International Cooperation on Climate-Friendly Technologies

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Abstract

We examine international cooperation on technological development as a supplement to, or an alternative to, international cooperation on emission reductions. R&D should be increased beyond the non-cooperative level if (i) the technology level in one country is positively affected by R&D in other countries, (ii) the domestic carbon tax is lower than the Pigovian level, or (iii) the domestic carbon tax is set directly through an international tax agreement. A second-best technology agreement has higher R&D, higher emissions, or both compared with the first-best-outcome. The second-best subsidy always exceeds the subsidy under no international R&D cooperation. Further, when the price of carbon is the same in the second-best technology agreement and in the case without R&D cooperation, welfare is highest, R&D is highest and emissions are lowest in the second-best R&D agreement.

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1. Introduction

The Kyoto Protocol is the result of international negotiations over many years. If honored, it will reduce emissions in the period 2000-12 compared with ‘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 emission limits on fewer than 40 countries and this group of countries is responsible for only about a third of global emissions of greenhouse gases (GHG). Second, the restrictions imposed by the agreement are modest: the difference between the sum of BaU emissions and the sum of emissions under the Kyoto Agreement is insignificant: see, for example, Hagem and Holtsmark (2001) and Böhringer and Vogt (2003). 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 impose stricter emission limits upon the signatories than the present agreement.

Given the weaknesses and uncertainties relating to the ‘Kyoto track’, several observers have asked whether other types of agreements 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), Victor and Coben (2005) and Golombek and Hoel (2006a).

Another idea would be to focus on technology improvements in order to reduce abatement costs, as this might increase a country’s willingness to undertake significant emission reductions. For example, it is beneficial to supplement a Kyoto type of agreement with technology elements if technological development depends not only on a country’s own R&D investment but also on R&D by other countries through cross-country technology spillovers. Even with no explicit agreement on emissions, an agreement leading to increased R&D, and thus to lower abatement costs, might result in a reduction in emissions. This is the background for the proposals of a climate agreement on technology development, see, for example, Barrett (2003, Section 15.13) and Barrett (2006). So far, there has been one initiative focusing on international cooperation on climate-friendly technologies - the Asia

Pacific Partnership on Clean Development and Climate (APP) - which aims at accelerating the development and deployment of clean energy technologies through expanding investment and trade in cleaner energy technologies. To the best of our knowledge, the results of APP, where Australia, Canada, China, India, Japan, South Korea and the United States are the partners, remain to be seen.

In the present paper we examine international cooperation on technological development as a supplement to, or an alternative to, international cooperation on emission reductions. The basic idea of cooperating on technological development is to spur innovation and/or diffusion of climate-friendly technologies.

Cooperation on technological development may be designed in several ways. For example, it may commit governments to finance or organize basic research on a limited number of technologies[1], or to develop technology standards that all countries commit to impose domestically. Alternatively, countries may cooperate on policies directed toward private agents, for example, by providing instruments (e.g., technology subsidies or tax breaks) that foster more R&D or increased application of new technologies. Cooperation on technological development may also seek to stimulate information sharing between firms by, for example, designing appropriate environments for research joint ventures: see Katsoulacos and Ulph (1998).

Below we focus on innovations by private firms that through economic instruments are encouraged to undertake R&D. However, we show in the concluding section that our results are also valid for cooperation on research financed directly by governments.

In section 2 we discuss how improved technology may affect carbon emissions. We distinguish between three types of improved technology that may decrease carbon emissions: increased energy efficiency, reduced costs of producing non-carbon energy, and reduced costs of carbon capture and storage (CCS). Whereas reduced costs of CCS will typically reduce carbon emissions, it is reasonable, but not obvious, that the two other forms of technological improvement will also reduce carbon emissions (for a given carbon tax). In the present paper we therefore assume that improved technology will reduce carbon emissions for any given carbon tax.

Section 3 presents a model of identical countries where there is a standard negative climate externality as well as a positive technology externality: each country's technology level increases not only as its own R&D increases, but also as a consequence of increased R&D in other countries. In Section 4 we examine the social optimum, which is our reference case. We also discuss how the social optimum can be implemented.

Our starting point (sections 5 and 6) is a situation where there is no cooperation on technological development: in each country the government sets an R&D subsidy non-cooperatively. Further, in each country there is an exogenous carbon tax, equal for all countries. The magnitude of the domestic tax rate reflects whether there is some cooperation on emissions (see discussion below). For a given R&D subsidy and a given carbon tax, profit maximizing firms determine R&D and emissions.

We consider three cases for the exogenous carbon tax. First, the carbon tax is chosen non-cooperatively, which implies that the tax will be set equal to a country's marginal climate cost. Second, countries participate in an international quota agreement with tradable permits. The domestic carbon tax rate will then be equal to the international quota price. Third, countries participate in an international tax agreement, that is, an agreement that dictates the domestic carbon tax to be used in all countries. With an international quota agreement or tax agreement, the domestic carbon tax will be somewhere between the marginal climate cost of a country and the Pigovian level, that is, the sum of marginal climate costs of all countries. A domestic carbon tax below the Pigovian level reflects that countries, for various reasons, are not able to reach a fully optimal agreement. These reasons could include incentives to free ride, and also political opposition to high taxes due to distributional consequences.

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[1] For an alternative view on government funding of research, see Kealey (1996) who argues that both basic and applied research will flourish under a policy of laissez-faire, whereas government funding of

We assume that in each country only a fraction of the total returns to R&D are captured by the investing firms. Therefore, even without any international R&D cooperation it is optimal for each country to subsidize R&D. In section 7 we show, however, that this non-cooperative subsidy is lower than the socially optimal subsidy, that is, R&D should be increased beyond the non-cooperative level, if at least one of the following three conditions are satisfies: (i) there are positive cross-country spillovers (i.e., the technology level in one country is positively affected by R&D in another country), (ii) the domestic carbon tax is lower than the Pigovian level, (iii) the domestic carbon tax is set directly through an international tax agreement.

In section 8 we analyze an international R&D agreement which specifies a common R&D subsidy to be implemented in all countries. Because this subsidy is determined by the group of all countries so as to maximize total welfare per country, taking into account how firms and countries will respond to the agreement in the next stages of the game, it is a second-best subsidy. Both the second-best subsidy and the non-cooperative subsidy depend on the exogenous carbon tax, and they tend to be lower the higher is the carbon tax. Yet, the second-best subsidy always exceeds the non-cooperative subsidy. This is the case even if the tax rate in the R&D agreement equals the Pigovian value, whereas the marginal climate cost is used as the tax rate in the non-cooperative case.

In section 9 we first compare the second-best outcome with both the first-best outcome and the different cases without R&D cooperation. Obviously, social welfare is higher under the first-best-outcome than under the second-best technology agreement (for a carbon tax below the Pigovian level). Moreover, we show that R&D, emissions, or both are higher under the second-best technology agreement than under the first-best-outcome.

When the domestic carbon tax is the same in the second-best technology agreement and the cases without R&D cooperation, welfare is highest, R&D is highest and emissions are lowest in the second-best R&D agreement. We also show that under an international carbon tax agreement, welfare and R&D are lower, whereas emissions

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science will lead to skewed research priorities and lost academic freedom.

are higher, than under an international quota agreement, provided that the domestic carbon tax is the same in the two cases.

In section 9 we also introduce and compare three agreements: a pure quota agreement is an agreement where quotas are set so that the carbon price is equal to the Pigovian level, but where there is no cooperation on R&D policies. A pure tax agreement is an agreement where the carbon tax is set in the agreement, equal to the Pigovian level, but there is no cooperation on R&D policies. Finally, in a pure technology agreement the R&D subsidy is chosen to maximize the social welfare of all countries, while the domestic carbon tax is at the non-cooperative level.

We show that generally, the pure tax agreement has lower welfare, lower R&D and higher emissions than the pure quota agreement. However, it is not generally possible to rank the welfare levels of either of these agreements with the welfare level of a pure technology agreement. However, we show that R&D and emissions or both are higher under a pure technology agreement than under either a pure quota agreement or a pure tax agreement.

Finally, in Section 10 we discuss some of our simplifying assumptions and point at topics for future research.

2. Technological progress

We assume that each country's income is increasing – up to a limit – in its own emissions. Put differently, each country has an emission level that would follow from its optimization problem if the solution of this problem was made without considering the environmental impact of the emissions. This is often called the country's Business as Usual (BaU) emission level, and it will typically depend on the technology level of the country. Reducing emissions below the BaU level is costly: that is, it reduces the country's income.

We formalize the cost of reducing emissions by the income function $R(e, y)$, where e are emissions and y is technology level. $R(e, y)$ is the aggregate income function of each country. The emission level that maximizes $R(e, y)$ is the BaU emission level, denoted $b(y)$. $R(e, y)$ is concave and differentiable, and for $e < b(y)$ the function $R(e, y)$ is increasing in both its arguments. We also assume that when $e < b(y)$, technology development reduces marginal abatement costs: that is, $R_{ey} < 0$ for $e < b(y)$. As will be seen below, this is a critical assumption: $R_{ey} < 0$ is a necessary condition to ensure that a profit maximizing firm will i) reduce its emissions if its technology level is increased, and ii) increase its technology level if the carbon price is increased. Since $R_{ey} < 0$ is a critical assumption, we use the rest of this section (and the Appndix) to explore under what conditions $R_{ey} < 0$.

There are three types of technology improvements that may lower carbon emissions:

- increased energy efficiency
- reduced costs of non-carbon energy
- reduced costs of carbon capture and storage (CCS).

Increased energy efficiency is sometimes vaguely described as the possibility of producing the same output with lower energy input. However, if increased energy efficiency can only be achieved by using more of other inputs, e.g., capital, this is simply a substitution effect. Increased energy efficiency can be defined as the possibility of producing the same output with lower energy input without increasing the use of other factors of production. An obvious way of modelling this is to include the technology variable y as one of the inputs in the production function, see e.g., Popp (2004, 2006). Our assumption $R_{ey} < 0$ means that an increase in the input "technology level" reduces the marginal productivity of fossil energy (R_e). In the Appendix we use a simple model of the production side of the economy to illustrate the effects of increased energy efficiency (and other technological changes). We show that $R_{ey} < 0$ if and only if the price elasticity of carbon energy with respect to its price (measured positively) is less than one. Most empirical studies of energy demand find price elasticities lower than one, suggesting that $R_{ey} < 0$ for technology improvements that increase energy efficiency.

Notice that increased energy efficiency will typically increase the maximal output level, that is, $R(b(y), y)$. Moreover, if $R_{ey} < 0$ for all emission levels, then BaU emissions $b(y)$ will decline as *y* increases.

Non-carbon energy, for example, hydropower, nuclear, solar, wind and bio-energy, are imperfect substitutes for carbon (fossil) energy. Technology improvements that lower the costs of non-carbon energy will typically increase the use of this type of energy, and provided the degree of substitutability between carbon and non-carbon energy is sufficiently large, the use of carbon energy will decline, implying $R_{ey} < 0$. If non-carbon energy is used even if there is no policy restriction on emissions, lowering its cost is clearly beneficial to the country, so $R(b(y), y)$ will increase as *y* increases.

Lower costs of non-carbon energy will have a substitution effect, implying that the use of carbon energy will decline for a given level of output. However, reduced cost of non-carbon energy will typically raise output, tending to increase the use of carbon energy. In the Appendix we show that the former effect dominates if the cross derivative of the production function with respect to the two energy inputs is negative.

Carbon capture and storage (CCS) will always have some costs, and will thus not be used if there are no restrictions on emissions. In that case, a lower CCS cost will not have any effect on BaU output. On the other hand, if restrictions on emissions are sufficiently strict, for example, if there is a sufficiently high carbon tax on emissions, then CCS will be used, and reduced cost of CCS will increase its use. In the Appendix we show that $R_{ey} < 0$ if the marginal costs of CCS are increasing in abatement. We believe this is a reasonable assumption, for example, because costs of transporting removed carbon to the storage site differ between plants (transport length to the storage site differs), or because CCS is less costly at large stationary sources than at smaller stationary sources (different technologies).

3. Technology spillovers

In this section we study how the benefit of R&D investment in one country spills over to other countries, thus improving their technology levels. In particular, we derive an equilibrium relationship between R&D investment and technology level at the country level.

We assume that there are *n* identical countries, and that each country invests in R&D. The technology level *y* of a particular country, henceforth referred to as the home country, is assumed to depend on its own R&D investment (x) and the amount of R&D investment by other countries (x^*).[2]

While technology spillovers allow a country to benefit from other countries' R&D investment, only a part γ (with $0 < \gamma < 1$) of other countries' R&D investment is beneficial for a country. The technology level of the home country (y) is assumed given by

$$y = x + \gamma(n-1)x^*. \tag{1}$$

In (1) we have assumed an additive structure of technology spillovers: that is, the technology level of a country depends on the sum of all countries' 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 home country – in a similar way to (1):

$$y^* = x^* + \gamma[x + (n-2)x^*]. \tag{2}$$

[2] With identical countries, R&D investment will be equal in all countries in equilibrium. However, in order to find the equilibrium it is expedient to distinguish between R&D investment in a particular country and R&D investment in the other countries.

[3] The modeling 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 an agent to learn from others may depend on its own R&D effort. Graevenitz (2002) discusses the policy implications of different modeling assumptions, whereas Golombek and Hoel (2004) apply the ideas of Cohen and Levinthal on climate policy. Sena (2004) gives an overview of the (empirical) literature on knowledge spillovers.

In (2) the first term is R&D investment in the particular foreign country, while the terms in the square brackets are the spillover effect from the ‘home’ country plus the spillover effects from all other countries.

For the subsequent analysis, it is useful to derive a relationship between R&D investment in one country and the technology levels of countries. From (1) and (2) we obtain

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

where the constants h and H are given by

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

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

It is straightforward to show that $0 < H < 1 < h$. Moreover, h is increasing in γ while H is declining in γ. For the limiting case of $\gamma = 0$ we have $h = H = 1$. Note that in an equilibrium with $y = y^{*}$, (3) reduces to

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

4. The social optimum

In this study welfare of each country is given by its net income $R(e, y)$ minus R&D expenditures and environmental costs. Below the unit cost of R&D investment is normalized to 1. Further, we let the marginal environmental cost for each country, δ, be constant and identical across countries. The environmental damage of a country is then δne in a symmetric equilibrium where each country has an emission level *e*. In the first-best social optimum, all firms must have the same emission level (e) as well as identical amounts of R&D investment (x). Hence, in this case, total net benefits per country are given by

$$R(e, y) - Hy - \delta ne \tag{7}$$

where we have used $x = Hy$, cf. (6). Maximizing (7) with respect to emissions e and the technology level y gives

$$R_e(e, y) = n\delta \tag{8}$$

and

$$R_y(e, y) = H. \tag{9}$$

Equation (8) 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.

Rewriting (9) as $R_y H^{-1} = 1$ gives us a straightforward interpretation of the second first-order condition: the marginal benefits of R&D investment when cross-country spillovers are taken into account ($R_y H^{-1}$) should equal marginal costs of R&D investment (normalized to 1). We will later show, see the latter part of Proposition 2, that the first-best social optimum can be implemented through a suitable carbon tax ($n\delta$) and a suitable technology subsidy.

5. Emissions and R&D in a four-stage game

We now analyze the market outcome when countries make individual decisions. The market outcome follows from a four-stage game, which determines emissions and R&D in each country. The four stages can briefly be described as follows[4]:

1. The government in each country sets an R&D subsidy (non-cooperatively or imposed through an international agreement)
2. R&D in each country is determined by profit-maximizing firms
3. The government in each country sets a carbon tax
4. Emissions in each country are determined by profit-maximizing firms.

[4] The assumption that R&D investment is determined before emissions reflects the fact that it takes more time to change the technology level (a stock) than emissions (a flow); for an alternative sequence of decisions see Golombek and Hoel (2006b).

We start with *stage 4*. In this stage the technology level y is given from stage 2 and the carbon tax t is given from stage 3. Because $R(e,y)$ is the income of a representative producer, profit-maximizing producers choose emissions in order to maximize $R(e,y)-te$, giving

$$R_e(e,y)=t. \tag{10}$$

Equation (10) defines emissions as a function of the carbon tax and the technology level:

$$e=e(t,y). \tag{11}$$

The assumption that $R(e,y)$ is strictly concave implies $e_t<0$, while $R_{ey}(e,y)<0$ implies that $e_y<0$.

In *stage 3* each government chooses its carbon tax. We assume that this tax rate is identical in all countries, denoted t. One possibility is that the tax rate is chosen non-cooperatively. In this case, each country finds, using (10), the tax rate that maximizes $R(e,y)-\delta\left[e+(n-1)e^*\right]$ when emissions in all other countries, e^*, are taken as given. This gives the tax rate $t=\delta$. Alternatively, $\delta<t\le n\delta$, that is, each country internalizes at least some of the cross-country climate externalities. (Full internalization corresponds to t being equal to the Pigovian tax rate $n\delta$.) There are (at least) two interpretations of a domestic tax being higher than the individually rational level $t=\delta$. First, countries participate in an international quota agreement with tradable permits. The international quota price *t*, which is used as the domestic tax rate, might be less than $n\delta$ reflecting that countries, for various reasons, are not able to reach a fully optimal agreement, for example, because of incentives to free ride. Second, there is an international agreement dictating the carbon tax to be imposed in each country. This tax might be less than $n\delta$, again reflecting that

countries, for various reasons, are not able to reach a fully optimal international agreement.[5]

Let *v* denote how a single country valuates emission reductions. If the tax rate is chosen non-cooperatively, then $v = t = \delta$. On the other hand, if a country participates in an international quota agreement ($t > \delta$), the cost for the country of a unit of emission is the quota price *t*, so $v = t > \delta$. Finally, if a country participates in an international agreement that directly specifies the domestic carbon tax ($t > \delta$), it is reasonable that countries in their R&D decisions value reduced emissions only by the effect lower emissions have on the country's own climate costs, that is, $v = \delta < t$.

Table 3 summarizes the discussion above. For all cases we assume that all countries use the same tax rate and have the same valuation of emissions (since countries are identical).

Table 1: Domestic carbon taxes and valuation of own emissions

	Carbon tax	Valuation of own emissions
Non-cooperative decisions	$t = \delta$	$v = t = \delta$
Quota agreement	$\delta < t \leq n\delta$	$v = t > \delta$
Carbon tax agreement	$\delta < t \leq n\delta$	$v = \delta < t$

In *stage 2* the producers in each country choose *x* to maximize their profits, taking the R&D subsidy rate, denoted σ, as given from stage 1. If there were no imperfections in the markets for innovations, then $R(e, y) - (1-\sigma)x - te$ is maximized, taking R&D in other countries (x^*) as given. Using (1), (10) and (11), we obtain $R_y(e, y) = 1 - \sigma$. However, according to Popp (2006) studies suggest that there are imperfections in the markets for innovations because the social returns to R&D are about four times higher than the private returns. The difference reflects limited intellectual property rights,

[5] Another interpretation is that each country has some type of altruism, implying that it (partly) internalizes the climate costs of other countries. We leave it to the reader to examine this case,

which means that output from R&D is to a large extent a public good, that is, it can be applied repeatedly without decay. Hence, a firm is able to capture only a fraction *k* of the entire social value of its successful R&D investment. Under the assumption of $k < 1$, we obtain

$$kR_y(e, y) = 1 - \sigma \tag{12}$$

where k is assumed to be identical across countries. Together with (10) this gives

$$y = y(\sigma, t). \tag{13}$$

The assumption that $R(e, y)$ is strictly concave implies $y_\sigma > 0$, while $R_{ey}(e, y) < 0$ combined with $R(e, y)$ being strictly concave imply that $y_t > 0$. Whereas we have not explicitly included *k* in the function for *y*, the concavity of $R(e, y)$ implies that *y* is higher the higher is *k*.

For the foreign countries we correspondingly have (remembering that the carbon tax is assumed to be the same in all countries)

$$y^* = y(\sigma^*, t). \tag{14}$$

We are now ready to proceed to the first stage of the game. We consider this in the two next sections, treating first the case of non-cooperatively determined R&D subsidies (section 6) and then R&D subsidies determined through an international technology agreement (section 7).

6. Non-cooperate determination of R&D subsidies

Above we introduced three carbon tax policy rules, see Table 1. Because these rules are exogenous, the carbon tax in stage 3 is assumed to be independent of the technology levels. It then follows from (13) and (14) (and $y_\sigma > 0$) that the technology levels are uniquely determined by the subsidy rates. A game of choosing subsidy rates is therefore equivalent to a game of choosing technology levels, and below we let countries choose their own technology level, taking the technology level of other countries (y^*) as given. Hence, our (home) country maximizes

$$R(e,y) - \left[hy + (H-h)y^*\right] - ve \tag{15}$$

w.r.t. y, where we have used (3) and v is a country's valuation of own emissions, see the discussion related to Table 1. Maximization of (15) and using (10) gives the first-order condition for the technology level:

$$R_y(e,y) = h + (t-v)(-e_y(t,y)). \tag{16}$$

Together with (12), i.e., $kR_y(e,y) = 1-\sigma$, we find the optimal subsidy

$$\sigma = 1 - k\left[h + (t-v)(-e_y(t,y))\right]. \tag{17}$$

When emissions are evaluated at the same rate as the carbon tax, i.e., $v = t$, we have

$$\sigma = 1 - kh < 1 - k \quad \text{for} \quad v = t. \tag{18}$$

Note that this expression gives the equilibrium subsidy whenever $v = t$, i.e., for the two first cases in Table 1 (non-cooperative decisions or quota agreement). As usual, $k < 1$ (firms are not capturing the full return to R&D investment) tends to make the subsidy positive, while $h > 1$ tends to make it negative (i.e., a tax on R&D). The latter effect represents the incentive for each country to free ride on R&D of other countries instead of doing R&D themselves.

If we instead have the third case in Table 1 (carbon tax agreement), that is, $v = \delta < t$, each country would choose the subsidy

$$\sigma = 1 - k\left[h + (t-\delta)(-e_y(t,y))\right] < 1 - kh < 1 - k \quad \textit{for} \quad v = \delta < t. \tag{19}$$

In this case the equilibrium subsidy is lower the higher is the carbon tax, at least for tax rates close to δ.[6] The reason is that each country is now committed to impose a carbon tax on its firms that exceeds its own evaluation of increased emissions ($t > v = \delta$). Thus, the tax tends to provide too much abatement relative to what is optimal for a county based on its pure self interest. A country will partly adjust for this affect through a low technology subsidy to its firms, which tends to reduce the technology level of the country. Under our assumption $R_{ey} < 0$, marginal cost of abatement will now increase (because *y* has been reduced), and hence emissions will be raised. A higher tax is therefore compensated by a lower technology subsidy. As seen from (19), the subsidy is *lower* i) the *more* the imposed tax rate exceeds the country's evaluation of increased emissions, i.e., the higher is ($t - \delta$), ii) the *more* emissions respond to a higher technology level, i.e., the higher is ($-e_y$), iii) the *more* private firms capture of the returns to R&D i.e., the higher is k, and iv) the *higher* is the rate of diffusion, i.e., the higher is γ and thus h.

The term in the square bracket in (19) is larger than 1 for all $t \in [\delta, n\delta]$ due to $h > 1$. From (18) and (19) we thus have the following proposition:

Proposition 1: The non-cooperative R&D subsidy rate is always lower than $1-k$*, and may even be negative (i.e., an R&D tax). If countries value reduced emissions by the carbon tax rate (*$v = t$*), the non-cooperative subsidy is* $1-kh$*. If countries instead value reduced emissions by its marginal environmental cost* δ *and* $t > \delta$ *(countries participate in an international carbon tax agreement), the non-cooperative subsidy is lower than* $1-kh$.

7. The benefits of improved technology

So far we have studied the four-stage game when the government in each country sets an R&D subsidy non-cooperatively. Before examining the case where the R&D subsidy is determined in an optimally designed international agreement (Section 8),

[6] For sufficiently high values of $t-\delta$, σ will be declining in *t* only if the term $-e_y(t, y)$ either increases or does not decline too much as *t* is increased.

we consider the more modest goal of increasing R&D in all countries compared with the case without any cooperation on R&D.

A common increase in R&D will give all countries an increase in their technology level relative to the non-cooperative outcome. Starting with an arbitrary value of *y*, the benefit for each country of a small increase in *y* is

$$\Delta = R_y(e,y) - H + (n\delta - t)(-e_y(t,y)) = h - H + (n\delta - v)(-e_y(t,y)) \qquad (20)$$

where we have used (16). The benefits of improved technology are thus *greater*:

- the *greater* is $h - H$, which is increasing in the international diffusion parameter γ
- the *greater* is the term $n\delta - v$. If $v = \delta$ (carbon tax agreement), this term is simply equal to $(n-1)\delta$. If $v = t$ (non-cooperative decisions or quota agreement), then $n\delta - v = n\delta - t$, which is higher the lower is the carbon tax *t*
- the *more* emissions are reduced as a consequence of improved technology ($-e_y$).

According to the second bullet point, under a carbon tax agreement it is beneficial to increase the R&D level, and this is the case *independent* of the magnitude of the imposed domestic tax. Moreover, unless $v = t = n\delta$ (full internalization of the climate costs of other countries through a quota agreement), there is a benefit of increased R&D investment beyond the non-cooperative level - even in the absence of cross-country technology spillovers - provided this makes emissions decline. The latter condition ($-e_y > 0$) requires that $R_{ey}(e,y) < 0$, see the discussion after (11). Finally, in the case of full internalization of other countries' climate costs and no cross-country technology spillovers ($h = H$), the equilibrium coincides with the first-best outcome, which of course cannot be improved upon.

8. An international technology agreement

In this section we analyze an international agreement which regulates technology policies - we assume that the agreement specifies a common R&D subsidy to be implemented in all countries. Because this subsidy is determined by the group of all countries so as to maximize total welfare per country, taking into account how firms and countries will respond to the agreement in the next stages of the game, it is a second-best subsidy. Due to (13) and (14), choosing a common subsidy is equivalent to choosing a common technology level (when the choice of the common carbon tax rule is assumed independent of the technology level). Below we therefore find the technology level y that maximizes total welfare per country, given by (7), subject to the constraint $e = e(t, y)$, see (11). The first-order condition of this problem is (using (10)):

$$R_y = H + (n\delta - t)e_y \leq H. \tag{21}$$

Using (12), we find that in order to obtain this outcome the second-best subsidy must be given by

$$\sigma = 1 - k\left[H - (n\delta - t)(-e_y(t, y))\right] > 1 - k. \tag{22}$$

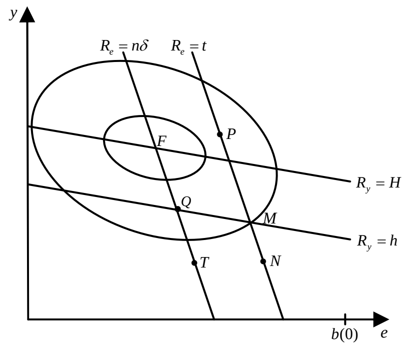
If the carbon tax is at the Pigovian level $t = n\delta$, the optimal subsidy is $1 - kH$. Using (8), (9) and (12) , we see that the first-best social outcome is now achieved. Below we therefore term $1 - kH$ the first-best subsidy. The discussion above leads to the following Proposition:

Proposition 2: In an international technology agreement, the second-best R&D subsidy is higher than $1 - k$. If the carbon tax is at the Pigovian level $t = n\delta$, the optimal subsidy is $1 - kH$, and the first-best social optimum is achieved.

Proposition 2 and (22) imply that the second-best R&D subsidy will be higher than the first-best subsidy $1 - kH$ if $t < n\delta$. On the other hand, the first-best R&D subsidy $1 - kH$ is higher than the non-cooperative R&D subsidy (because $H < 1$), cf. Proposition 1. These results tend to suggest that R&D investment, and hence the technology level, is higher under a second-best technology agreement than in the first-best outcome, and also that the technology level is higher in the first-best outcome than in the case without any R&D agreement. One should, however, be careful because the ranking of technology level does not follow directly from the level of marginal benefit of increased R&D; it also depends on how emissions are determined. We consider this issue in the next section.

9. Comparison of emissions and R&D

In the previous sections we have considered five outcomes, namely the first-best social optimum (Section 4), three cases with an exogenous carbon tax and non-cooperative determination of R&D (Section 6) and an international technology agreement with an exogenous carbon tax (Section 8). In this section we compare these cases.



In Figure 1 we have drawn the two curves representing $R_e(e, y) = n\delta$ and $R_y(e, y) = H$, corresponding to equations (8) and (9). It is easily verified that the properties of the function $R(e, y)$ imply that these two curves are downward sloping in the (*e*,*y*) diagram and that $R_e(e, y) = n\delta$ is steeper than $R_y(e, y) = H$. At the intersection point *F* of these two curves, both equations (8) and (9) hold, so this point represents the First-best social optimum.

In Figure 1 we have also drawn two iso-welfare curves. Along each such curve net benefits (per country) – given by (7) – are constant, and net benefits are higher the closer the curve is to the maximum point *F*. From the conditions (8) and (9) of the first-best social optimum, it follows that the iso-welfare curves are horizontal at the intersections with $R_e(e, y) = n\delta$, and vertical at the intersections with $R_y(e, y) = H$.

We have also drawn curves for $R_e(e,y)=t<n\delta$ and $R_y(e,y)=h$ in Figure 1. Since $n\delta>t$, the curve $R_e(e,y)=t$ must lie to the right of the curve $R_e(e,y)=n\delta$. Similarly, since $H<h$, the curve $R_y(e,y)=h$ must lie below the curve $R_y(e,y)=H$.

Because relation (10) is valid both with and without cooperation on R&D, these equilibria are located somewhere on the line $R_e(e,y)=t$. Notice that the exact position of this curve depends on *t*, and will lie further to the left the higher is *t*. Without any cooperation on R&D, the equilibrium condition for R&D is given by (16). If emission reductions are valued by the domestic carbon tax ($v=t$), then $R_y(e,y)=h$, so the equilibrium must be at the point *M* in Figure 1. Note that if $t=\delta$, *M* represents the case of non-cooperative decision of the tax rate as well as the R&D subsidy. If $\delta<t\le n\delta$, *M* represents the case of an international quota agreement. Next, if emission reductions are valued by the marginal cost of emission ($v=\delta$) and $t>\delta$, we must have $R_y(e,y)>h$ at the equilibrium, implying point *N* in Figure 1. Hence, *N* represents the case of an international tax agreement. Notice that *N* coincides with *M* for the limiting case of $t=\delta$. Comparing *M* or *N* with *F* we have the following:

Proposition 3: Emissions are higher and R&D lower in the case of no cooperation on R&D than in the first-best social optimum.

With a technology agreement R&D is determined by (21), implying that $R_y(e,y)<H$. The equilibrium, which in Figure 1 is represented by the point *P*, is therefore on the line $R_e(e,y)=t$ somewhere above the curve $R_y(e,y)=H$. In Figure 1, emissions and the technology level are higher at *P* than at *F* (first-best outcome). However, this ranking depends on the way we have drawn the curves in Figure 1. In general, several rankings are possible. For example, the technology level may be lower and emissions higher in *P* than in *F*. However, from Figure 1 we see that *if* emissions are lower in *P* than in *F*, then the technology level is higher in *P* than in *F*. To sum up:

Proposition 4: The ranking of R&D investment and emissions between the second-best technology agreement and the first-best outcome is ambiguous. However, either R&D or emissions or both must be higher in the second-best technology agreement than in the first-best outcome.

We can also use Figure 1 to compare *M/N* (no R&D cooperation) with *P* (an R&D agreement) when the domestic carbon tax *t* is the same in these equilibria, that is, when the equilibria are located on the same line $R_e(e, y) = t$. We immediately get the following result:

Proposition 5: For any given domestic carbon price t, an R&D agreement gives higher welfare, higher R&D and lower emissions than the case of R&D policies being determined non-cooperatively. Moreover, with non-cooperative R&D policies the carbon tax agreement (implying $v = \delta$) has lower welfare, lower R&D and higher emissions than a quota agreement (implying $v = t$) when t is the same in the two cases.

The case of no agreement whatsoever is given by the point *M* in Figure 1 for $t = \delta$. Starting from this point and introducing an international quota agreement with a carbon price equal to the Pigovian level ($t = n\delta$), but without introducing R&D cooperation, will move the equilibrium to *Q* in Figure 1, which we term a pure quota agreement. From Figure 1 it is clear that the move from *M* to *Q* increases welfare, increases R&D and reduces emissions. If we instead, starting from point *M* in Figure 1 for $t = \delta$, had introduced R&D cooperation without any cooperation on emissions, henceforth termed a pure R&D agreement, we would move from *M* to *P* (for $t = \delta$), which increases welfare, increases R&D and reduces emissions.

In Figure 1, *P* has higher R&D and higher emissions than *Q*. While this seems plausible, it does not hold as a general result. We now show that *P* may have higher R&D or higher emissions than the equilibrium *Q*, and that the welfare ranking can go either way. We start with the welfare ranking.

In the limiting case of (almost) no technology spillovers, that is, $\gamma \approx 0$ and thus $h \approx H \approx 1$ the two lines $R_y = H$ and $R_y = h$ will (almost) coincide. Hence, *Q* will (almost) coincide with *F*, implying that welfare is higher under *Q* than under *P*. On the other hand, for the limiting case of (almost) no concern for the environment, that is, $\delta \approx n\delta \approx 0$, *P* will (almost) coincide with *F*, implying that welfare is higher under *P* than under *Q*. These two cases have an obvious interpretation: If there are two externalities, the welfare gain of correcting only one of them is largest when one corrects the most important one. In the limiting cases above, one of the externalities was negligible.

Consider again the limiting case of (almost) no technology spillovers ($\gamma \approx 0$), that is, when *Q* (almost) coincides with *F*. Assume moreover that $R_{ey} \approx 0$ for emissions along the curve $R_e = \delta$. Then $e_y = \frac{-R_{ey}}{R_{ee}} \approx 0$, and using (21), *P* will (almost) be on the curve $R_y = H$. If $R_{ey} < 0$ for emissions to the left of the curve $R_e = \delta$, then the curve $R_y = H$ will be downward sloping to the left of the curve $R_e = \delta$ (as in Figure 1). In this case *P* must lie southeast of *F*, and therefore also southeast of *Q* since *Q* (almost) coincides with *F*. This is thus an example of a pure R&D agreement giving lower R&D and higher emissions than a pure quota agreement. Next, consider the limiting case of (almost) no concern for the environment ($\delta \approx n\delta \approx 0$), that is, *P* (almost) coincides with *F*. In this case *P* will be located to the northwest of *Q*. This is thus an example of a pure R&D agreement giving higher R&D and lower emissions than a pure quota agreement.

Finally, starting from the point *M* in Figure 1 for $t = \delta$ and introducing an international tax agreement where $t = n\delta$, henceforth termed a pure tax agreement, will move the equilibrium to *T* in Figure 1. *T* will have a lower welfare level than *F*. For the case $\gamma \approx 0$ and $R_{ey} \approx 0$ along the curve $R_e = n\delta$ (implying $e_y \approx 0$), *T* will (almost) coincide with *F* and welfare will therefore be higher under *T* than under *P*. If $\delta \approx n\delta \approx 0$, *P* will (almost) coincide with *F*, implying that welfare is higher under *P* than under *T*.

The results above are summarized in the following Proposition:

Proposition 6: The ranking of social welfare, R&D investment and emissions between the pure technology agreement and the pure quota agreement or the pure tax agreement is ambiguous. However, either R&D or emissions or both must be higher in the pure technology agreement than in the pure quota/tax agreement.

10. Concluding remarks

The aim of the present paper has been to improve our understanding of the incentives to invest in climate-friendly R&D and to abate under different institutional arrangements. We seek to identify the main forces at work when improved technology lowers costs of abatement. Our modelling strategy is to study these forces within a simple framework as possible. Below we discuss some of our simplifying assumptions, arguing that whereas the exact formulas derived in the present paper clearly depend on these assumptions, the main results of the present paper can be generalized.

First, throughout the paper we have assumed that R&D was undertaken by private firms and could be influenced by the government through an R&D subsidy. However, our conclusions would be similar if we interpret R&D as being directly financed by the government. As noted in section 5, a game of choosing R&D subsidy rates is equivalent to a game of choosing technology levels. Moreover, with cooperation over R&D the equilibrium condition $x = Hy$ implies that choosing y (via a common subsidy rate) or choosing x directly gives exactly the same outcome. The second-best technology agreement is thus the same if R&D is set directly by governments or indirectly through the choice of a common R&D subsidy.

We now argue that also for the case of no R&D cooperation, our results are not qualitatively changed if R&D is not determined indirectly through a subsidy, but directly by the government: Above our (home) country chose technology level y (via a subsidy rate) in order to maximize $R(e, y) - \left[hy + (H-h)y^*\right] - ve,$ taking y^* as given. This problem has (16) as its first-order condition. Assume now that R&D is not determined indirectly through a subsidy, but directly by the government. Inserting (1) and (3) into (15), we find that the net benefit of a country is given by $R(e, x+\gamma(n-1)x^{*}) - x - ve$. Maximizing this expression w.r.t. x , taking x^{*} as given, yields $R_{y}(e, y) = 1 + (t - v)(-e_{y}(t, y))$, which is almost identical to (16), the only difference being that h is replaced by 1. However, our main results are unaffected: Propositions 1 and 2 (about subsidy rates) are no longer relevant, while it is straightforward to see that Propositions 3-6 remain valid also for the case in which RD investments are set directly by the governments.

Second, countries have been assumed to be identical. Countries may differ along a number of dimensions, for example, with respect to climate costs, size (which may be related to climate costs), technology diffusion and income. At least for some of these factors, for example, the technology diffusion parameter, it is easy to derive formulas that are not based on identical countries. However, our main results would not change.

Third, we have assumed that all countries participate in the technology agreement. We suspect that our main results would not change of there in addition to the cooperating countries was a group of countries that did not have any, or only marginal, R&D investments (typically, a group of developing countries). One could thus interpret our cooperating countries as some relatively small group of large countries, for example, China, the EU, Japan and USA, which stand for a major part of global R&D expenses.

Yet, a topic for future research may be to endogenise the number of participating countries in an international environmental agreement (IEA). One approach is to endogenise the number of signatories through applying the ‘standard’ IEA model in which countries decide in the first stage of the game whether they will participate in the IEA, whereas in the second stage the group of signatory countries chooses abatement in order to maximize welfare of the IEA member countries, see, for example, Barrett (1994) and Finus (2001). Within this framework the equilibrium number of signatories is typically small. In addition, if costs or benefits change so that the potential net benefit of cooperation increases, the number of signatories shrinks. Both of these unwarranted properties may call for a new approach of modelling IEAs.

Several factors may be of importance in explaining how an IEA should be designed in order to attract broad participation. For example, burden sharing and lobbying are factors that may play a role in determining the number of participating countries. In fact, these factors may favour technology agreements over emission based agreements, that is, quota or tax agreements: under an emission agreement, 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 they will be borne by the taxpayer to finance public R&D or to give tax breaks/subsidies to private firms investing in 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. These arguments suggest that it might be easier to obtain broad participation in a technology agreement than in an emission agreement.

Finally, we have also a simplifying assumption related to verifiability. Under a technology agreement, the common technology subsidy internalizes that improved technology in one country is beneficial also for other countries. The common technology subsidy in a technology agreement is therefore higher than the technology subsidy each country would have offered to its domestic firms in the case without an international climate agreement. Because each country prefers – based on pure self-interest – a lower subsidy than the one dictated by the agreement, each country has an incentive to set various non-verifiable domestic policy instruments so that the country achieves its individually rational level of the technology subsidy. This may be possible, at least to some extent, because technology policies are often an integral part of a country’s tax system, making it really hard, if possible at all, for an international agency to verify all aspects of other countries’ R&D policies.

In contrast, carbon emissions are easy to calculate, for example, based on fossil fuel use: using various sources of statistics, an international agency can determine whether a country has honoured an emission agreement or not. Thus, the limited verifiability of a technology subsidy suggests, *cet. par.*, that a technology agreement is less efficient than an emission based agreement.

There is also another problem of verifiability when R&D investments are subsidized, or more generally, when R&D firms receive government support. R&D is a vague concept, and it is therefore hardly feasible to define R&D in such a way that an agency (regulator) can clearly distinguish between R&D activities and non-R&D activities. Therefore, when firms face an R&D subsidy (or some other instruments that spur their R&D activity) they have an incentive to categorize more activities as R&D, thereby receiving a higher amount of subsidies than intentionally. Note, however, that under an international emission based agreement where the R&D policy of a country is determined at the national level, it will typically be optimal to offer some type of support to the domestic R&D firms because the social returns to R&D may by far exceed the private returns ($k<1$ in our model). Therefore, the verifiability problem at the firm level is present both under R&D based and emission based agreements.

Obviously, the non-verifiability problem of a technology agreement weakens the case for placing too much emphasis on international technology cooperation. But it does not suggest that it is optimal to fully disregard international R&D cooperation. Overall, our results and discussion suggest that some steps towards including technology elements in an international climate agreement – even in an imperfect manner – may be a valuable supplement to emission based agreements. Thus, a topic for future research is to explore design of international climate agreements that are both emission and technology based when there is hidden information at the national/firm level.

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Appendix

Below we study under what conditions $R_{ey}(e, y) < 0$, distinguishing between three types of technology progress; increased energy efficiency, lower costs of non-carbon energy and lower costs of carbon capture and storage (CCS). We let each type of technology improvement be represented through a technology variable, which is treated as an input.

Let *E* be effective energy:

$$E = E(y_E, \phi(F, G)),$$

that is, a composite good produced by fossil (*F*) and non-fossil (*G*) energy. In addition, the amount of effective energy is increasing in the technology variable y_E ($E_1 > 0$), reflecting increased energy efficiency. The energy input *E* is used together with a vector of other inputs *v* – typically different types of materials - to produce gross output $\Phi(v, E)$. Let *Q* be net output in the economy:

$$Q = \Phi(v, E) - p_F F - q(y_G)G - C(F - e, y_C) - p_v v.$$

Net output *Q* is obtained by subtracting the costs of using fossil energy $p_F F$, the cost of using non-fossil energy $q(y_G)G$, the cost of CCS $C(F - e, y_C)$, and the costs of other inputs $p_v v$ from gross output $\Phi(v, E)$. The cost of non-fossil fuels is lower the higher is the technology variable y_G ($q_G < 0$), and the cost of CCS is lower the higher is the technology variable y_C ($C_2 < 0$). Emissions are denoted *e*, and these are measured in the same unit as fossil energy *F*. Hence, $F - e$ is abatement.

Next, we define the income function

$$R(e, y_G, y_C, y_E) = \max_{F,G,v}\{\Phi(v, E) - p_F F - q(y_G)G - C(F - e, y_C) - p_v v\}$$

With reasonable assumptions on the underlying functions above, $R(e, y_E, y_G, y_C)$ will be strictly concave and increasing in its arguments. To check whether it is reasonable that marginal productivity of fossil energy, $R_e(e, y_E, y_G, y_C)$, is declining in the three technology variables, we shall consider three simplified versions of the model.

Increased energy efficiency

First, we focus on energy efficiency, that is, we ignore non-fossil energy and CCS. Let $y = y_E$, and assume that the net income function is given by

$$R(e, y) = \Omega(\alpha(y)e) - p_F e$$

where $\Omega' > 0$ and $\Omega'' < 0$. Increased energy efficiency is thus modelled as fossil energy augmenting technology improvement through $\alpha(y)$, which is assumed increasing in y. It is straightforward to derive that $R_{ey} < 0$ if and only if $\Omega' + \alpha(y)e\Omega'' < 0$. This inequality holds if and only if the price elasticity of *e* with respect to p_F (measured positively) is less than 1, that is, if $El_{p_F}(-e) = \dfrac{\Omega'}{-\alpha(y)e\Omega''} < 1$, where the elasticity is defined at the point where $R_e = 0$.[7] The magnitude of this price elasticity is an empirical question, yet we find it reasonable that it is below one: most empirical studies of energy demand find price elasticities lower than one.

Reduced costs of non-carbon energy

Second, we focus on reduced costs of non-carbon (non-fossil) fuels, that is, we ignore increased energy efficiency and CCS. Let $y = y_G$, and assume that the net income function is now given by

$$R(e, y) = \max_G \left\{\Theta(e, G) - p_F e - q(y)G\right\}$$

[7] This result also holds if gross output is given by $\Phi\left(\alpha(y)^{\beta} e^{1-\beta}\right)$.

where Θ is increasing in its arguments and strictly concave, and $q(y)$ is declining in y. For an interior solution for G, we have $\Theta_G(e,G) = q(y)$, which implicitly defines the function $G = G(e, y)$ where $G_y > 0$. It is straightforward to derive that $R_{ey} = \Theta_{eG} G_y$, which is negative if and only if $\Theta_{eG} < 0$. Further, the relation $R_e = \Theta_e(e, G(e, y)) - p_F = 0$ implicitly defines $e = e(p_F, y)$ where $e_{p_F} < 0$ because of concavity. We also have $G_e < 0$ if and only if $\Theta_{eG} < 0$. Hence, $R_{ey} < 0$ if and only if demand for non-carbon energy $G(e(p_F, y), y)$ is increasing in the price of carbon energy p_F; a higher price of carbon energy will reduce emissions ($e_{p_F} < 0$), which will increase non-carbon energy G if and only if $\Theta_{eG} < 0$, which is a sufficient condition for $R_{ey} < 0$. We think the condition $\Theta_{eG} < 0$ is reasonable because typically carbon and non-carbon energy are substitutes.

Reduced costs of carbon capture and storage (CCS)

Finally, we focus on reduced costs of CCS, that is, we ignore improved energy efficiency and lower costs of non-carbon energy. Let $y = y_C$, and assume that the net income function is given by

$$R(e, y) = \max_F \left\{ \Psi(F) - p_F F - \beta(y)\chi(F - e) \right\}$$

where $\Psi' > 0$, $\Psi'' < 0$, $\chi' > 0$, $\chi'' > 0$ and the variable $\beta(y)$ is assumed to be declining in y. The optimal amount of fossil energy is given by $\Psi'(F) = \beta(y)\chi'(F - e) + p_F$, which implicitly defines the function $F = F(e, y)$ where $F_y > 0$. From the envelope theorem we have $R_e = \beta(y)\chi'(F - e) = \Psi'(F(e, y)) - p_F$. Thus $R_{ey} = \Psi''(F) F_y$, which is negative under our assumptions. Hence, $R_{ey} < 0$ under the reasonable assumptions of a concave production function and marginal costs of CCS being increasing in abatement ($\chi'' > 0$).

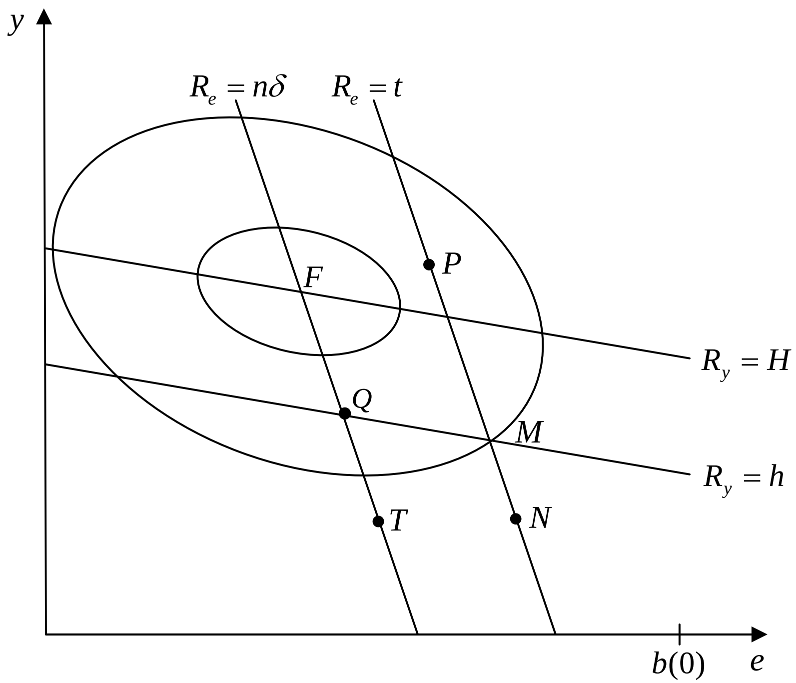

Figure 1

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