When the technology agreement specifies a common R&D subsidy to be used in all signatory countries, the second-best emission agreement outperforms the second-best technology agreement if technology spillovers are sufficiently low. The opposite may hold if technology spillovers are sufficiently large. We have shown that if there exists a second-best technology agreement that directly specifies R&D expenditure in each country, it is more efficient than a technology agreement that specifies an R&D subsidy.

Throughout the paper we have assumed that all countries in the world are participating in the agreement. A more realistic assumption is that some countries participate, whereas others do not sign the agreement. As is well known, when only some countries take action in order to increase their abatement, emissions in other countries might increase through the carbon leakage (see, for example, Hoel, 1994, Golombek et al., 1995, and Gurtzgen and Rauscher, 2000).

The carbon leakage might work through lower international prices of carbon or via the price of energy-intensive tradable goods. Yet when abatement technologies are endogenous, as in the present paper, there is an additional effect that might lower the carbon leakage: when some countries improve their technologies through R&D, abatement costs in the non-participating countries will also be reduced through technology spillovers from the signatories. This issue is analysed by Golombek and Hoel (2004), who consider the case of the world consisting of two countries (or two groups of countries). Countries are either identical or differ with respect to their environmental concerns, which may reflect different income levels. In each country the technology level depends on both domestic and foreign R&D expenditure. Golombek and Hoel identify cases in which increased environmental concern in one country lowers emissions in both countries.

The lesson from Golombek and Hoel (2004) is that the isolated effect of technology diffusion from one country to another may be lower emissions in the other country due to lower costs of abatement there. As demonstrated in the present paper, R&D expenditure and the price of carbon typically differ between second-best technology agreements and second-best emission agreements. Thus, for international climate agreements with incomplete participation, a topic for future research is whether the carbon leakage is lower under technology agreements than under emission agreements.

Appendix 1

Denoting the left hand side of (24) by $L(e,\sigma)$ we have

$$\frac{\partial L}{\partial \sigma} + \frac{\partial L}{\partial e}\frac{de^T(\sigma)}{d\sigma} = 0 \tag{32}$$

or

$$\frac{de^T(\sigma)}{d\sigma} = \frac{\frac{\partial L}{\partial \sigma}}{-\frac{\partial L}{\partial e}} \equiv \frac{\frac{\partial L}{\partial \sigma}}{P} \tag{33}$$

where the denominator $-\frac{\partial L}{\partial e} \equiv P$ is positive due to the second-order conditions of the maximization problem of each country. From (24) we have

$$\frac{\partial L}{\partial \sigma} = R_{ye}y_\sigma + R_{yy}y_e y_\sigma + (R_y - h)y_{e\sigma} \tag{34}$$

From (10) we find that the sum of the first two terms is zero. Inserting (34) into (33) thus gives us (25).

From (10) we have

$$y_e = \frac{R_{ey}(e, y(e,\sigma))}{-R_{yy}(e, y(e,\sigma))} \tag{35}$$

By differentiating this expression and using (10) we get

$$y_{e\sigma}(e,\sigma) = \frac{R_{ey}R_{yyy} - R_{yy}R_{eyy}}{-R_{yy}^3} \tag{36}$$

The denominator in this last expression is positive, but the numerator cannot be signed without making further assumptions about the function *R*.

Appendix 2

Consider the income function

$$R(e,y)=\alpha e+\beta y-\frac{\chi}{2}e^2-\frac{\phi}{2}y^2-\mu ey-\frac{\pi}{3}y^3+constant \tag{37}$$

where e and y as before denote emissions and the technology level. We shall show that if the first-best outcome is characterized by zero emissions, then the first-best outcome can be implemented through a technology agreement for suitable parameter values $(\alpha,\beta,\chi,\phi,\mu,\pi,m,n,\gamma,\delta)$. As argued after (30), a second-best quota agreement cannot implement this first-best solution. The second-best technology agreement therefore outperforms the second-best quota agreement in this example.

Condition (28) characterizes a first-best outcome with zero emissions. The technology level in (28) is the one following from (29), that is, the socially optimal technology level under zero emissions (y^0). Further, (30) characterizes the condition under which a technology agreement can achieve the first-best outcome with zero emissions, provided that the technology level is y^0 under the technology agreement. In addition to meeting the two conditions (28) and (30), the parameter values must ensure that it is optimal to have positive emissions in the case of no international agreement (in order to make the problem interesting). The last requirement implies that (12), which characterizes (positive) optimal emissions under no agreement, is changed to $R_e(0,y^N)>\delta$, where y^N is the technology level under no agreement, given that it is optimal with no emissions. This technology level is determined in (13) for $e=0$.

We find that for $\alpha=\beta=\phi=\mu=\pi=10$, $\chi>4.5$, $\gamma=0.7$, $n=100$ and $m>0$, all three conditions are met if $5.3\leq\delta\leq5.4$. All derivatives of the income function (37) also have the correct sign, including the income function being concave. Other values of $(\alpha,\beta,\chi,\phi,\mu,\pi,n,\gamma)$ will imply another condition on δ in order to meet the three requirements.

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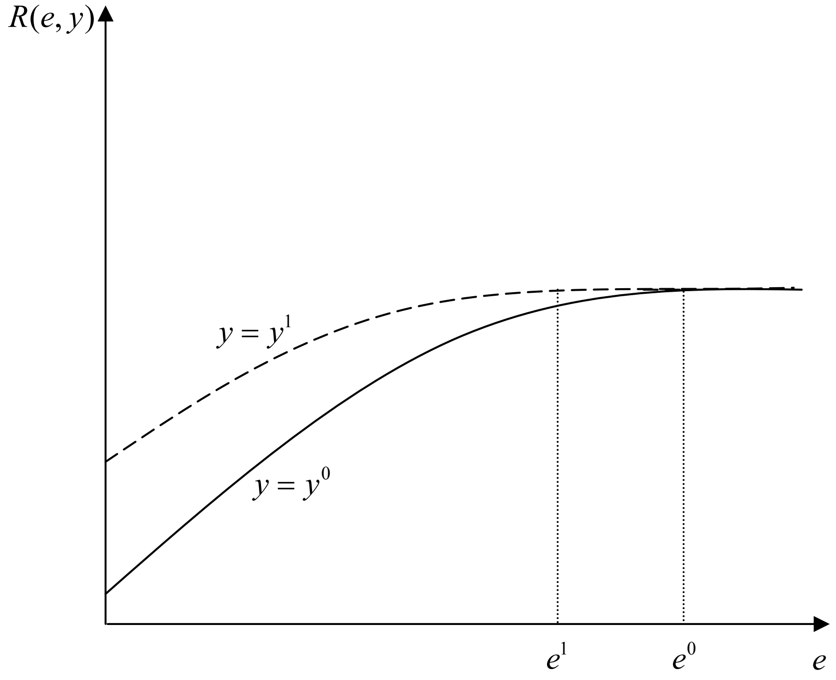

Figure 1

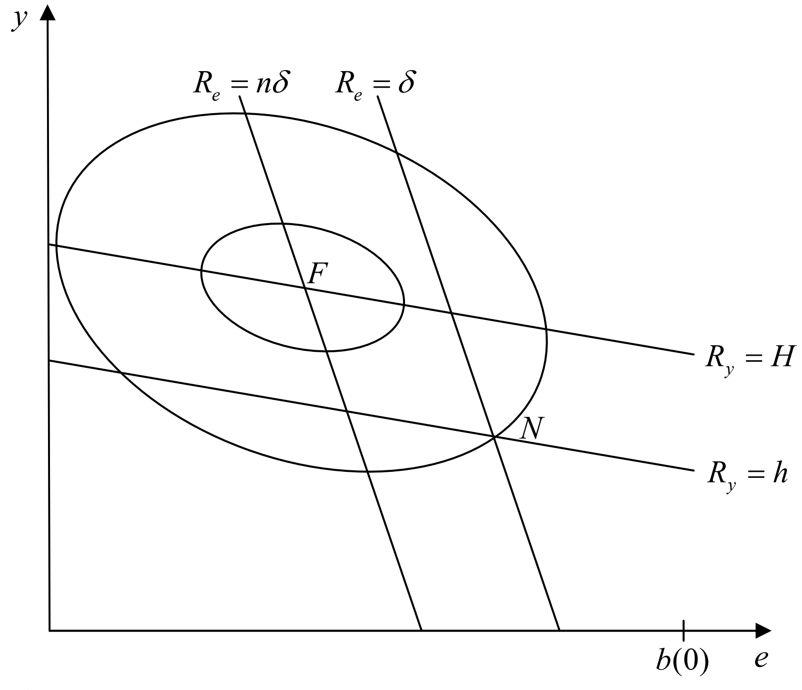

Figure 2

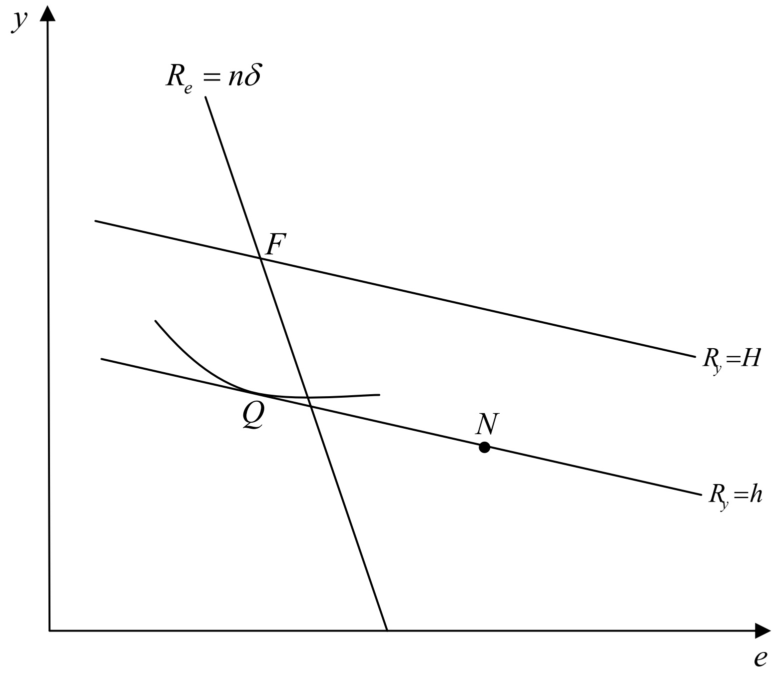

Figure 3

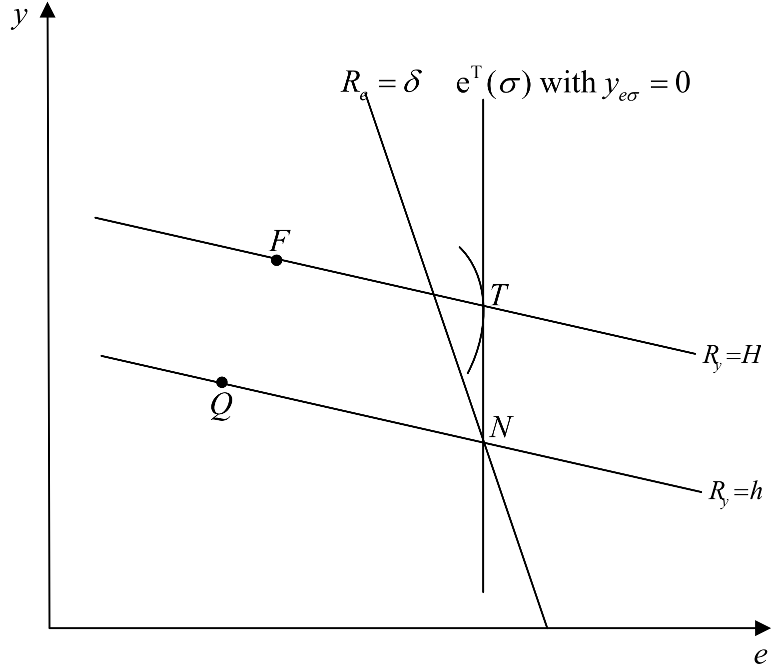

Figure 4

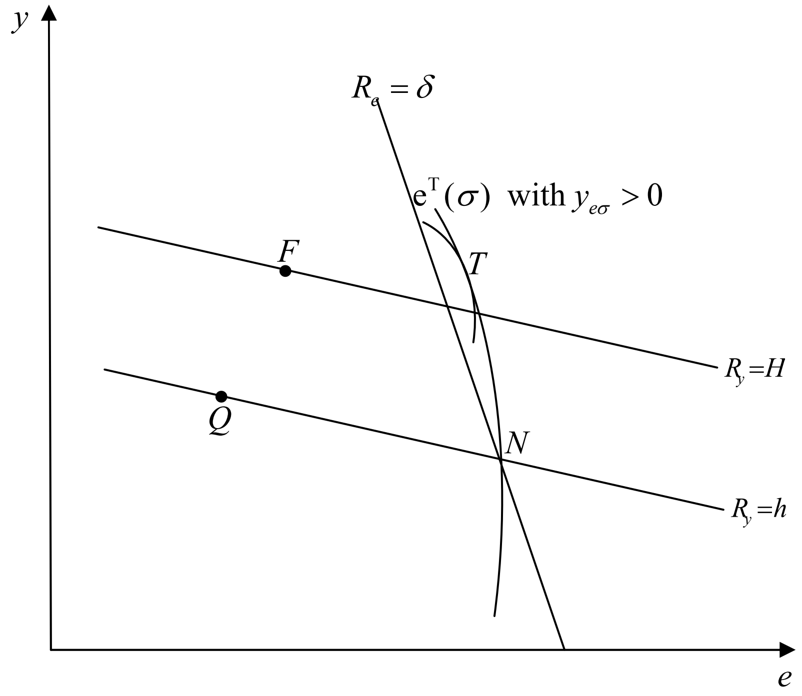

Figure 5

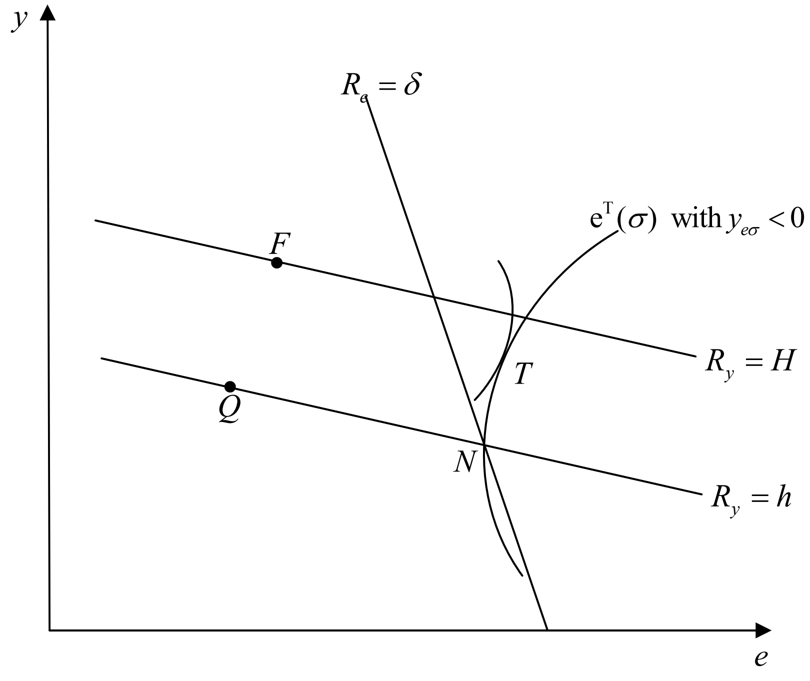

Figure 6

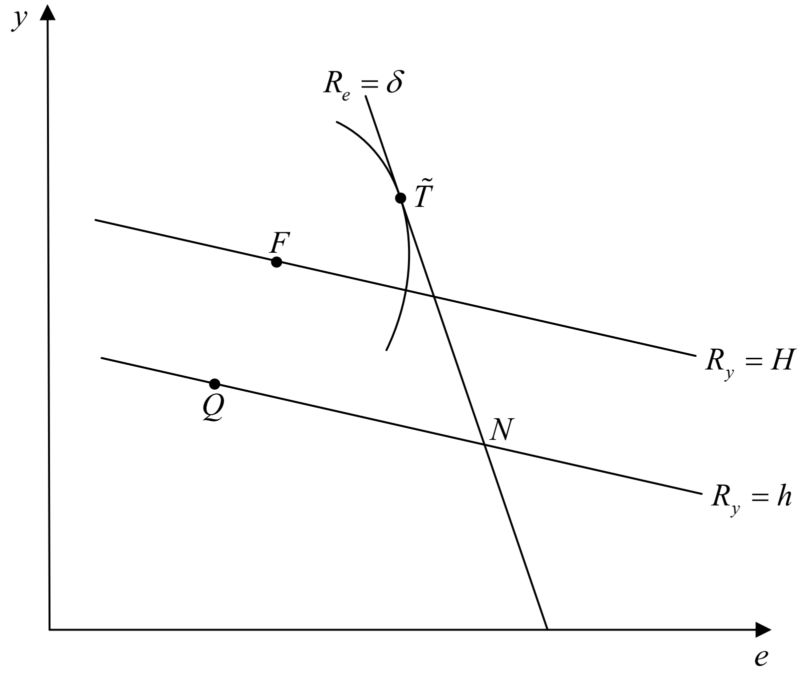

Figure 7