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Cost-effective environmental policy: Implications of induced technological change

Abstract:
Cost-effective environmental policy generally requires that all emission sources are faced with the same tax. In this paper I discuss how the existence of induced technological change may alter this result, if at least some of the effect is external to the firm. Focusing on learning by doing effects in abatement activities, it is shown that emission sources with external learning effects should be faced with a higher tax than emission sources with only autonomous technological change. By using simple numerical simulations, it is further investigated to what degree a cost-effective climate policy differs from a free quota market, under various assumptions about learning effects, diffusion of technology and environmental targets. The results indicate that optimal taxes may be significantly higher in the industrial world than in the developing world. Moreover, the industrial world's share of global abatement may be much higher in a cost-effective solution than in a free quota market. The global cost savings of a fully flexible implementation of the Kyoto Protocol are further questioned, as potential spillover effects of technological growth in the industrial world are not internalised in the market.

Keywords: Induced technological change, Learning effects, Climate policy, Cost-effectiveness

JEL classification: Q20, O30, H23.

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1. Introduction

One of the key results of environmental economics is that marginal abatement costs should be equalised across pollution sources (unless marginal damage costs vary with the source). Consequently, all polluters should be faced with the same Pigouvian tax rate or quota price in order to achieve a cost-effective solution. This is an appealing result, because it calls for a maximum of flexibility across the emission sources. For instance, with respect to greenhouse gas emissions, this requires a single tax rate for all polluters, or a quota market with no restrictions.

In this paper I discuss how the existence of *induced technological change* (ITC) affects the general result above. There are several sources of ITC (see e.g. Gustavsson et al. 1999). The most important ones are probably learning by doing and R&D activity. In the context of environmental problems learning by doing may be a result of abatement activities. Since abatement means cutting back on emission, some might object to the thought of 'learning by abating'. However, in most cases reducing emissions means that new, cleaner technologies are developed and adopted. This could be end-of-pipe installations, clean production processes, or alternative energy sources. There are a number of studies on the relationship between cumulative experience with new technologies and unit costs, i.e., so-called learning rates (e.g., Grübler et al. 1999). Their findings indicate that learning by doing is important to include in a study of aggregate abatement costs, which accordingly should be interpreted as a mix of reducing certain polluting activities, substituting towards cleaner technologies etc. (see, e.g., Goulder and Mathai (2000) and Parry and Toman (2000)).

Based on theoretical analyses in the paper I argue that a cost-effective solution no longer implies equal marginal abatement costs, as long as abatement activities contribute to learning effects. That is, if current abatement activities lead to increased knowledge and reduced costs in the future, these future benefits should be taken into account in the present situation. As the learning effects in general will differ across pollution sources (e.g., different industries or different regions), this calls for differentiated marginal abatement costs.[1]

Nevertheless, different marginal abatement costs do not necessarily imply that the optimal tax rate should differ between emission sources. This depends crucially on whether or not the learning effects are completely internal to the firm. If all the benefits of ITC are reaped by the firm, the company will

[1] One might argue that future cost reductions should also be included in the calculation of marginal abatement costs. This is a definitional question, and in the continuation I will sometimes use the term 'current marginal cost' for clarification.

take this into account in its decision so that total costs over time are minimised. In most cases, however, it is reasonable to believe that spillover effects to other firms and other industries are also important. Gustavsson et al. (1999) find empirical evidence of both domestic within-industry and economy-wide spillovers, and indications of global spillovers between open economies. Thus, eco-innovations are characterised by a double externality problem. In the theoretical analyses below I discuss how the optimal taxes should be designed, depending on whether the learning effects are internal or external to the firm.

Related questions have been analysed earlier with respect to market power and imported goods (see, e.g., Buchanan, 1969), in which case differentiated emission taxes may be a second best solution. Parry (1995) analyses the optimal emission tax when there is market failure in environmental R&D, and concludes that the tax may well be *below* marginal damage costs due to excessive entry of research firms. In the case of learning by doing a first best solution could be to supplement taxes with subsidies or tax incentives for clean technologies. This is suggested by Papathanasiou and Anderson (2001), who discuss the marginal social costs of investments in carbon-free technologies with external learning effects. However, as shown by Kverndokk et al. (2001), this policy could be damaging if inventors are afraid that new technologies are not given the same credit as existing ones. Moreover, it may be less challenging to impose different taxes across regions or industries, than subsidising (in a cost-effective way) clean technologies with spillover effects.

The concepts of 'learning by doing' (Arrow 1962) and 'endogenous growth theory' (Romer 1986) are well known to economists, and have been linked to environmental impacts in a number of theoretical studies (see e.g. Bovenberg and Smulders, 1995). Still, according to Carraro and Hourcade (1998), most applied economic models focusing on environmental issues do not take into account ITC. In a static context, or in a dynamic model without learning by doing effects, a cost-effective solution will require equal marginal abatement costs, confirming the traditional result. One reason for not taking into account ITC is that empirical data have been considered fairly weak so far.

Recently, however, some studies have implemented ITC into models of CO_2 emissions. Goulder and Mathai (2000) investigate how ITC affects the optimal abatement path and carbon taxes, both in a cost-effectiveness and a cost-benefit analysis. Moreover, they study both learning by doing and R&D. With learning by doing, they find theoretically that ITC has an ambiguous effect on both the initial abatement level and the slope of the path, whereas the optimal carbon tax falls. However, they do not take into account the possibility of spillover effects, and in their analysis ITC comes in addition to (not

instead of) autonomous technological change.[2] Goulder and Mathai also present some numerical simulations, in which they find that initial abatement rises slightly. The present paper builds on the model presented by Goulder and Mathai (2000), as shown in the next section.

Grübler et al. (1999) discuss how technological change may be modelled with respect to energy technologies. They point out that learning rates typically vary between 10 and 30 per cent, which means that a doubling of cumulative experience reduces unit costs by this amount. The rates are usually highest in the early stages of development, and lowest when the technology is mature. They use this insight in a macro-scale model and find that a 'dynamic technology' scenario produces a far less polluted future than the baseline scenario with no endogenous learning effects, as cleaner energy technologies are being used.

Other related studies are e.g. Parry and Toman (2000), who find that learning by doing may significantly reduce the costs of early abatement credits related to the Kyoto commitments. However, only slightly more abatement is justified in the pre-commitment period (i.e., before the Kyoto period 2008-12). Both internal and external learning effects are considered. Buonanno et al. (2000) investigate whether restrictions on emission trading in the Kyoto Protocol is cost saving when environmental R&D is modelled explicitly. Their conclusion is negative. However, spillover effects are not considered. Both Grübler and Messner (1998) and Dowlatabadi (1998) find that including learning effects into the model implies that the optimal abatement increases initially compared to a similar model where the technological change is autonomous. Goulder and Schneider (1999) conclude that the costs of achieving a certain emission target drops with ITC, but that the gross costs (i.e., ignoring environmental benefits) of a given carbon tax probably increases due to more abatement. Baudry (2000) points out that increased R&D effort reduces the optimal abatement level initially as future costs are reduced.

None of the studies referred to above investigate the impact of different learning effects between regions (or other kinds of differentiation). Thus, based on the theoretical model presented below, I construct a simple numerical model that can be used to study CO_2 policies (other greenhouse gases are not considered, but could be an interesting extension of the analysis). Then I investigate how a cost-effective outcome differs from a free quota market (or equal taxes). The model describes the costs of

[2] This means that the ITC scenario is a more technology optimistic scenario than the scenario without ITC. It would have been interesting to also test the impact of *replacing* autonomous technological change with ITC (see the numerical section below).

reducing CO_2 emissions in the Annex B and Non-Annex B regions as defined by the Kyoto Protocol,[3] and how abatement costs are reduced over time due to technological growth. Technological growth in the Annex B region is assumed to be (partly) induced through learning by doing with spillover effects, whereas in Non-Annex B technological growth is assumed to be (partly) due to diffusion of technology from the industrial world. This differentiation is more or less in accordance with observations made by Sachs (2000) and Coe et al. (1997). Market barriers such as financial restrictions and structural barriers, which are important for alternative energy sources (Oliver and Jackson, 1999), are not considered here.

The numerical example discusses how optimal carbon taxes and abatement levels differ between a cost-effective solution and the outcome of a free quota market. First I focus on scenarios that are never allowed to increase the CO_2 concentration level above 550 ppmv (i.e., a doubling of pre-industrial level). Then I turn to scenarios that in addition to the long run target comply with the Kyoto Protocol, and ask if a fully flexible implementation of the protocol is more or less cost-effective. Most economists would return an affirmative reply to this question, whereas others are more doubtful. For instance, Grubb et al. (1999) put forward the "potential tension between cost minimization in the first commitment period, and the generation of sufficient - and efficient - pressures required to change course towards long-term stabilization", and mention the fear that "too much flexibility" will be an obstacle to crucial innovations. The simulations seem to support this latter view, i.e., involving developing nations into the Kyoto Protocol may be far less important for cost minimisation than concluded in most other studies (e.g., Weyant, 1999).

In the next section the theoretical model is outlined and investigated. Section 3 deals with the numerical model, whereas section 4 concludes.

2. Cost-effective abatement with learning by doing

2.1. Cost-effective solution

The model structure used in this paper is based on Goulder and Mathai (2000). The main extension is the inclusion of different emission sources. In order to keep the analytical framework clear, I focus on the case with two emission sources j=F,G (the results can easily be generalised to more emission

[3] The Annex B countries are the ones that have committed to specific emission targets in 2008-12. These are mainly the OECD countries and the so-called Economies in Transition (EIT), i.e. the Eastern Europe and the former Soviet Union. After the agreement was signed, the U.S. has withdrawn from the treaty, which means that the most important party no longer belongs to the Annex B region.

sources). This could be e.g. different sectors or industries, different end users, different groups of countries, or different gases (e.g. climate gases comprised by the Kyoto Protocol). In the following I will mainly speak about different regions, as the numerical part focuses on abatement in Annex B vs. Non-Annex B. Let $C^j(A_t,H_t)$ denote the total abatement costs at time t in region j, where A denotes abatement level and H denotes the state of knowledge or level of technology. Following Goulder and Mathai, it is assumed that $C_A>0$, $C_{AA}>0$, and $C_H<0$. That is, costs are assumed to be an increasing and convex function of abatement, and a decreasing function of knowledge. Abatement is simply defined as the emission reduction compared to a fixed business-as-usual emission path $E^{0,j}_t$.

As mentioned above, growth in knowledge or technological innovation may occur in different manners. Here it is assumed that current abatement affects technological progress, i.e. through learning by doing. That is, by gaining experience with the use of clean technologies, the productivity increases and costs are reduced. The learning effects may either be internal to the firm, or external through spillover effects within the industry or region. I will also allow for spillover effects across emission sources, i.e., from one industry to another or from one region to another (e.g., from western economies to newly industrialised countries).

In this section I focus on the cost-effective solution for complying with a given environmental constraint. This could either be a flow constraint, i.e., restricting total emissions in each period, or a stock constraint, i.e., restricting the emission path so that the concentration level is below a given target (e.g., the CO_2 concentration). As the former may be expressed as a special case of the latter, I concentrate on the stock problem.[4]

The optimisation problem for a social planner may then be described as follows:

(1) $$\min_{A^j} \int e^{-rt}\left(C^F(A_t^F, H_t^F) + C^G(A_t^G, H_t^G)\right)dt$$

s.t.

(2) $$\dot{H}_t^j = \alpha^j H_t^j + k^j \psi^j(A_t^j, H_t^j) + l^j \theta^j(H_t^i, H_t^j), \qquad i, j \in \{F, G\},\ i \neq j$$

(3) $$E_t = (E_t^{0,F} - A_t^F) + (E_t^{0,G} - A_t^G)$$

[4] With a 100 per cent natural decay of the stock in each period, and a one-to-one relationship between emissions and stock in equation (4), the problem is turned into a flow problem.

(4) $\dot{S}_t = f(S_t, E_t)$

(5) $S_t \leq \bar{S} \qquad \forall t$

H_0, S_0 given

The objective function in equation (1) simply states that the total abatement costs for the two regions should be minimised. That is, distributional effects across regions are not considered.

The knowledge accumulation or technological progress described in equation (2) consists of three parts. The first expresses the autonomous technological change, i.e., the progress that occurs irrespective of abatement, at the rate α. The second part expresses the learning by doing effect, which occurs when k>0. The technological change is a function $\psi()$ of both abatement activity and the current level of technology (i.e., the state of knowledge may affect the learning by doing effect). The abatement activity can either be within the firm or within the industry or region (spillover effects). For a social planner this is irrelevant as long at the firms are identical, but I return to this question in the next subsection. The shape of the function is not clear, and for the moment no restrictions are imposed on its partial derivatives except that $\psi_A>0$.

The third part covers the potential spillover effect, i.e., technological diffusion, from one region to another, which occurs when l>0. $\theta^j()$ is assumed to be a non-decreasing function in H^i ($i \neq j$), and a non-increasing function in H^j. This means that diffusion is slowing down when the technological difference between two regions shrinks. For instance, developing a more efficient energy technology in the US may sooner or later become available for industries in East Asia. Of course, transaction and patent costs should be included in a full cost assessment, but there is no doubt that technological diffusion generally is beneficial for the receiving country. I will not dwell upon diffusion in the theoretical discussion, ignoring its impact on the shadow price of knowledge (implicitly assuming $l \approx 0$). Instead I return to this matter in the numerical simulations below.

Equation (3) calculates total emissions in each period, E_t, as the sum of BaU emissions net of abatement in both regions. Equation (4) expresses that the stock change may be a function of both the current stock level S_t and the emission level, whereas equation (5) states that the stock should not exceed the given target $\bar{S}$ in any period.

The current value Hamiltonian can now be constructed in the following way (the time notation is omitted):

$$
\begin{aligned}
H^c = & -\left[C^F(A^F,H^F)+C^G(A^G,H^G)\right]-\tau\left[f(S,(E^{0,F}-A^F)+(E^{0,G}-A^G))\right]+ \\
& \mu^F\left[\alpha^F H^F + k^F\psi^F(A^F,H^F)+l^F\theta^F(H^F,H^G)\right]+ \\
& \mu^G\left[\alpha^G H^G + k^G\psi^G(A^G,H^G)+l^G\theta^G(H^F,H^G)\right]
\end{aligned} \tag{6}
$$

where E has been replaced by using equation (3). τ denotes the shadow cost of the pollution stock, and μ^F and μ^G denote the shadow price of the knowledge stock in the two regions.

In this problem there are two control variables, A^F and A^G. The necessary conditions may then be found by derivating (6) w.r.t. these two variables:

$$\frac{\partial H^c}{\partial A^F} = -C^F{}_A(A^F,H^F)+\tau\cdot f_E(S,E)+\mu^F k^F\psi^F{}_A(A^F,H^F)=0 \tag{7}$$

$$\frac{\partial H^c}{\partial A^G} = -C^G{}_A(A^G,H^G)+\tau\cdot f_E(S,E)+\mu^G k^G\psi^G{}_A(A^G,H^G)=0 \tag{8}$$

Moreover, the shadow cost of pollution should develop according to the following equation, where r is the discount rate and f_S is the natural decay rate at concentration level S:

$$\dot{\tau} = (r - f_S(S,E))\tau \tag{9}$$

From (7) and (8) the following relationship between optimal abatement in the two regions is found:

(10)

$$C^F{}_A(A^F,H^F)-\mu^F k^F\psi^F{}_A(A^F,H^F)=C^G{}_A(A^G,H^G)-\mu^G k^G\psi^G{}_A(A^G,H^G)=\tau\cdot f_E(S,E)$$

The first terms on each side of the first equation denote the current marginal abatement costs in each region, whereas the second terms denote the marginal value of future improvements in technology due to current abatement. Hence, equation (10) expresses that marginal abatement costs should be equalised across regions *when the future cost reductions of current abatement is taken into account*.

That is, as induced technological change due to learning by doing will be equal across regions only by accident, a cost-effective solution is in general characterised by different (current) marginal abatement costs.

Of course, it is nothing new in the fact that future abatement costs should be taken into consideration - after all the choice of abatement activities often involves investment in new equipment or machinery, which will be used also for future abatement. Still, the conventional result requires that *marginal abatement costs at each point of time* are equalised, as investments in new machinery are fixed costs. Equation (10), however, differs from this condition in that it specifies that even current marginal abatement costs should in general differ across regions. For instance, if the abatement cost structure and stock of knowledge is identical in the two regions, but induced technological change only occurs in region F, more abatement should take place in region F according to (10).

Maintaining the assumption that induced technological change only occurs in region F, i.e. that $k^G=0$, equation (10) can be expressed in the following manner:

$$\text{(11)} \qquad \frac{C^F{}_A(A^F, H^F)}{C^G{}_A(A^G, H^G)} = 1 + \frac{\mu^F k^F \psi^F{}_A(A^F, H^F)}{C^G{}_A(A^G, H^G)}$$

This equation states that the relationship between marginal abatement costs in region F and G should equal unity plus the ratio between current marginal value of future cost reductions from abatement in region F and marginal abatement costs in region G. That is, if current abatement in region F brings about significant learning effects and cost reductions in the future compared to the marginal abatement costs in region G, then the cost-effective solution may require large differences between the marginal abatement costs in the two regions.

To investigate the impact of ITC on cost-effective abatement levels in the two regions, equation (10) is differentiated with respect to k^F, assuming $k^F=k^G=0$ initially. In the rest of this section I also assume that $f_E=1$, i.e., there is a one-to-one relationship between emission and the pollution stock in each period. Then I obtain:

$$\text{(12)} \qquad \frac{dA^F}{dk^F} = \frac{\dfrac{d\tau}{dk^F} + \mu^F \psi_A^F - C_{AH}^F \dfrac{dH^F}{dk^F}}{C_{AA}^F}$$

(13) $$\frac{dA^G}{dk^F} = \frac{\frac{d\tau}{dk^F}}{C_{AA}^G}$$

From Goulder and Mathai (2000) we know that $d\tau/dk \leq 0$, i.e., that induced technological change reduces future costs and thus the costs of dealing with the pollution stock. Consequently, equation (13) states that abatement in region G is decreasing (or unchanged) in each period when ITC is introduced for the other region.

It is not clear from equation (12) whether abatement in region F is increased or not in a given period when ITC is introduced for this source. The second term in the numerator is positive, and the third is non-negative unless abatement is significantly reduced (initially the term is equal to zero). These two terms cover the improvements in technology. The first term in the numerator is the same as for region G, and is negative. Hence, the sign of the expression is ambiguous. However, since the pollution stock constraint is given and abatement in region G is non-increasing, abatement in region F must eventually increase at some point of time to comply with the environmental constraint.[5]

Condition (10) is illustrated in Figure 1 for the case with $k^G=0$, i.e., with no learning by doing in region G. For illustrative purposes the abatement cost functions and initial knowledge stock are set equal for the two regions. In addition to the earlier assumptions above, it is assumed in the figure that $C_A(0,H)=0$ and $\psi_{AA}(A,H)<0$ (these are both in accordance with the numerical specifications in Section 3). That is, marginal abatement costs are increasing from zero, and there are diminishing returns in the learning process. In order to know the shape of the second part of equation (10) we must also know how the state variable μ^F varies with A. This is not straightforward, and here it is simply assumed that μ^F is positive and not increasing in A.[6] This implies that the absolute value of the second part of equation (10) is decreasing in A.

The identical marginal abatement cost curves for the regions F and G are shown as the solid line in the figure called MAC. In the conventional framework without ITC, the cost-effective solution is where

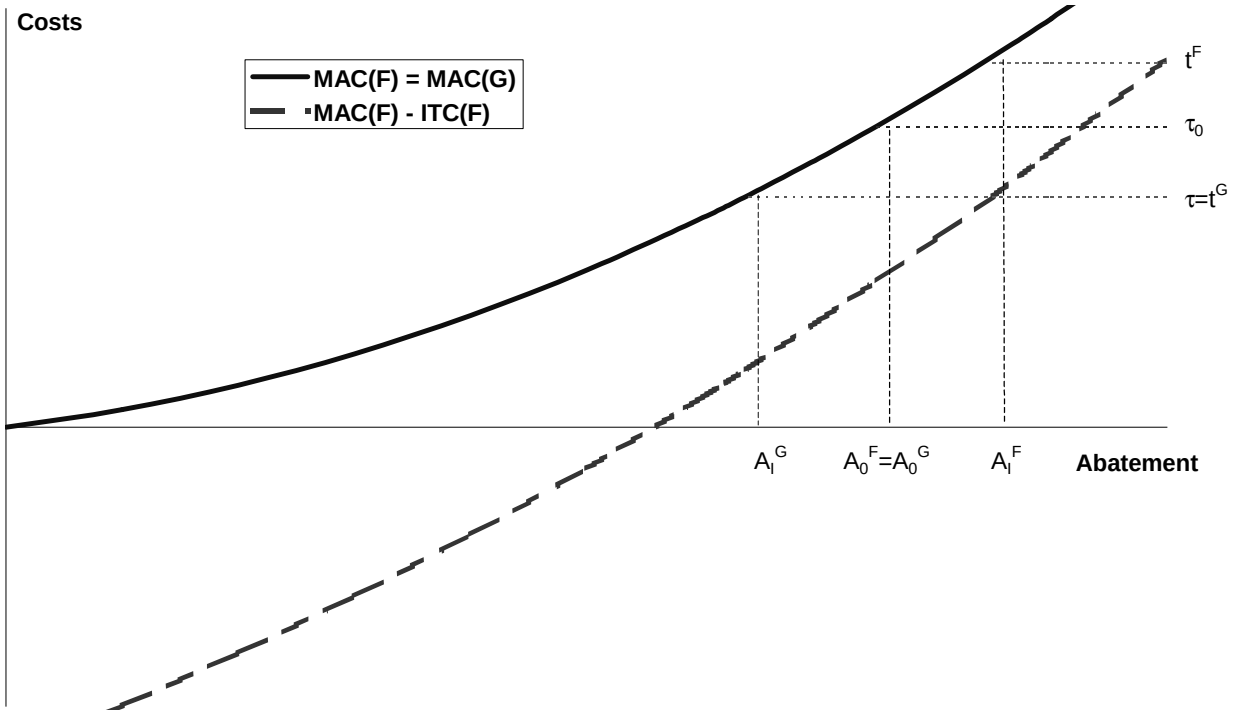
[5] In the flow pollution problem the first equation in (10) still holds. In this case it is easy to show that introducing ITC in region F implies that abatement drops in region G and rises in region F at each point of time. The reason is of course that total emission is fixed in each period.

[6] Higher abatement will increase future knowledge, and with diminishing returns to learning in the abatement cost function, this means that the shadow price of knowledge falls for fixed future abatement. However, future abatement may either increase or decrease as a consequence of higher current abatement, changing the size of the shadow price. Hence, the shape is in general ambiguous.

these curves meet the shadow cost of the pollution stock, τ_0 (i.e., with abatement equal to $A_0^F=A_0^G$). However, future reductions in abatement costs due to ITC in region F should be taken into account according to equation (10). That is, the cost-effective solution should then be where the curves MAC(F)-ITC(F) and MAC(G) have the same value, and this value is equal to τ. Note from above that the level of τ is lower with ITC than without. It is seen from the figure that abatement in region G (A_I^G) has decreased with ITC, as documented above. In the figure abatement in region F (A_I^F) has increased - as explained above this might not be the case in every period.

With the assumptions made above, the curve MAC(F)-ITC(F) will always start below zero. This means that there are net gains from abatement up to a certain level in each period (of course, on the condition that positive abatement is required in the future).

Figure 1. Cost-effective abatement with induced technological change



2.2. Optimal tax policy

From a policy point of view, what should the optimal tax policy look like, in order to achieve the cost-effective solution? To see this, consider N identical, atomic firms in each region, minimising their costs (lower case letters are used to identify individual firms as opposed to the whole region):

$$(14)\ \min_{a^s} \int e^{-rt}\left(c(a^s,h^s)+t^j(e^{0,s}-a^s)\right)dt = \int e^{-rt}\left(\frac{1}{N}C^j(Na^s,h^s)+t^j(e^{0,s}-a^s)\right)dt, \qquad s\in\ j=F,G$$

where t^j is the emission tax faced by region j. Note that h^s=H and a^s=A/N in any equilibrium.

Now, an important question is whether the induced technological change is internal or external to the individual firm. I assume that the learning effects in each firm depend on a weighted sum of abatement within the firm and total abatement in the region.[7] In order to correspond with the aggregate learning by doing function (see equation (2)), the firm specific function must be $\psi(\varphi Na^s+(1-\varphi)A^j,h^s)$, where φ is a parameter between zero and one (a similar function is used by Parry and Toman, 2000). Then, φ=1 means that ITC is a totally internal effect, whereas φ=0 means that ITC is only due to spillover effects within the region. In equilibrium $A^j=Na^s$, which means that the value of φ directly indicates the relative importance of internal and external learning effects. Knowledge growth in the individual firm is thus given by:

$$(15)\qquad \dot{h}^s = \alpha^j h^s + k^j\psi^j(\varphi Na^s + (1-\varphi)A^j, h^j), \qquad s\in\ j=F,G$$

The Hamiltonian can now be constructed for each firm, with $\mu^s=\mu/N$. Differentiating with respect to the control variable a^s, and substituting firm specific with aggregate variables, gives the following conditions:

$$(16)\qquad C_A^j(A_t^j,H_t^j)-\varphi^j\mu^j k^j\psi_A^j(A_t^j,H_t^j)-t_t^j=0 \qquad ,j=F,G$$

To achieve the cost-effective solution in equation (10) the following condition for the optimal tax rates is obtained:

[7] Alternatively, A could be specified as a Cobb Douglas function of A_{EX} and A_{IN}. However, this would imply that abatement within the region had no learning effects in a firm unless there were some abatement also within the firm, and vice versa (assuming atomic firms).

(17) $$t^F - (1-\varphi^F)\mu^F k^F \psi_A^F(A^F, H^F) = t^G - (1-\varphi^G)\mu^G k^G \psi_A^G(A^G, H^G) = \tau \cdot f_E(S,E)$$

First, note that with φ^j=1, the optimal tax rate should be equal for the two regions, even though current marginal abatement costs in general should differ due to learning by doing. The reason is that if the induced technological change is totally internal to the firm, each firm takes into account that more abatement today lowers its abatement costs in the future. Therefore, the firm will abate more than if they had a static perspective (i.e., the firm allows the current marginal abatement costs to be higher than the tax rate). Moreover, the optimal tax rate should equal the shadow cost of emission, as Goulder and Mathai (2000) also demonstrate in their framework, and thus increase by the rate ($r-f_S$) over time according to equation (9) (assuming f_E constant).

On the other hand, if $\varphi^j<1$ (and $k^j>0$) for at least one region, equation (17) states that the optimal tax rate should in general differ across the regions. In particular, if ITC only occurs in region F, the optimal tax rate should be higher for this region than for the other. The tax difference is equal to the product of the marginal value of abatement on ITC (which is illustrated in Figure 1) and the spillover parameter φ. In this case the firms are stimulated to abate more and so achieve more technological progress in the whole region. With external, but no internal, effects on technological change in region F (φ^F=0), and no ITC in region G, the optimal tax rates should equal t^F and $t^G=\tau$ in Figure 1. It is also clear from equation (17) that the optimal tax rate should be higher than the shadow cost of emission in regions with spillover effects of ITC.

With spillover effects of ITC in region F only, it is easy to see that the optimal tax in region G should increase by the rate ($r-f_S$), i.e., the same rate as with no spillover effects of ITC at all. The optimal tax in region F, however, no longer increases by this rate. By time differentiating (17), using (9) and rearranging, the following is obtained:

(18) $$\frac{\dot{t}^F}{t^F} = (r - f_S)\frac{\tau \cdot f_E}{t^F} + \mu^F k^F \frac{\psi_{AA}^F \dot{A}^F + \psi_{AH}^F \dot{H}^F}{t^F}$$

Note that the first part of the expression is the growth rate of the shadow cost of pollution, adjusted for the ratio between the shadow cost and the tax level. Since the ratio is less than one, this first part is smaller than ($r-f_S$). The second part consists of a fraction with two components in the numerator. The signs of both components are ambiguous, and so it is impossible to draw general conclusions about the growth rate of the optimal tax in region F. However, it can be seen that higher abatement growth over time decreases the

growth rate of the optimal tax. Furthermore, if improved knowledge intensifies the learning by doing effects, the tax grows more rapidly than otherwise. In practice, the optimal tax may actually *decrease* over time despite a positive discounting (this is further discussed in the numerical simulations).

Goulder and Mathai (2000) find that the optimal tax level is reduced when ITC is introduced (and no spillover effects exist), as the shadow cost of pollution drops. What is the impact on the optimal tax level when there are different emission sources and spillover effects are in place? Differentiating equation (17) with respect to k^F, assuming $k^F=k^G=0$ initially, the following is found (assuming $f_E=1$):

$$\frac{dt^F}{dk^F} - (1-\varphi^F)\mu^F\psi_A^F = \frac{dt^G}{dk^F} = \frac{d\tau}{dk^F} \tag{19}$$

The tax level in region G obviously falls in line with the reduction in the shadow cost of pollution. However, the tax level in region F may either decrease or increase. With complete spillover effects (i.e., $\varphi^F=0$), the question is whether the marginal value of more abatement on technological progress ($\mu^F\psi^F_A$) exceeds the drop in the shadow cost. From equation (12) and (19) combined it is seen that if the optimal tax level for region F increases initially, it follows that abatement in the region increases at least as long as the optimal tax increases (but not the other way around).

Assuming spillover effects in one region, what are the extra social costs of facing both regions with the same tax rate compared to the optimal tax policy given by equation (17)? For instance, there has been a discussion about the degree of flexibility in implementing the Kyoto Protocol, with respect to quota trading, carbon sinks and the so-called Clean Development Mechanisms (i.e., replacing domestic abatement with emission reductions outside the Annex B area). Is it really cost-effective to strive for a maximum of flexibility, or are there cost savings in the long term by putting stronger measures on CO_2 emissions in the industrial world, where spillover effects of learning may be important? Another interesting question is how the distributional impacts on the different regions are with respectively identical taxes and a cost-effective tax policy?

These are difficult questions to answer within a theoretical framework, but will be studied in the numerical section below. However, before I turn to the simulations, it is useful to discuss under what conditions one may expect significant cost differences. First of all, there must be a considerable learning effect through abatement. That is, the current value of the future cost reductions by abating today must be comparable with the actual costs today. Both the partial derivatives ψ_A and C_{AH}, and the

discount rate are important here. Second, the marginal abatement cost functions must not be too steep.[8] If so, there are substantial current cost increases by deviating from the conventional result that marginal costs should be equal.

3. Numerical examples related to climate policy

In this section I will present some numerical simulations related to climate policy that shed light on the theoretical findings above. The aim is to investigate how learning by doing and spillover effects may affect the cost-effective climate policy. I will assume that learning by doing effects are only present in the Annex B region, whereas technological change in Non-Annex B countries is exogenous or due to diffusion of technology from the industrial world. Moreover, for simplicity the learning effects are assumed to be fully external to the firms,[9] which implies that the cost-effective solution is characterised by different carbon taxes or quota prices in the two regions.

3.1. Numerical model description

Goulder and Mathai (2000) present numerical simulations for the global emissions of CO_2. Thus, as the theoretical model above is based on their work, it is natural to use some of their numerical data and functions as well, where suitable. In addition, some new functions are calibrated based on available data. This is explained more fully in the Appendix. In the current section I only present the numerical functions.

The following simplistic function for CO_2 concentration in the atmosphere is used:

(20) $$\dot{S}_t = \beta E_t - \delta(S_t - PIL)$$

where β=0.30, δ=0.008, and PIL=278 ppmv (preindustrial level). The concentration level starts at 360 ppmv in the first period (1995-2004). The A1 marker scenario from IPCC's Special Report on Emission Scenarios (IPCC, 2000) is used as baseline. CO_2 emissions in A1 peak in the middle of this century for both Annex B and Non-Annex B.[10]

The following abatement cost functions are used for the two regions:

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[8] Steep is of course a relative term. What is interesting is the elasticity of marginal costs with respect to abatement level.

[9] I will come back to the effects of only partially external learning effects.

[10] IPCC (2000) presents four equivalent marker scenarios. In Section 3.3 I use the A2 scenario, which is less optimistic with respect to reductions in carbon intensity without climate policy.

(21) $$C(A^j, H^j) = M_C^j \frac{(A^j)^{\alpha_{C1}^j}}{(E^{0,j} - A^j)^{\alpha_{C2}^j}} \frac{1}{H^j} \qquad , j = Annex\,B, Non - Annex\,B$$

For Annex B the parameter values are M_C=220, α_{C1}=2 and α_{C2}=1, whereas for Non-Annex B the values are M_C=180, α_{C1}=2 and α_{C2}=1. That is, abatement in Non-Annex B is slightly less costly than in Annex B, but not much. This seems to be in accordance with the available information given in Tol (1999) (Table 4, abatement cost functions) and McKibbin et al. (1999) (Table 9, results of global permit trading).

The learning by doing effect in Annex B is assumed to have the following characteristic:

(22) $$\psi^j(A^j, H^j) = M_\psi^j (A^j)^\gamma (H^i)^\phi, \qquad j = Annex\,B$$

with γ=0.5 and ϕ=0.5. This function implies that there are diminishing returns in the learning process in the short run (γ<1), but in the long run knowledge accumulation becomes easier as technology improves (ϕ>0). The value of M_ψ is both uncertain and critical for the results. Thus, I investigate both a 'medium learning' scenario in the main simulations (with M_ψ=0.011), and an 'optimistic learning' scenario (M_ψ=0.045) and a 'pessimistic learning' scenario (M_ψ=0.0045) in the sensitivity section (3.4).

The autonomous technological change is assumed to be 0.25 per cent per annum in Annex B, and 0.82 per cent in Non-Annex B. The latter rate is found based on the assumption that the technological growth rate in Non-Annex B in the long term is closely related to the growth rate in Annex B (i.e., due to technological diffusion from industrialised to developing countries).[11]

I will also simulate scenarios where the technological diffusion is modelled explicitly (see the last term in equation (2)). In this case the autonomous technological change is assumed to be equal in the two regions, i.e., 0.25 per cent per year. Diffusion is assumed to have the following functional form:

(23) $$\theta^j(H^i, H^j) = \sigma^j(H^i - H^j), \qquad j = Non - Annex\,B,\ i = Annex\,B$$

[11] Consequently, the autonomous technological change in Non-Annex B is assumed to be higher in the 'optimistic learning' scenario (2.0) and lower in the 'pessimistic learning' scenario (0.50).

The value of σ^j is highly uncertain, and so is the initial ratio H^j/H^i. In the main simulations σ^j is conservatively set equal to 0.01, and $(H^j/H^i)_0$=0.25. That is, diffusion brings about 1 per cent reduction in the technological gap between Annex B and Non-Annex B each year. However, these values are varied in the sensitivity section.

The discount rate is set equal to 5 per cent. The model solves (using GAMS) with 10-years periods from 2000 (1995-2004) to 2400. Beyond this year the effects may be ignored due to discounting.

3.2. Stabilising CO_2 concentration - cost-effective abatement

In this section I investigate abatement scenarios that keep the CO_2 concentration below 550 ppmv in all future periods. I compare two scenarios. The 'cost-effective scenario' minimises global abatement costs over time, by distributing abatement between Annex B and Non-Annex B, and between time periods, so as to manage the CO_2 goal at least costs (taking into account ITC in Annex B). The 'free quota market scenario' also minimises global abatement costs, but in addition the scenario requires a free quota market (or equal carbon taxes) across the world in each period. Without ITC these scenarios would of course be identical, as the cost-effective solution would be characterised by equal carbon taxes.

Figure 2. Annex B's share of global abatement in cost-effective and free quota market scenario

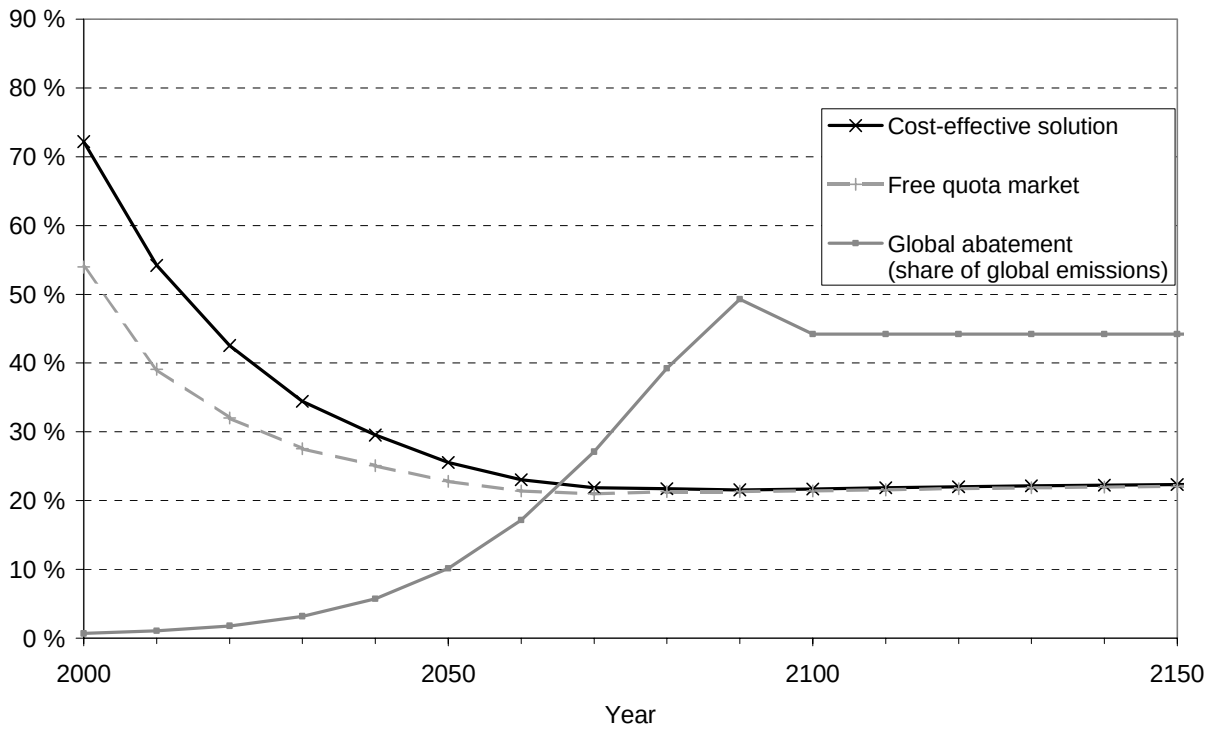


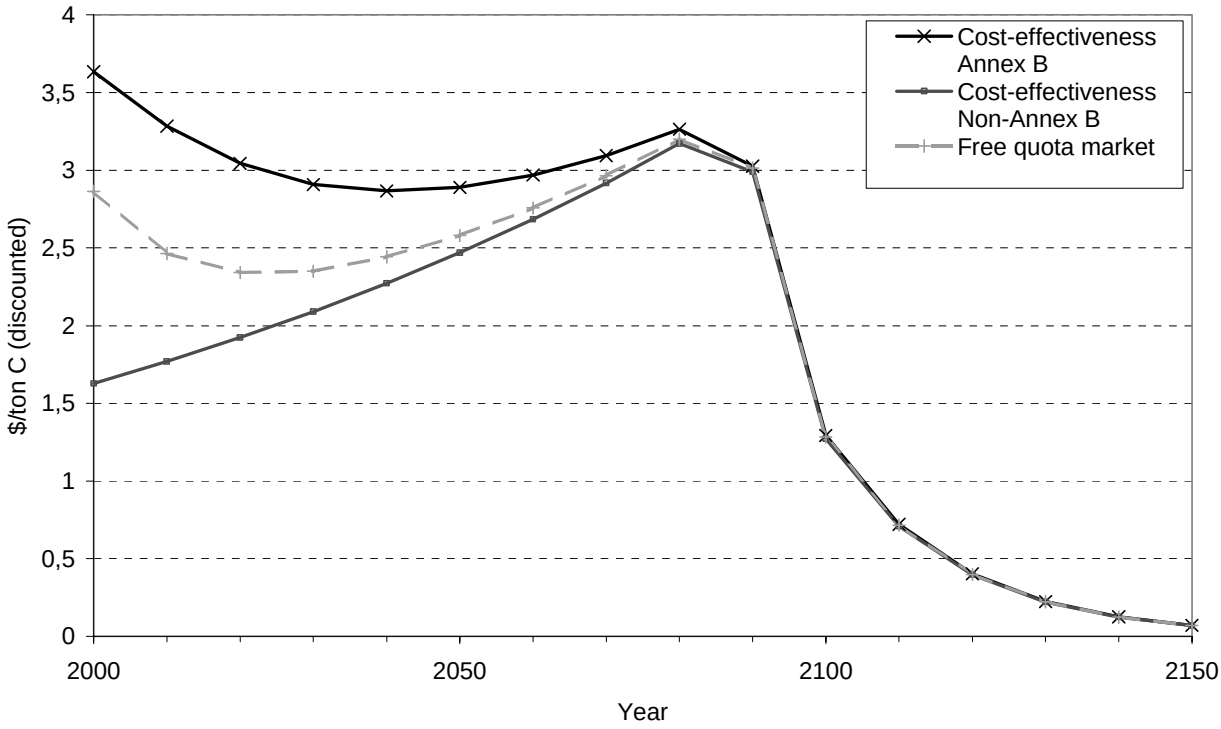
Figure 2 shows the share of global abatement of CO_2 that takes place in Annex B in the two scenarios. According to the results, the Annex B region should abate significantly more in the cost-effective scenario than in the free quota market, especially in the first part of the century. In the first period the difference is 18 percentage points. Due to the discounting the global abatement level is quite low in the first periods (see the figure). Consequently, the marginal abatement cost curves are fairly flat, which partly explains the large differences in Annex B's share of abatement. Around 2050 the global abatement levels are higher, and the difference between the two scenarios is reduced to 3 percentage points. In 2090 the CO_2 concentration limit of 550 ppmv is reached, and global abatement stabilises around 44 per cent (the overshooting in 2090 is due to the resolution time in the model).

Figure 3 presents how the (discounted) optimal carbon tax or quota price should evolve over time in the two scenarios and the two regions.[12] Note that in the free quota market scenario the taxes are equalised across the two regions. In the first period the optimal carbon tax in Annex B should actually be more than two times higher than in Non-Annex B. The difference shrinks over time, but firms and consumers in western economies should even in 2030 be faced with 40 per cent higher carbon taxes than firms and consumers in developing economies, given these assumptions. Consequently, learning by doing with spillover effects leads to a significant departure from the traditional free market solution. The quota price realised in the free quota market lies between the two quota prices that are realised in the cost-effective outcome. Notice that the carbon tax in both scenarios suddenly drops around 2080-90 when the concentration limit is reached.

Goulder and Mathai (2000) found that, without spillover effects, the optimal carbon tax should increase by the rate $r+\delta=0.058$ (i.e., discount rate plus decay rate) until the upper limit of the concentration level is reached. With spillover effects in Annex B only, it was documented above that the optimal tax in Non-Annex B should increase by the same constant rate, i.e., 0.058. This is also seen in the Figure 3 above. In Annex B, however, it was theoretically unclear if and how the tax rate should grow over time. The numerical simulations suggest that the optimal carbon tax in Annex B initially should rise by the rate 0.040, i.e., less than the discount rate (note that the figure displays discounted tax levels). Towards the end of the century, when the concentration limit is getting close, the rate approaches 0.058. Thus, I conclude that spillover effects of ITC call for a less steep carbon tax path in Annex B.

[12] The carbon taxes in Figure 3 are much lower than expected quota prices realised by the Kyoto protocol. This is further discussed in Section 3.3.

Figure 3. Discounted optimal carbon taxes in Annex B and Non-Annex B in cost-effective and free quota market scenario



Despite the significant differences between the abatement shares and optimal carbon taxes in the two scenarios, the simulations conclude that the global, discounted costs are almost equal. The cost-effective scenario reduces costs by merely 0.25 per cent. The 'investment' in learning is covered within the fifth 10 years period, and almost the entire cost savings are reached before the end of the century. One explanation for the modest cost savings is that Annex B countries, which are affected by the ITC, emit less than one quarter of global emissions in the last decades of this century. However, note that the results presented above are very sensitive to the size of the learning by doing effects, which is quite uncertain (see the sensitivity analyses in Section 3.4).

It is also interesting to see how the abatement costs are distributed between the two regions in the two scenarios. In the cost-effective scenario Annex B takes a larger share of abatement, and thus their costs are 9 per cent higher than in the free quota market scenario. Abatement costs in Non-Annex B (which are much higher than in Annex B due to higher emissions) are 3 per cent lower in the cost-effective outcome. Consequently, the cost distribution is much more affected than the total global costs.

Usually the learning effects are not only due to spillovers from other firms. As demonstrated in Section 2, a firm will take into account the *internal* learning effects in its abatement decisions. To investigate the effects of only partial spillover effects, I run a scenario where half of the learning effects experienced by a firm are due to spillovers (i.e., φ=0.5 in equations (15) - (17)). In this case the free quota market scenario produces more abatement in Annex B, i.e., 64 per cent vs. 54 per cent with only spillovers. However, the free quota market is still significantly different from the cost-effective one, where Annex B abates 72 per cent of global abatement. On the other hand, the cost savings from a cost-effective solution have declined considerably, from 0.25 per cent with complete spillovers to 0.04 per cent with partial spillovers. Thus, the need to correct the free quota market is significantly reduced when the learning effects are partially internal.

Until now it is assumed that the technological rate of change in Non-Annex B is autonomous. However, it is more reasonable to assume that a major part of the technological improvement is due to diffusion of technology from industrial countries in Annex B. On the other hand, as mentioned in Section 3.1, the diffusion rate is very uncertain, and so the results should be considered with caution (although a conservative diffusion rate is used). Still, the results presented below do not seem to be very sensitive to the speed of diffusion (see Section 3.4).

The difference between the cost-effective and the free market scenarios obviously becomes enhanced when diffusion is modelled explicitly. The initial cost-effective abatement share of Annex B increases from 72 to 80 per cent, whereas the free market scenario results in only 54 per cent. The optimal carbon tax in Annex B is now 3.6 times higher than in Non-Annex B initially, compared to 2.2 times higher without diffusion. Substantial effects of diffusion are also observed for the next 50 years or so. The cost differences rise as well; a free quota market is now 0.8 per cent more costly than a cost-effective one (versus 0.25 per cent without diffusion).

Although the parameter values chosen in the numerical simulations may be conservative (see the sensitivity analyses in Section 3.4), it is tempting to conclude from above that the cost savings are so small that the effects of ITC should be ignored, i.e., the free market should not be altered. However, two points should be made here. First, the free quota market scenario does *not* ignore the spillover effects of ITC in Annex B - it only imposes the restriction that the quota price should be equalised across the two regions. This is seen e.g. in Figure 3 where the optimal carbon tax in the free quota market scenario does not increase by the rate $r+\delta$=0.058, but by the rate 0.035 which is actually lower than the corresponding rate for Annex B in the cost-effective outcome. The reason is that in the free

quota market scenario the optimal common tax rate is a balance between the optimal tax rate for Annex B and the optimal tax rate for Non-Annex B. That is, even with a free quota market the spillover effects of ITC should be taken into account. Second, in the climate change debate the question is not about altering a free quota market, but about to what degree abatement in Non-Annex B should be used as a substitute for Annex B abatement obligations. The current analysis may indicate that the cost savings from this substitution are not very high in the long term, when learning by doing is taken into account. In the next section I will discuss this more directly, by simulating scenarios that fulfil the Kyoto Protocol. Before that, however, I will briefly compare the results of a model with and without ITC.

So far the presentation has focused on the difference between two scenarios that are both based on a model with ITC in Annex B. What about the effects of introducing ITC into the model, i.e., compared to scenarios with only autonomous technological growth? In the theoretical section it was shown that Non-Annex B abatement should fall in each period. The numerical simulations suggest that the reduction is 8 per cent initially. For Annex B and global abatement the theoretical results were ambiguous, although accumulated Annex B abatement over time should rise. Here the numerical simulations suggest that Annex B abatement should increase in every period (a doubling initially), and that global abatement should increase in the first five periods, for then to fall slightly.

It was also proven in Section 2 that the optimal carbon tax is reduced in Non-Annex B when ITC is introduced in Annex B. The numerical results indicate a permanent drop of 8 per cent until the concentration limit is reached. One could not conclude theoretically whether the optimal carbon tax in Annex B would rise or fall. The numerical simulations suggest a doubling in the first period, but the difference shrinks gradually over time. From 2070 the optimal carbon tax is lower with ITC than without. Goulder and Mathai (2000) concluded that introducing ITC through learning by doing (but without spillover effects) unambiguously reduced the optimal carbon tax. The results in the present paper indicate that this conclusion probably is reversed if the learning effects are fully external to the firm.

Another interesting comparison between ITC and no ITC is to replace the technological growth effect of ITC with an autonomous technological change that gives the same technological improvement in the long run.[13] In this case introducing ITC leads to an even higher Annex B abatement in the first two

[13] This is especially relevant since much of today's knowledge about carbon taxation is based on studies with only *autonomous* technological change incorporated.

periods than above, at the same time as Non-Annex B abatement is almost unchanged. From 2060, however, both Annex B and Non-Annex B abatement are nearly the same as with no ITC. That is, replacing autonomous technological change in Annex B by ITC seems to significantly increase the initial Annex B abatement at the sacrifice of a small but persistent part of Non-Annex B abatement (until the concentration target is reached). In this case the optimal carbon tax in Non-Annex B is more or less unchanged with or without ITC, whereas ITC increases the tax in Annex B for more than a century (initially by 120 per cent).

3.3. Cost-effective fulfilment of the Kyoto Protocol

Following the discussion above, I now investigate how the Kyoto Protocol should be implemented with respect to flexibility between Annex B and Non-Annex B. Economists have in general favoured a maximum of flexibility, i.e., that the shadow cost of abatement should be equalised across regions. The results above, however, may indicate that it is cost-effective to incur a higher carbon tax in Annex B countries than in Non-Annex B countries. That is, the Clean Development Mechanism (CDM) in the protocol should only be used with some restrictions. In this section I will run simulations that fulfil the overall Kyoto requirements for the period 2005-2014 (called 2010),[14] but that differ with respect to implementation of the protocol. Then I will compare the costs between the scenarios, and find the cost-effective carbon tax in the two regions.

Taking a closer look at the results above, we observe that the cost-effective abatement in 2010 is much lower than the Kyoto Protocol prescribes. This is not surprising, given a discount rate of 5 per cent and a concentration target of 550 ppmv, and has been demonstrated in earlier studies (e.g., Wigley et al., 1996). However, as shown by Kverndokk et al. (2000), not only the discount rate and concentration target matter, but also the baseline emission path used. Given a concentration target of 550 ppmv, Kverndokk et al. compare the cost-effective emission path based on the A1 baseline scenario used above with the corresponding emission path based on the so-called A2 scenario with much higher baseline emissions at the end of the century (see IPCC, 2000). Their conclusion is that the A2 emission path should start significantly lower than the A1 emission path, as the latter scenario offers cheap abatement in the future.

Following this, I use A2 rather than A1 as the baseline scenario, and choose a lower discount rate, i.e., 2.5 per cent. This implies that the cost-effective abatement scenario (with the same concentration target as before) is more in line with the Kyoto Protocol. Then three Kyoto scenarios are simulated.

[14] As the model consists of 10-years periods, this is the best approximation of the actual Kyoto period 2008-2012.

All scenarios are obliged to the 'Kyoto restriction' that global abatement in the period 2010 should equal the difference between Annex B's baseline emissions in 2010 and 95 per cent of 1990 emissions. Moreover, after 2010 all scenarios follow a cost-effective abatement path that complies with the stabilisation target. In the first scenario ('Kyoto-CE') I simulate the cost-effective solution, i.e., taking into account spillover effects from ITC, with no other limitations than the Kyoto restriction. Secondly, I run a scenario ('Kyoto-flex') that mimics the maximum flexibility implementation of the protocol, i.e., where marginal abatement costs in 2010 are equalised across the two regions. Third, a scenario ('Kyoto-fix') is run that fixes abatement in Annex B exactly in accordance with the Kyoto requirement, i.e., with flexibility only within the Annex B region.

Figure 4. Optimal carbon tax in different Kyoto scenarios with and without diffusion

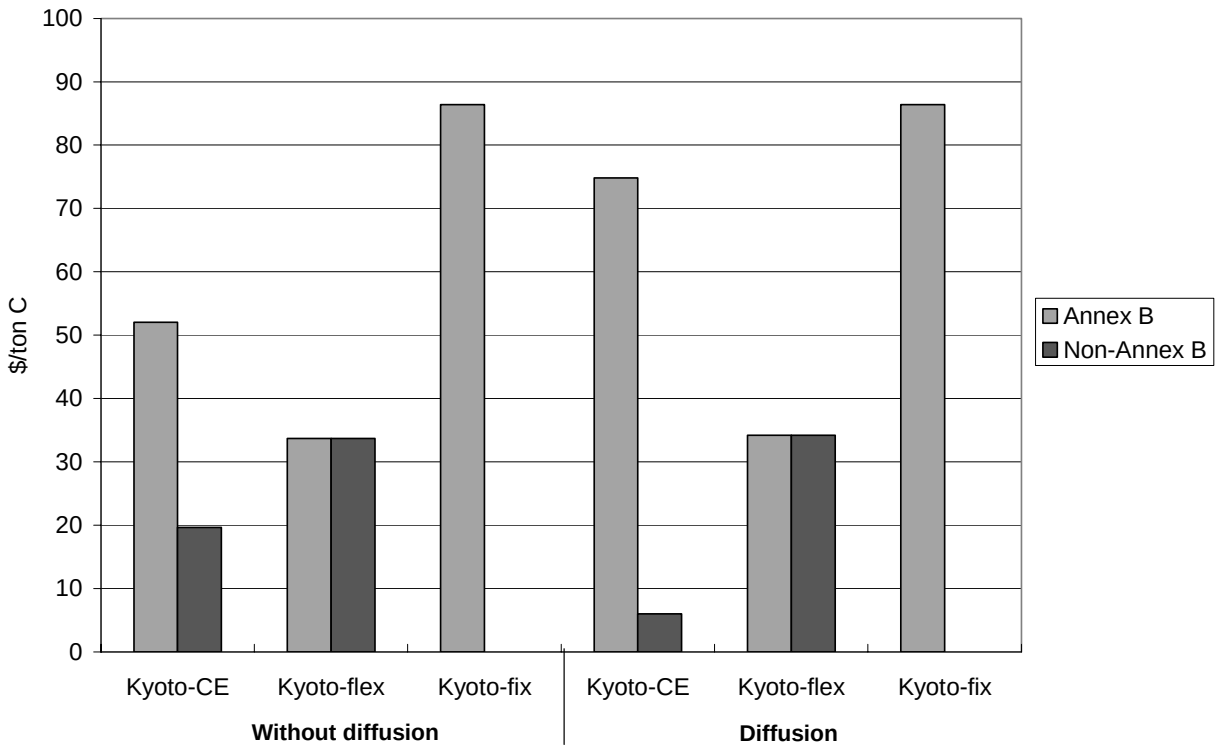
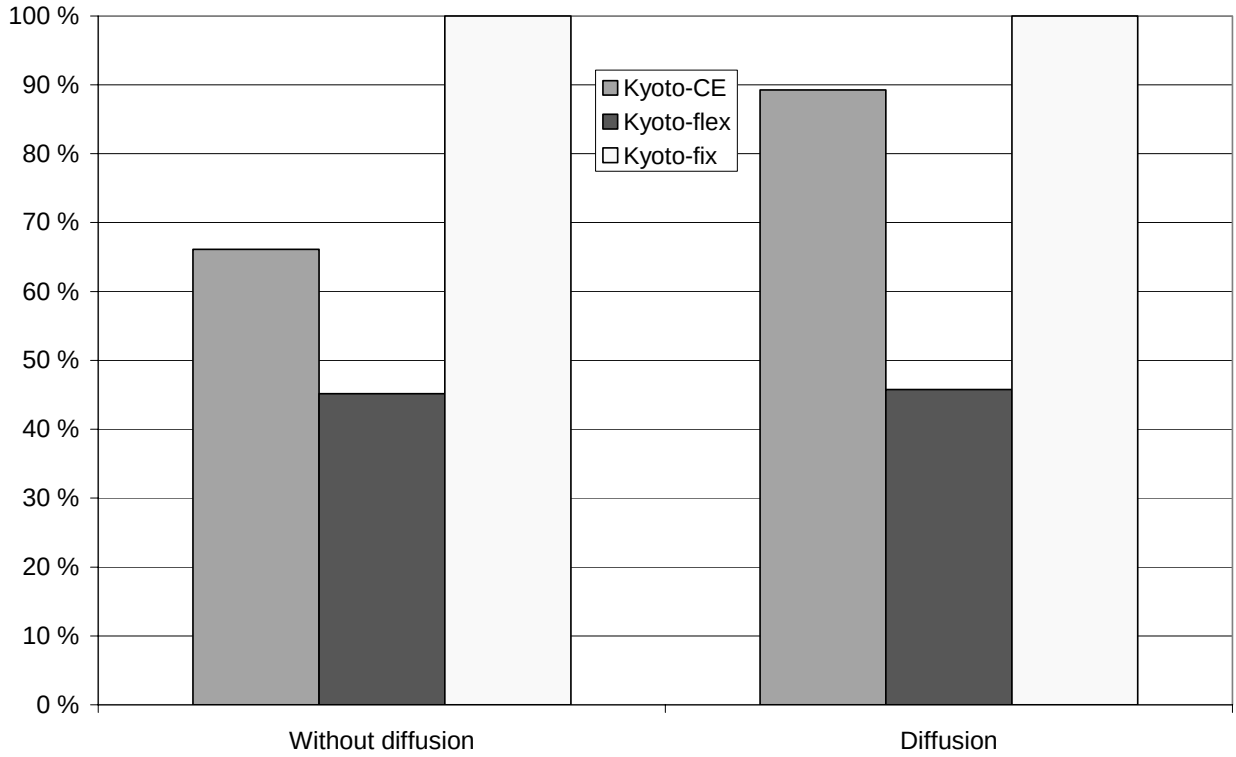


Figure 4 shows how the optimal carbon tax or quota price should be in the different scenarios, with and without diffusion. In the Kyoto-fix scenario a carbon tax of $86 per ton carbon is necessary in the Annex B region. In the Kyoto-flex scenario, where the tax is equalised between Annex B and Non-Annex B the carbon tax is reduced to $34. These two outcomes are in accordance with the various model analyses in Weyant (1999), which is not surprising as the abatement cost functions were

calibrated based on those results. Looking at the cost-effective outcome, we note that the optimal carbon taxes in Annex B and Non-Annex B lie between the tax levels in the two other scenarios. Without diffusion the cost-effective outcome is slightly nearer the Kyoto-flex scenario. On the other hand, with diffusion incorporated in the model, the cost-effective outcome is very close to the Kyoto-fix scenario. These findings are confirmed by Figure 5, which shows Annex B's share of abatement for the same scenarios. A completely flexible regime implies that Annex B carries out 45 per cent of global abatement, versus 100 per cent in the Kyoto-fix scenario. Without diffusion the cost-effective outcome suggests that the share should be 66 per cent, whereas including diffusion increases the rate to 89 per cent.

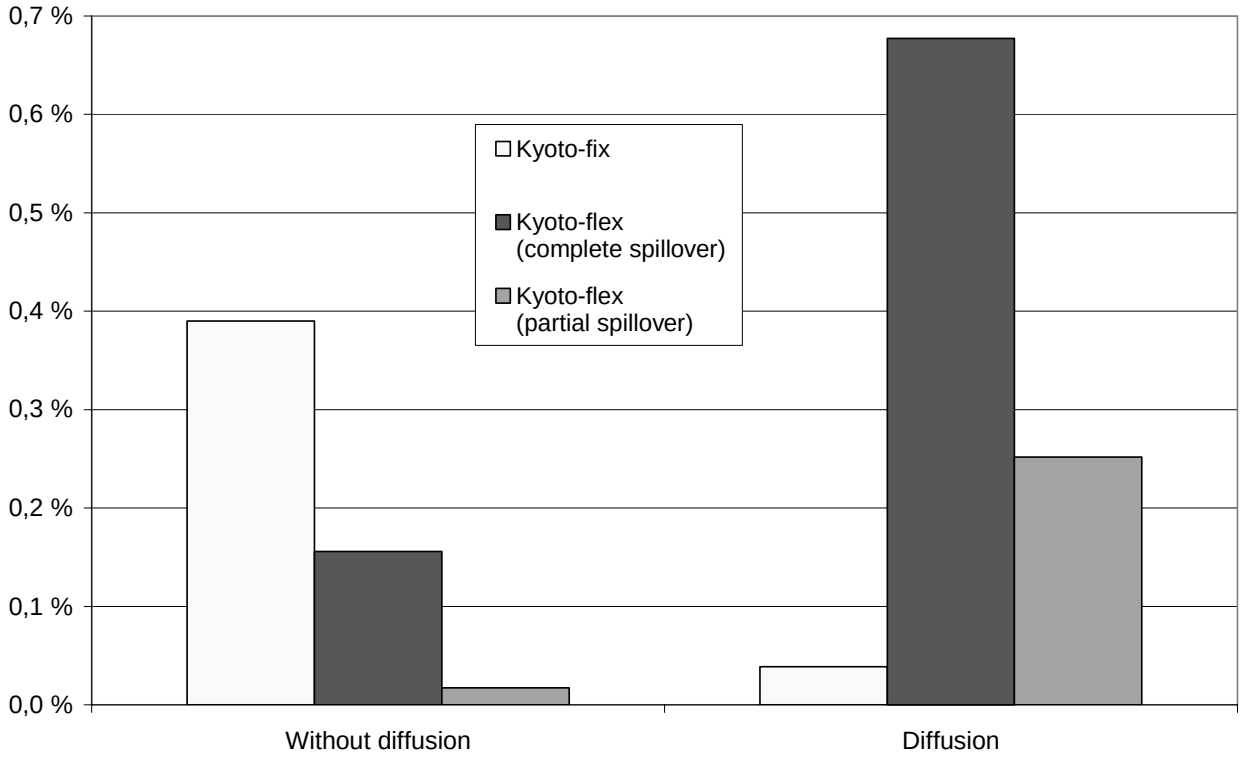
Figure 5. Annex B's share of global abatement in different Kyoto scenarios with and without diffusion



The global (discounted) costs of the scenarios are shown in Figure 6 as percentage differences from the cost-effective implementation of the Kyoto Protocol. The Kyoto-flex scenario is simulated with both complete and partial spillover effects. Before studying the figure, note that all Kyoto scenarios (without diffusion) are less than two per cent more costly than a cost-effective outcome *with no Kyoto*

restriction.[15] The figure shows that with complete spillover effects and no diffusion the Kyoto-flex scenario is about 0.15 per cent more costly than the cost-effective implementation of the protocol, whereas the Kyoto-fix scenario is about 0.4 per cent more costly. With only partial spillover effects, the cost increase is negligible, in line with the findings in Section 3.2. When diffusion is incorporated, the results are completely turned around, i.e., full accomplishment within Annex B is almost cost-effective. Even with partial spillover effects, a free quota market is more costly than the Kyoto-fix scenario. That is, the results suggest that carrying out all abatement in Annex B may be less costly in the long run than full flexibility. Although based on a simple model with uncertain parameters, this finding is quite striking, compared to the massive claim of full flexibility among economists.[16]

Figure 6. Global (discounted) costs as percentage differences from a cost-effective implementation of the Kyoto Protocol, with and without diffusion



[15] This cost-effective scenario uses A2 as its baseline emission path and a discount rate of 2.5 per cent, and is therefore not the same scenario as in the preceding subsection. Total global, discounted abatement costs over the time horizon are about $14,000 billion. With diffusion the Kyoto restriction increases costs by around 4 per cent compared to the cost-effective one, due to too *little* abatement.

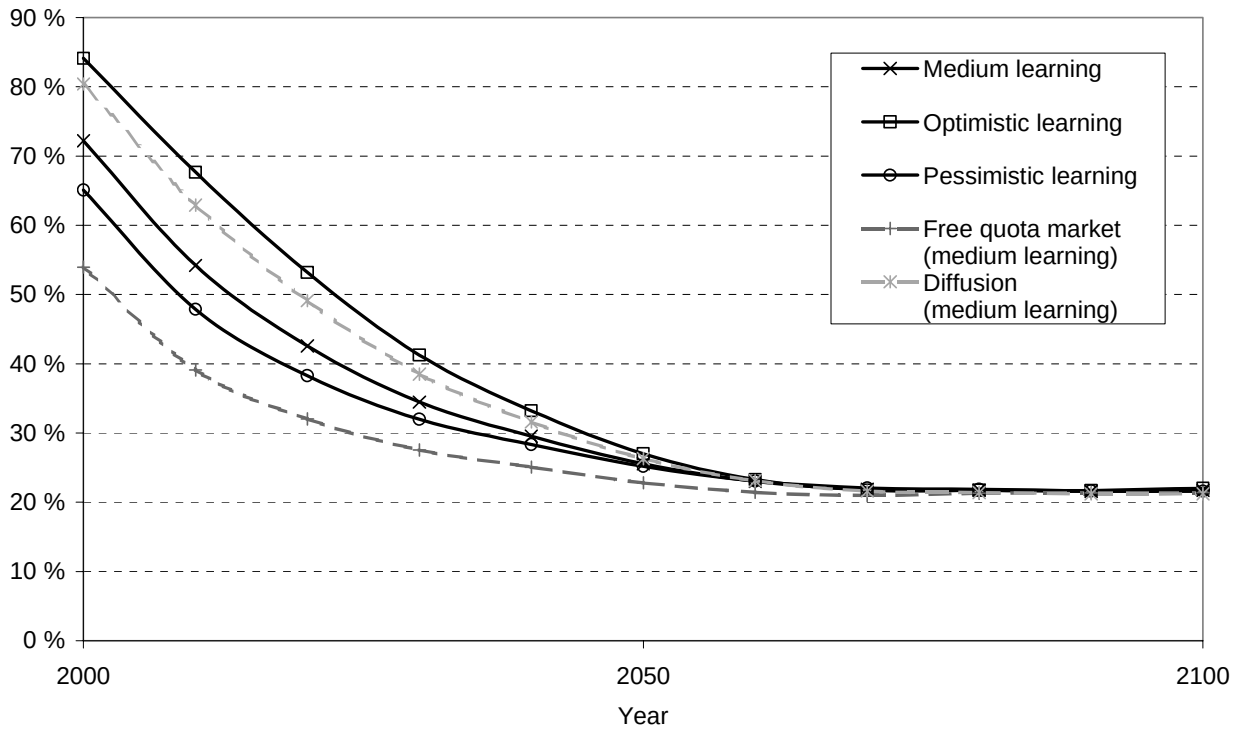
[16] The Clean Development Mechanism (CDM) in the Kyoto Protocol actually requires that abatement measures outside Annex B should bring about other benefits as well, related to local environmental or development matters. This may be interpreted as a positive externality that can be set up against the spillover effects discussed in my paper.

3.4. Sensitivity analyses

I close the numerical illustrations with a few sensitivity analyses. Rather than showing the effects of a bunch of parameters, I single out some of the most important factors. Moreover, I concentrate on the stabilisation scenarios. The results are summed up in Table I.

Perhaps the most important, and uncertain, parameter is the learning rate (M_ψ). Thus, I have investigated an 'optimistic learning' scenario and a 'pessimistic learning' scenario (see the Appendix). Figure 7 displays Annex B's share of global abatement with different learning assumptions (without diffusion). As a comparison the figure also shows the corresponding abatement share in the free quota market scenario, and in the cost-effective scenario *with* diffusion (both with 'medium learning' assumption). It is clear from the figure that the learning assumption has significant impact on Annex B's share of abatement. With 'optimistic learning' the share is initially 84 per cent, compared to 54 per cent in the free quota market scenario. The optimal carbon tax is almost unchanged initially in Annex B, but is halved in Non-Annex B (see Table I). Applying the 'optimistic learning' assumption has more effect than implementing diffusion into the model. Even with 'pessimistic learning' there is a significant difference between the cost-effective and the free quota market scenario.

Figure 7. Annex B's share of global abatement in cost-effective scenarios with different learning assumptions



Assuming 'optimistic learning' implies that the cost savings from carrying out the cost-effective solution are 1.4 per cent. If diffusion is modelled explicitly, the cost savings increase to 5 per cent. That is, a free quota market may be far from cost-effective if the learning potential is large. This conclusion is strengthened if the baseline emissions increase steadily throughout the century (as in the A2 marker scenario), but weakened if a significant share of the learning effects is internal to the firms.

The results are less sensitive with respect to the speed of diffusion. Doubling the rate from 1 to 2 per cent per year (which is more in accordance with, e.g., Dowlatabati, 1998) implies that the cost savings increase from 0.8 to 1.0 per cent. Changing the initial knowledge ratio between Annex B and Non-Annex B has only marginal effects on the cost savings. The discount rate also has only modest impact on the difference between the cost-effective and the free quota market scenarios.

Finally, a more or less flat marginal abatement cost curve implies that it is inexpensive to move lots of abatement from Non-Annex B to Annex B. This is clearly seen in Table I, where the initial share of abatement in Annex B increases dramatically in the cost-effective scenario compared to the free quota market. On the other hand, it also implies that it is cost-effective to delay most of the abatement until later periods due to discounting and autonomous technological change. Thus, the cost savings are quite small in this case, too.

Table I. Summary of sensitivity analyses

	Abatement share Annex B 1.period		Optimal carbon tax 1.period		Costs savings
	Cost-effective	Free market	Annex B	Non-Annex B	Global
Base case (without diffusion)	*72%*	*54%*	*3.6*	*1.6*	*0.25%*
Optimistic learning	84%	54%	3.7	0.8	1.4%
Pessimistic learning	65%	54%	3.2	2.0	0.06%
Higher discount rate (r=0.075)	76%	54%	1.4	0.5	0.21%
Marg.Abat.Costs flat[a]	78%	13%	5.3	1.1	0.40%
Base case (with diffusion)	*80%*	*54%*	*5.4*	*1.5*	*0.8%*
Higher diffusion rate (σ=0.02)	83%	54%	5.2	1.3	1.0%
Optimistic learning	90%	54%	8.5	1.0	5.0%
Pessimistic learning	73%	54%	3.8	1.7	0.2%

[a] α_{C1}=1.5, α_{C2}=0.01, M_C= 69 (Annex B) and M_C= 26 (Non-Annex B) (see equation 21).

4. Conclusions

A cost-effective environmental policy does *not* imply equal Pigouvian taxes across emission sources, if external learning by doing effects exist. This is the main message put forward in this paper. It has been shown that emission sources where abatement activities bring about learning by doing effects should be faced with a higher tax than emission sources with only autonomous technological change, provided at least some spillover effects. With only internal learning effects, current marginal abatement costs should still be different across emission sources in a cost-effective solution. However, as the learning effects are fully recognised within the firm, the emission taxes should be equal.

Technological change is a major issue in analyses of several environmental problems (see e.g. Ehrlich et al., 1999), not least climate change. By using simple numerical simulations, it was investigated to what degree a cost-effective climate policy differs from a free, global quota market, assuming external learning by doing effects in the industrial world (that is, the Annex B region of the Kyoto Protocol). The results indicate that optimal taxes may be significantly higher in the industrial world than in the developing world. Moreover, the industrial world's share of global abatement may be much higher in a cost-effective scenario than in a free quota market. However, the global cost savings from implementing the cost-effective outcome rather than a free quota market seem to be small, unless the learning effects are substantial. The distribution of abatement cost between the regions is much more altered.

Much of the technological growth in developing countries is due to diffusion of technology from industrial countries. Implementing this effect into the model leads to even larger differences between the cost-effective solution and the outcome of a free quota market. The global cost savings may be significant, too, at least if the spillover effects are substantial.

Goulder and Mathai (2000) demonstrated that introducing *internal* learning by doing effects in addition to autonomous technological change implies that the optimal carbon tax is reduced. The simulations above indicate that with complete *spillover* effects in Annex B, the optimal carbon tax in this region is *increased* for the next 70 years. Even with partial spillover effects, the optimal carbon tax is increased for some decades. That is, the effect on optimal taxes of introducing learning by doing depends crucially on the degree of spillover effects.

Finally, focusing on the Kyoto Protocol it was shown that a fully flexible implementation may be relatively far from a cost-effective one, as potential spillover effects of technological growth in the

industrial world are not internalised in a free quota market. Some abatement in the Non-Annex B region is optimal, but the abatement share of Annex B should be significantly higher than what the free quota market generates. With diffusion of technology implemented into the model, the 'full flexibility' regime is actually more costly than a regime with no abatement in Non-Annex B, but full flexibility within Annex B. This is in contrast with the study by Buonanno et al. (2000), who concluded that emission trade restrictions were not cost-effective even with endogenous R&D investments. However, they incorporate neither spillover effects nor diffusion in their model, which are essential in the present study.

The results of this study are of course sensitive to a range of numerical specifications, and the simplifying nature of the model makes it unfeasible to consider problems like industry relocation. However, the conclusions challenge the general view that a maximum of flexibility is always cost-effective. Future research will hopefully increase our knowledge about technological change and how it affects the costs of dealing with the climate change problem. Various policy measures may be on hand for internalising the external learning effects discussed in this paper - restrictions on emission trading may be better suited than directed subsidies or other measures.

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Appendix

Numerical model construction

In this appendix I explain more fully how the abatement cost functions and the technology growth functions are derived.

The abatement cost functions are partly based on Goulder and Mathai (2000). However, they use an aggregated function for global CO_2 abatement, whereas I need one function for Annex B and one for Non-Annex B. Moreover, their cost function seems to be more convex than what other studies suggest.[17] Thus, I use the same functional form as Goulder and Mathai (see equation (21)), but calibrate new parameter values.

Weyant (1999) contains a multi-model evaluation of the costs of the Kyoto Protocol. In the introduction, Weyant and Hill (1999) present figures with marginal abatement costs in the US, the EU, Japan and Canada-Australia-New Zealand, for 11 of the models included in the special issue. Up to 15 per cent emission reduction, the curves are either linear or slightly convex in most cases. For instance, when abatement increases from 5 to 10 per cent, marginal costs increase on average by around 2.5 times. Moreover, with free permit trading in Annex B the carbon tax necessary to reduce emissions in accordance with the protocol varies between $20 and $220 per ton carbon, with an average around $85. This corresponds to an emission reduction around 15 per cent (which also varies a lot across models). I search for parameter values that roughly satisfy these characteristics, and end up with the following for the Annex B region: M_C=220, α_{C1}=2 and α_{C2}=1.

It is more difficult to construct a marginal cost function for the Non-Annex B region. For simplicity I assume that the shape of the function is identical to the one for Annex B (i.e., α_{C1} and α_{C2} are equal), but that the level may be different. To find M_C I use the fact that free global permit trading in the Weyant studies reduces the carbon tax on average by around 2.8 times. Applying this on baseline emissions and the calibrated marginal cost function for Annex B above, I derive the value of M_C=180 for Non-Annex B.

[17] The cost function in Goulder and Mathai (2000) implies that marginal costs are increased by more than four times when abatement increases from 5 to 10 per cent of baseline emissions, and by more than five times when abatement are increased from 10 to 20 per cent. Studies in e.g. Weyant (1999) seem to have less convex functions (see below).

The learning by doing effect in Annex B characterised in equation (22) is taken directly from Goulder and Mathai (2000), and so are the two parameters $\gamma=\phi=0.5$. However, it is difficult to find the appropriate value of M^j_ψ. Goulder and Mathai calibrate the parameter based on Manne and Richels (1992), where cost savings between an optimistic technology scenario and the central scenario are calculated. However, as these cost savings are not related to a certain emission reduction, this calibration seems quite ad hoc. Most empirical studies on learning effects are connected to so-called learning curves, where an association between accumulated use of a technology and unit costs are estimated. According to Grübler et al. (1999), a doubling of accumulated use of a new technology often leads to cost reductions of 20-30 per cent (sometimes even higher). Such learning curves have been observed for e.g. solar photovoltaics (Oliver and Jackson, 1999). When a technology is mature, the relative cost reduction seems to fall slightly. These results clearly underpin the importance of learning effects related to emission abatement (e.g., through replacing fossil fuels by cleaner energy technologies), but are not possible to use in calibrating the value of M_ψ^j.

Thus, I rather choose to simulate three alternative technology scenarios, where I in each case assume a certain cost reduction following from 5 per cent abatement in Annex B in the first 10-years period. In the 'medium learning' scenario, which was used in the main simulations, I assume that this abatement leads to 5 per cent cost reduction after 10 years. In the 'optimistic learning' scenario the cost reduction is assumed to be 20 per cent, whereas in the 'pessimistic learning' scenario the cost reduction is assumed to be 2 per cent. Then the value of M_ψ^j is calibrated to be 0.011, 0.045 and 0.0045, respectively, for j=Annex B.[18] As a comparison, Parry and Toman (2000) assume in their numerical example that with x% abatement in the pre-commitment period of the Kyoto Protocol (i.e., before 2008-12), then the costs of x% abatement in the commitment period are reduced by either 5 or 30 per cent.

The autonomous technological change is assumed to be 0.25 per cent per annum in Annex B, which is in the lower end of estimates used in other studies *not* modelling ITC (see Matsouka et al., 1995). It seems reasonable to assume that the technological growth rate in Non-Annex B in the long term is closely related to the growth rate in Annex B, due to technological diffusion from industrialised to developing countries. Since ITC is not modelled in Non-Annex B, I calibrate the rate of autonomous technological change in this region so that the technological growth over the first century is equal to

[18] Note that the function in (22) uses annual abatement as input, not 10 years abatement, even though the model consists of 10 years periods.

the growth in Annex B. Then the rate becomes 0.82 per cent per year in the 'medium learning' scenario (2.0 and 0.50 per cent in the 'optimistic learning' and 'pessimistic learning' scenario).

When the technological diffusion is modelled explicitly (see equation (23)), it is assumed that the autonomous technological change is the same in Non-Annex B as in Annex B, i.e., 0.25 per cent per year. The speed of diffusion and the initial ratio of technology in the two regions are, however, difficult to identify, particularly as it applies to CO_2 abatement. Coe et al. (1997) found significant spillover effects of R&D from industrial to developing countries. Using five-years time periods they concluded that 1 per cent increase in total R&D capital stock in the western world increased total factor productivity in the developing world of 0.06 per cent. Moreover, in another estimation they found that the elasticity of total factor productivity in a developing country with respect to the ratio of GDP per capita in the country over GDP per capita in the industrial world five years earlier, was 0.046 (the coefficient was close to being significantly different from zero). Arora et al. (2001) also find evidence of spillover effects from industrial to developing countries. According to Buonanno et al. (2000) in 1990 the stock of knowledge in the US, Japan, Europe and FSU, covering about 20 per cent of the global population, constituted 85 per cent of the global stock of knowledge. In my simulations I start with a conservative diffusion rate of 1 per cent, i.e., σ^j =0.01, and a more moderate technological gap between Annex B and Non-Annex B, i.e., $(H^j/H^i)_0$=0.25. As a comparison, Dowlatabati (1998) applies a technological diffusion rate of 24 per cent over a 10 years period for energy efficiency. These figures are of course tested in the sensitivity analyses.

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