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CLIMATE POLICIES AND ECONOMIC GROWTH

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ABSTRACT: A Climate Agreement, like the one reached in Kyoto in 1997, on reducing greenhouse gas emissions may have important effects on the global and the national economies. The aim of this paper is to make some basic numerical evaluations of the economic effects of climate policies, imposing a ceiling on the use of energy input in production in a single economy. First, we make an evaluation under immobile and internationally mobile domestic factors of production, and infer how much international factor mobility, so-called carbon leakage, can magnify the adverse effects. Next, we introduce optimal endogenous growth, so that environmental policies can potentially lead to the introduction of less-polluting energy technologies. The general conclusion of this is that induced R&D in less-polluting energy technologies is likely to reduce the economic burden of climate policies only marginally. Under an internationally tradable emissions permit scheme, however, the endogenous technical change reacts quite vigorously to the price of the pollution right. Finally, we solve for the optimal subsidy to R&D in clean energy technology in a market economy, and find it to be quite sizeable.

Key Words: Climate policies, economic growth, R&D

JEL Code: Q43, Q48

1. Introduction

In Kyoto, Japan, in December 1997 the participating member countries of the United Nations agreed on action to curb the climate change. The Kyoto Climate Protocol stipulates that the industrial (OECD) countries cut overall by 5 per cent their emissions of the greenhouse gases (the most important of which are carbon dioxide CO_2 and methane CH_4) from the level of 1990 to the average in the period 2008-2012. The protocol assigned different percentage reductions to the various parties, for the USA 5 per cent, for the European Union as a whole 8 per cent, Japan 6 per cent, and less for the transition countries, like zero for Russia. No similar quantitative responsibilities were agreed upon the developing countries.

The problem of the climate change is immense and of a scale unprecedented in the history of global concerted action in international policies and the environment, because the problem has a truly global character and an intergenerational dimension of hundreds of years. The research on this problem has also been enormous. The results involve, however, huge uncertainties, both from a scientific point of view on what are the consequences in nature of climate change, and what are the economic consequences of inaction and action in climate policies and by which means action should be implemented internationally and also within each signatory country.

The Kyoto process has been under intensified negotiations since the preliminary stage of approving the Protocol in 1997, most notably related to the definition and treatment of the so-called carbon sinks, such as forests, and specification of the role of international measures, such as joint implementation, clean development mechanisms and international trade of emission permits in meeting the targets set by the Agreement. The whole process had to face a new situation as the Bush administration announced in 2001 that the USA will not ratify the Agreement due to its harmful economic impacts. However, in spite of this, the EU has committed to bear its burden adopted in the Kyoto Agreement.

The aim of this paper is not to question whether the Climate Agreement is the best environmental response to the threat of global warming. We simply take as a starting point that due to environmental concerns, being omitted in the following analysis altogether, a country or a region of countries or several regions of them sign a Climate Agreement which cuts their emissions through imposing a path where their emissions stemming from the use of one essential factor of production, energy, will be gradually reduced. The aim in the following is to make a simple analysis of the effects of climate policies on the growth rate of the economy, using numerical calibrations. We start from the basic aggregative analysis in the case of no international factor mobility and then enlarge it to allow for factor mobility, where domestic factors of production can relocate abroad as a result of the reduced real reward caused by the scarcity of the energy factor. Next, we make some introductory remarks on a disaggregated economy. The main part of the paper is devoted to the case of endogenous growth where the rate of innovation in the energy sector is endogenous, and can react to the climate policies. We want to study, how essential is endogenous technical change and R&D into clean energy from the point of view of overall economic growth. Recently, endogenous growth and energy policies has been studied theoretically by, e.g. Smulders and de Nooij (2003) and van Zon and Yetkiner (2003). Our approach is to give more numerical substance to this field of study under optimal growth and to explicitly consider the case of the open economy.

The results of the paper illuminate, how much the energy constraint bites of economic growth. Under endogenous growth we are able to illustrate how the position adopted by the environmentalists that strict environmental policies lead to a boost in the economy, holds qualitatively, but is in quantitative terms only a minor remedy. On the other hand, the price of the tradable permit has a significant impact on R&D activity to introduce more energy-saving technology. We also derive the optimal subsidy rate for R&D and find it to be quite large in size, but diminishing over time, as the cost of new technological inventions decreases over time.

The rest of the paper is organised as follows. In Section 2 we outline the basic framework to be used in the paper and present the result on the growth differential between the Kyoto and the reference laissez faire or business-as-usual (BAU) -path. Then we briefly consider the qualification caused by disaggregating the economy into a number of industries with different intensities in the use of energy input in production. Section 3 specifies optimal growth under endogenous R&D in “clean” energy. In section 4 we carry out numerical solution of the model to see how much the incentives to increase less polluting energy technology in production, created by strict environmental considerations, can alleviate the economic burden of climate policies. The other point of interest is the role of emission trading in this connection. Section 5 considers implementation of environmental policies and solves for the optimal subsidy on R&D activities in a market economy, and Section 6 concludes.

2. The basic case under mobile and immobile factors of production

Throughout in the paper we take an aggregative view on a single economy, which is so small that its policies with regard to the environment and use of energy do not have any effects on the world financial and energy market. The aggregative production function with constant returns to scale of the Cobb-Douglas form, presented by Nordhaus (1992) to be a local approximation to any smooth production function, for this economy is

$$Q_t = F(K_t, L_t, E_t) = A_t K_t^{\alpha'} L_t^{\beta} E_t^{\gamma} = Ae^{\lambda t} R_t^{\alpha} E_t^{\gamma}\ , \qquad (1)$$

where Q is production (GDP), A_t is the level of total factor productivity and λ is its growth rate, assumed to be exogenous and given from outside, K is the stock of capital, L the labour force, E the use of energy resources, and all parameters are positive with $\gamma = 1 - \alpha' - \beta, \alpha = 1 - \gamma$. Let us for simplicity first aggregate the two inputs, capital and labour to a single input R, which may or may not be internationally mobile.

The first order conditions for optimal growth in this open economy are the following,

$$Ae^{\lambda t} F_{R}(R_t, E_t) = W_t,\ Ae^{\lambda t} F_{E}(R_t, E_t) = P_{Et}^{*}\ , \qquad (2)$$

where W is the real factor reward and P_E^* is the real price of energy, given to the economy from the world markets. The baseline case is that where we solve from (2) for the real factor reward W_t, consistent with the full employment of domestic resources, $R_t = \bar{R}_t$, and for the amount of the energy input on the basis of its international price P_E^*. Note that we assume that energy is also a domestic factor of production. Let us now stipulate that the use of energy is limited by international climate policies, so that the tightening of its use takes place at the rate μ,

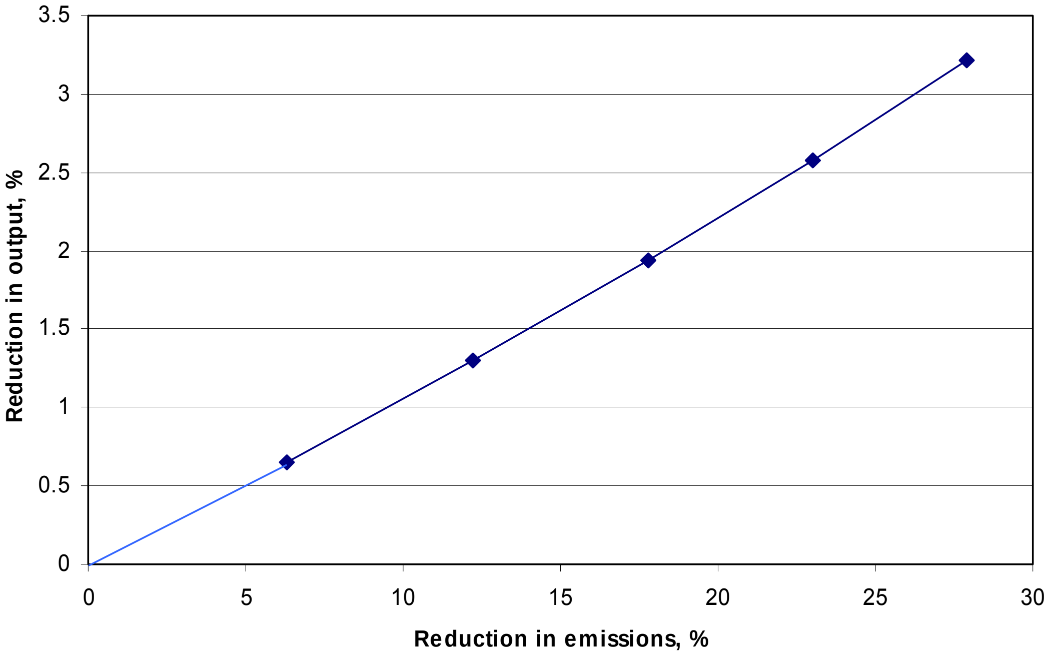
$$E_t = E_0^{-\mu t}, \mu > 0 . \tag{3}$$

We insert (3) into (2) and again solve again for W_t, but now the other endogenous variable is the domestic price on energy $P_{Et,}$ which consists of the international price, added by the domestic tax rate τ imposed on the use of energy, i.e., $P_{Et} = P_{Et}^*(1+\tau_t)$. So, now we solve for the tax required to achieve the climate target. As the energy input tightens, this will drive down the real return on the domestic resources in (2) due to the fact that the factor inputs are cooperative, i.e., the reduction of the amount of a factor decreases the marginal productivity of the other factor. We next assume that the international mobility of the domestic resources is as follows,

$$R_t = R_{t-1}(W_t / W_{t-1})^{\varphi}, \quad \varphi \geq 0. \tag{4}$$

This means that when the domestic reward goes down, factors move out of the country abroad, where no reduction in reward is assumed to take place. Let us now make the simulations with this basic set up over a time span of 30 years by varying the μ parameter in Eq. (3). We pay attention to the relation between the cut in the level of emissions and output at the end of this time span with respect to the baseline of no climate policies. In Figure 1 we start with the case of no international mobility (φ = 0 in Eq. (4)) of domestic factors of production. Throughout in the sequel use the value of $\gamma = 0.1$.

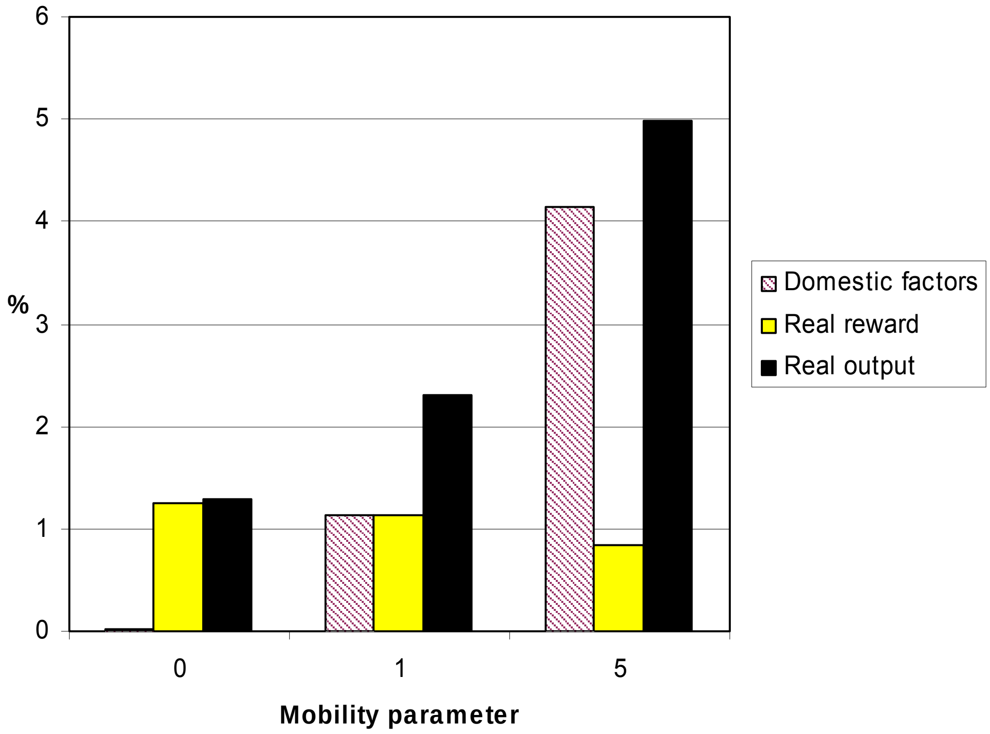
Figure 1. The case with no factor mobility; reduction in output as a function of the ambition of the climate policies over 30 years



From the figure we see that the Kyoto target (0.25 % p.a., altogether 6.3 %) reduces the level of output by 0.6-0.7 per cent in the end point steady state, and that the adverse effect grows almost linearly with the ambition of the climate target so that a reduction of emissions by 30 per cent would roughly cut 3.5 per cent of the long-run level of real GDP.

Let us then turn to the case of factor mobility, where we allow the parameter φ in Eq. (4) to vary. We examine only one case of those presented in Figure 1, namely that where the climate target is double that of the Kyoto Agreement, i.e. 0.5 per cent p.a., leading to the cut of the emissions altogether by 12 per cent over the 30 year time span considered. The results are presented in Figure 2.

Figure 2. The case of factor mobility, reduction with respect to the case of no climate constraint, per cent, as a function of the mobility parameter φ in Eq. (4) (for explanations see the text)



We see that there are diverging effects on factor rewards and the total GDP. As factors leave the country, through the so-called carbon leakage, the rate of return on the remaining more scarce factors of production will, ceteris paribus, rise. The negative impact on real wages is therefore smaller, the higher the carbon leakage. But, the volume of GDP is, however, predominantly determined by the intensity of factor mobility so that the overall negative impact on domestic GDP can be markedly higher under the international mobility of factors of production than under no mobility.

What could be a relevant estimate for the degree of factor mobility? One basic case would be that where the return on domestic factors is required to remain intact of climate policies, so that a full compensation in factor rewards is required if climate change reduces the reward earned in the domestic economy. In terms of Figure 2, this would mean that the amount of domestic resources would be reduced by the same amount as the energy input is reduced, i.e. 12 per cent.[1] GDP would fall by the same relative amount. However, this extreme case would mean full mobility of both capital and labour, which may not be a realistic assumption with respect to the latter. Let us therefore consider a modified case, where only capital is fully mobile and labour is totally immobile. In this case, the capital stock reacts in the following way to restore the rate of return (marginal productivity) on capital unchanged,

$$d\log(K) = \frac{\gamma}{1-\alpha'} d\log(E)\,. \tag{5}$$

From this we can calculate the change in the total domestic resource to be around 0.05 times the reduction of the use of energy input, which implies less than one per cent reduction in the amount of domestic resources over the 30 years.[2] On the basis of Figure 2 this would imply a value of the φ parameter around unity and thereby the reduction in domestic output would be around 2 per cent, while in Figure 1 it was less, 1.3 per cent.

The price of energy, i.e., the domestic tax τ will behave, in contrast, in such a way that its rise is the less, the higher is the carbon leakage. This is based on the fact that as output is reduced the need to cut emissions will dwindle as well.

The above model considered a single economy using a simple aggregative growth model. In reality, the economy is decomposed of a multitude of production activities with a different intensity in the use of the polluting energy input. Let us make an introductory remark on this case, but, however, without any numerical illustrations. If the domestic price of energy is raised to curb emissions, this will lead to a reallocation of resources from the energy-intensive sectors to those that use other inputs in an intensive way, provided that the economy is able to reallocate its resources smoothly and rapidly from the existing uses to new ones. This is, of course, only so in an ideal situation; in practice the economies are slow to adjust, and the adjustment entails costs. But these are very hard to grasp in empirical terms.

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[1] This is a result of the fact that the marginal productivities (real rewards) are homogeneous of degree zero of the factors, i.e. they are a function of the ratio of the amount of factors.

[2] From (5), and using the definition of R above in connection with (1), we can further write $d\log R = (\alpha'/\alpha) d\log(K) \approx (0.3/0.9)*(0.1/0.7) d\log(E) = 0.05 d\log(E)$.

According to the basic *Rybczynski* theorem of the trade theory, if full employment prevails, and then the availability of one input, here energy, in the production is limited, the production of those goods (industries) which are the most energy intensive will go down and other industries will rise in comparison to the BAU. This will mitigate the burden of climate policies.

Let us now continue the analysis of the aggregative growth model by introducing endogenous technological change in it.

3. Optimal growth under endogenous technology

Above we have considered the case with given exogenous technology and technical change, which do not react to environmental policies. Recently in the literature of endogenous growth where technical change is endogenous, the case of environmental concerns and limitations also in the field of energy has been analysed. The starting point in these analyses has been the endogenous growth model by Romer (1990), which has been applied to environmental issues and use of energy by distinguishing the energy sector on the model, as done by Smulders and de Nooij (2003) and Zon and Yetkiner (2003).[3]

The endogenous growth model has, however, the feature of the scale economy so that the steady state growth rate depends positively on the scale, i.e. size, of the economy. This does not fit with the stylised facts of growth, see Jones (1995), Li (2000), and instead the specification of semi-endogenous growth has been incorporated in the so-called non-scale growth models. These models imply that technological change is endogenous, but the steady state growth is exogenous, see Li (2000) and Eicher and Turnovsky (1999). These incorporate the endogenous growth model as a special case.

Output Q of final goods is produced by capital K, labour L_Q and energy E,

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[3] See also the recent special issue on endogenous technological change and the economics of atmosphere stabilisation of the Energy Journal (2006).

$$Q = AF(K, L_Q, E), \tag{6}$$

where A is again total factor productivity. Total labour $\bar{L}$ is again assumed to be immobile and can be allocated, in addition to production Q, to two R&D activities, of which one enhances total factor productivity and one which creates energy-saving technology with less polluting energy production. We specify the R&D technology in the following manner, see Jones (1995),

$$\dot{A} = \eta_A A^{\lambda_A} (\theta_A \bar{L})^{\psi}, \tag{7}$$

where a dot over X denotes the time differential dX/dt, $0 < \lambda_A \leq 1$ and θ_A is the share of total labour input $\bar{L}$ allocated to general R&D activities, η_A is the productivity of a research worker in producing new technological inventions and $0 < \psi \leq 1$, which depicts the diminishing marginal productivity of research work. The stock of knowledge A on right-hand side describes the cumulative nature of knowledge in the form of intertemporal spillovers in its production. The amount of pollution or greenhouse gas emissions P depend on the extent of energy input (energy production) so that

$$P = E / B \leq \bar{P}, \tag{8}$$

where B is the indicator of the level of embodied energy technology in terms of its “cleanness“, with initial value of unity, and $\bar{P}$ is the target stipulated by the international climate policy agreement, similarly as above. In effect, this means that more advanced energy technology expands the effective number of energy inputs available to the economy. In addition, the country can buy (in net terms) permission rights in the amount P* from abroad, so that the effective number of energy inputs is

$$E = B\bar{P} + P^*. \tag{9}$$

Similarly as in (9) we specify for the technical change and R&D activity in the less polluting energy technology sector,

$$\dot{B} = \eta_B B^{\lambda_B} (\theta_B \bar{L})^{\xi}, \tag{10}$$

with similar parameter constraints as above in connection with (7). The labour input available for production of final goods is then $L_Q = (1-\theta_A - \theta_B)\bar{L}$.

The economy is a small open economy with complete access to world capital markets as in Alho (1993). The domestic production is used to investment $\dot{K}$, consumption C and net exports of the homogeneous good X, less the imports of permission rights.

$$Q = \dot{K} + C + X - qP^*, \tag{11}$$

where q is the international price of the emission rights in terms of the final good. The total net exports are $\tilde{X} = X - qP^*$. The net wealth of the country is

$$V = K - D + q\bar{P}, \tag{12}$$

where D is the foreign net financial debt. The national wealth accumulates by savings and the change in the value of the pollution rights,

$$\dot{V} = Q - rD - C + \dot{q}\bar{P} + q\dot{\bar{P}} \ . \tag{13}$$

By differentiating (12) and combining it with (11) and (13), we come to the outcome that the foreign financial debt accumulates by

$$\dot{D} = rD - X \ . \tag{14}$$

Identity (11) also gives us the constraint

$$\dot{K} = Q - C - \tilde{X} \ . \tag{15}$$

The intertemporal social welfare criterion of the economy is of the following form,

$$\int_0^\infty e^{-\sigma t} U(C_t) dt \ . \tag{16}$$

In (16) we have simply assumed that national environmental goal in itself does not play a role as to welfare. This assumption is not, however, crucial for the argument below, because it only affects the path of consumption, but not production in which we are only interested here, see e.g. Alho (1993). In (16) U is a standard concave utility function and σ is the subjective rate of time preference, being equal to the international real rate of interest r. With these preliminaries we can write the current value Hamiltonian function as follows

$$\begin{aligned} &H = U(C) + \alpha_C(AF(K,(1-\theta_A-\theta_B)\bar{L},E) - C - \tilde{X}) + \nu(rD - X) + \\ &\mu_A(\eta_A A^{\lambda_A}(\theta_A \bar{L})^{\psi}) + \mu_B(\eta_B B^{\lambda_B}(\theta_B \bar{L})^{\xi}), \end{aligned} \tag{17}$$

where α_C, ν, μ_A, μ_B are the costate variables of the state variables K, D, A and B. The decision variables are C, X, P*, and θ_A, θ_B. The necessary and sufficient conditions for an inner point optimum are as follows,

$$U_C - \alpha_C = 0 \tag{18}$$

$$-\alpha_C - \nu = 0 \tag{19}$$

$$AF_E - q = 0 \tag{20}$$

$$\alpha_C F_L = \mu_A A^{\lambda_K - 1} \eta_A \psi (\theta_A \bar{L})^{\psi - 1} \tag{21}$$

$$\alpha_C AF_L = \mu_B B^{\lambda_B} \eta_B \xi (\theta_B \bar{L})^{\xi - 1} \tag{22}$$

$$\dot{\alpha}_C = -\alpha_C AF_K + \sigma \alpha_C \tag{23}$$

$$\dot{\nu} = -\nu r + \sigma \nu \tag{24}$$

$$\dot{\mu}_A = -\alpha_C F - \mu_A \lambda_K A^{\lambda_K - 1} \eta_A (\theta_A \bar{L})^{\psi} + \sigma \mu_A \tag{25}$$

$$\dot{\mu}_B = -\alpha_C AF_E \bar{P} - \mu_B \lambda_B B^{\lambda_B - 1} \eta_B (\theta_B \bar{L})^{\xi} + \sigma \mu_B \ . \tag{26}$$

As r = σ, (19) and (24) imply that $\dot{\alpha} = 0$. This further implies that U_C is a constant and thereby the level of consumption stays constant over time. Furthermore, Eq. (23) implies that $AF_K = r$, i.e. that there is in the absence of adjustment costs an instantaneous adjustment of the capital stock to the equilibrium size of it.

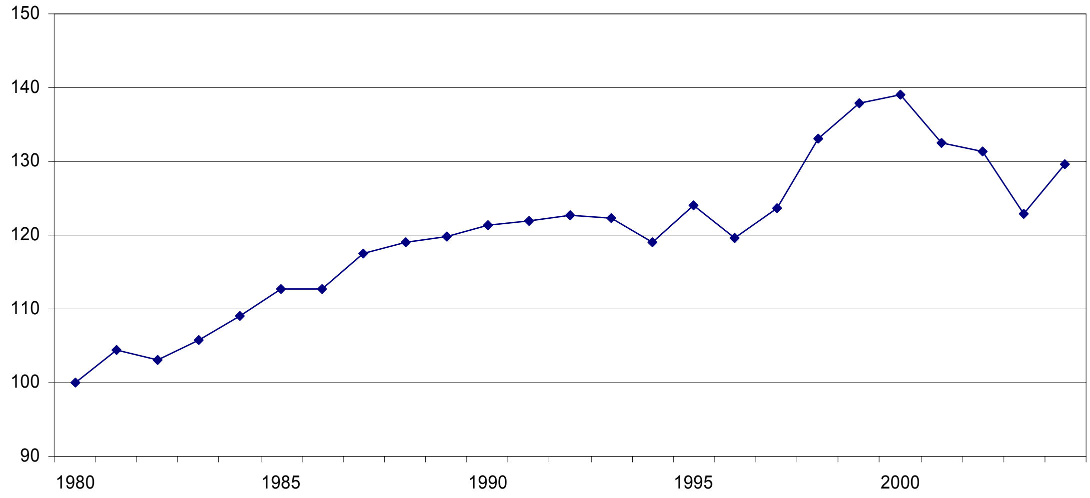
4. Numerical simulation in the case of a single R&D sector in energy technology

Let us now illustrate numerically the solution to optimal growth. We concentrate on the simplified case where there is no separate capital, and output is produced only with labour (resource) and energy, and endogenous technology and R&D only exists in the energy sector. So, we keep the level of overall technology, total factor productivity as fixed A = 1 in (6) throughout, but the energy technology indicator B changes over time.

In the calibration, we assume that the technology of R&D improvements is similar as in the basic model of endogenous growth, i.e. $\lambda_B = 1$ in Eq. (10). We calibrate the η_B parameter in such a way that the rise in the stock of energy technology is under the baseline of no climate policies some 1.3 % per annum. Empirically, compare this to Figure 3 to see how the B indicator has evolved in Finland over the recent decades. At the margin the new inventions in less polluting energy technologies are more difficult so that we fix the marginal productivity parameter ξ of R&D activity in (10) to the value of 0.5.

Similarly, as in Section 2, we fix initially L to be 100 units, E 10 units, and (6) is a Cobb-Douglas production function with $\alpha = 0.9$. These imply that the initial level of output Q is around 78 units. The time span in the simulations is 30 years, and we consider 2010 to be the starting point, which is used only for illustrative purposes.

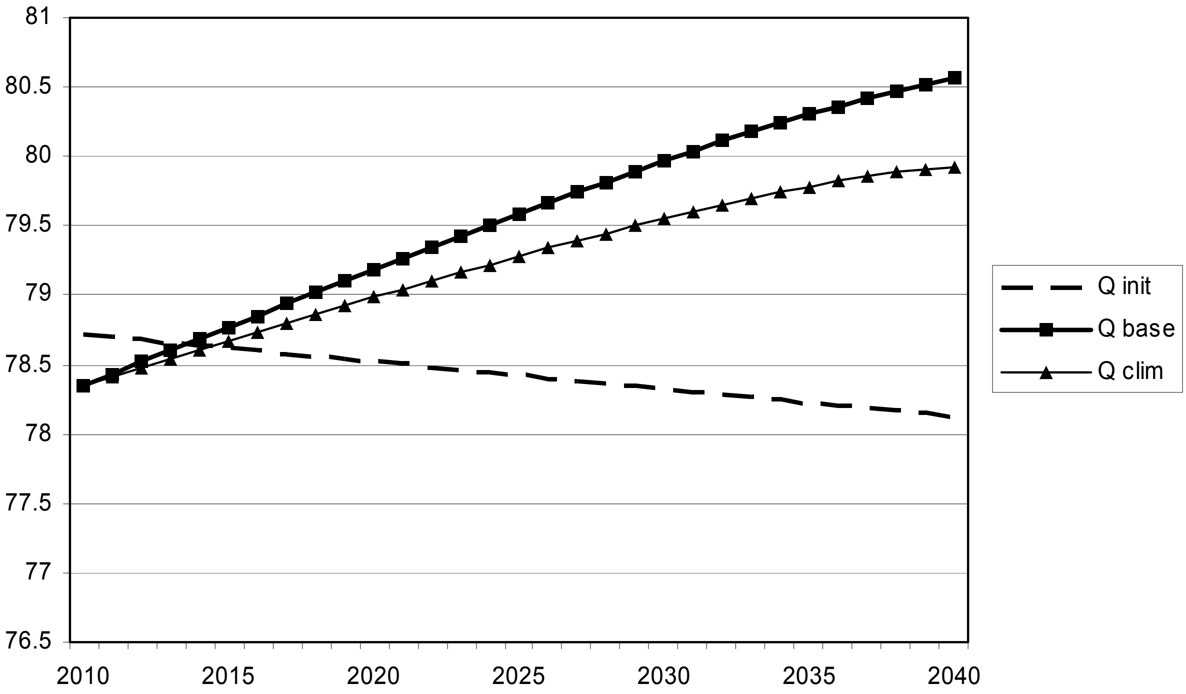
Figure 3. Consumption of energy in relation to emissions of CO_2 in Finland (indicator of B), index "year 1980 =100"



Now we get the following picture, see Fig. 4, for optimum growth, where, similarly as under Kyoto, the speed of emission reduction is 0.25 per cent p.a. We first concentrate on the case where there is no option to purchase emission rights from abroad ($P^* = 0$).

As normal in growth theory, we solve the model under rational expectations for the co-state variables. As stated above, the level of consumption stays constant over time, but, of course, it is not the same in the alternative scenarios. The steady state consumption level can be solved from the intertemporal budget constraint so that the present value of the stream of consumption is the same as the present value of the aggregate income less the initial net foreign debt. Here we have for simplicity considered the marginal utility of consumption to stay unchanged between the cases analysed.

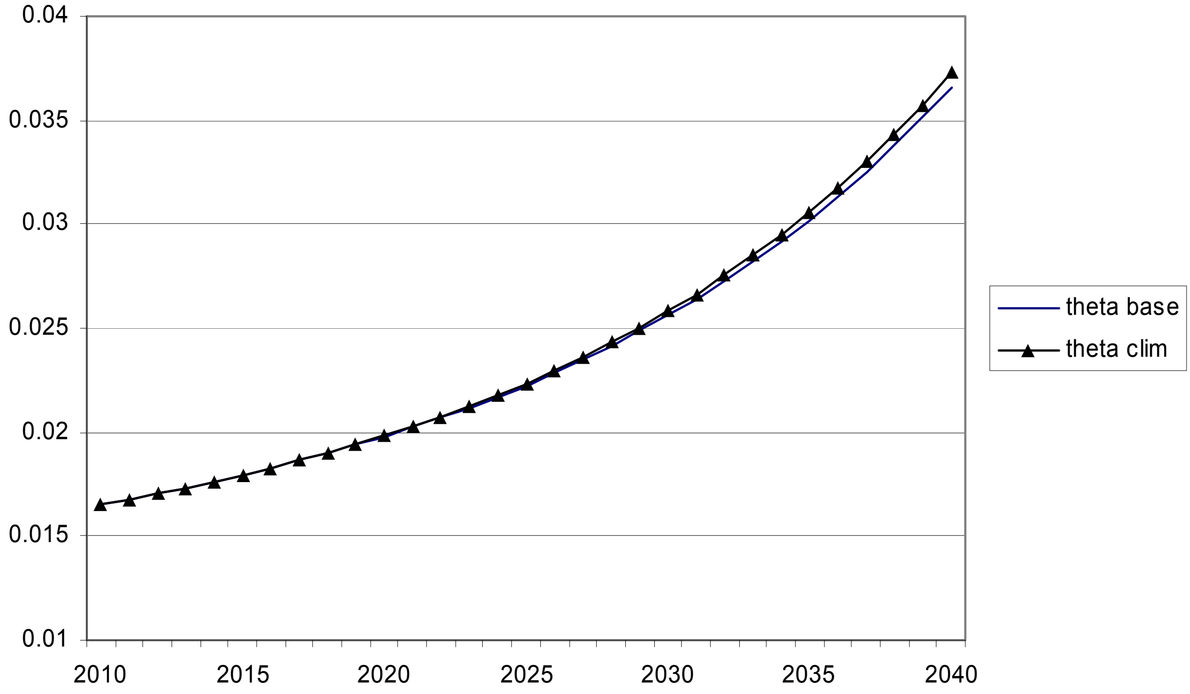
Figure 4. Optimal growth under a climate constraint and endogenous R&D in the energy technology, Q init = volume of final good production under fixed technology, Q base = endogenous technology, no climate constraint, Q clim= endogenous technology and the climate constraint



Endogenous growth under no climate constraint will lead to a higher steady state output level than with fixed technology. As is plausible, in the case of endogenous technology there is an incentive to carry out R&D in clean energy technology so that a growing part of the workers is shifted to generate the less polluting energy technology. The gap between the business as usual and the scenario under climate policies widens over time and is after 30 years 0.8%. In effect, this means that the endogenous R&D does not markedly change the overall cost of climate policies, as depicted above in Section 2 under a fixed technology.

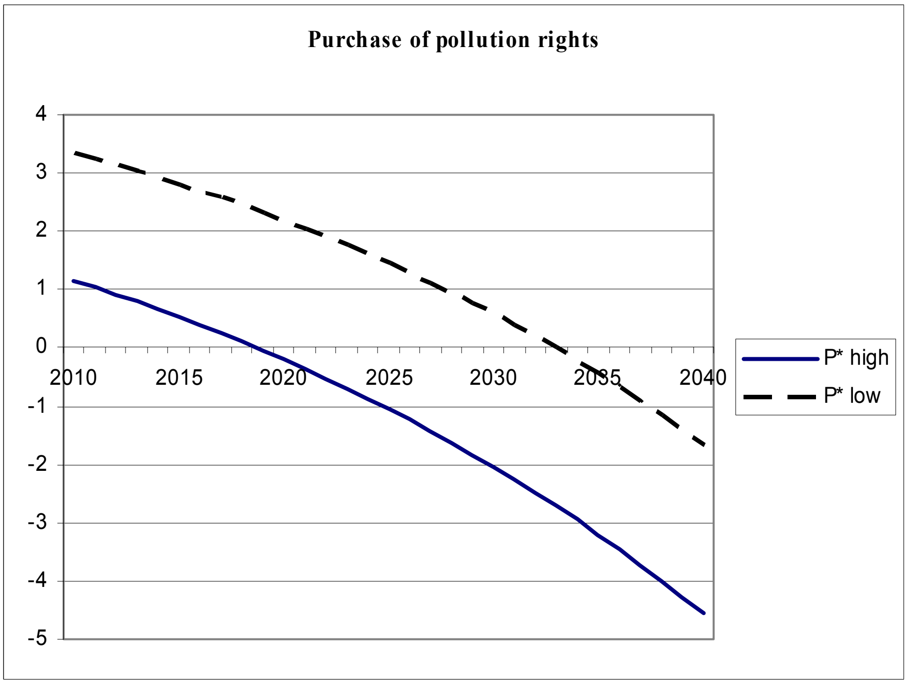
The environmentalists often claim that strict environmental regulation creates incentives for R&D which outweighs the adverse effect of these environmental policies. This claim does not hold empirically here. It is true that under climate policies a somewhat larger R&D activity is carried out in the optimal growth path under climate policies than under no climate policy, but this difference is very marginal, see Fig. 5. For instance, after 30 years the share of labour devoted to R&D in the energy technology is only 0.07 percentage points higher under the scenario of climate policy than under the baseline, so that the two R&D allocation paths are almost identical. There are two basic reasons for this. The share of energy in output is not so vital, and the energy constraint considered here is not so binding after all. In this sense, our result here is similar to that by Smulders and de Nooij (2003), who conclude that induced innovation may never offset the effects of reduction of energy inputs.

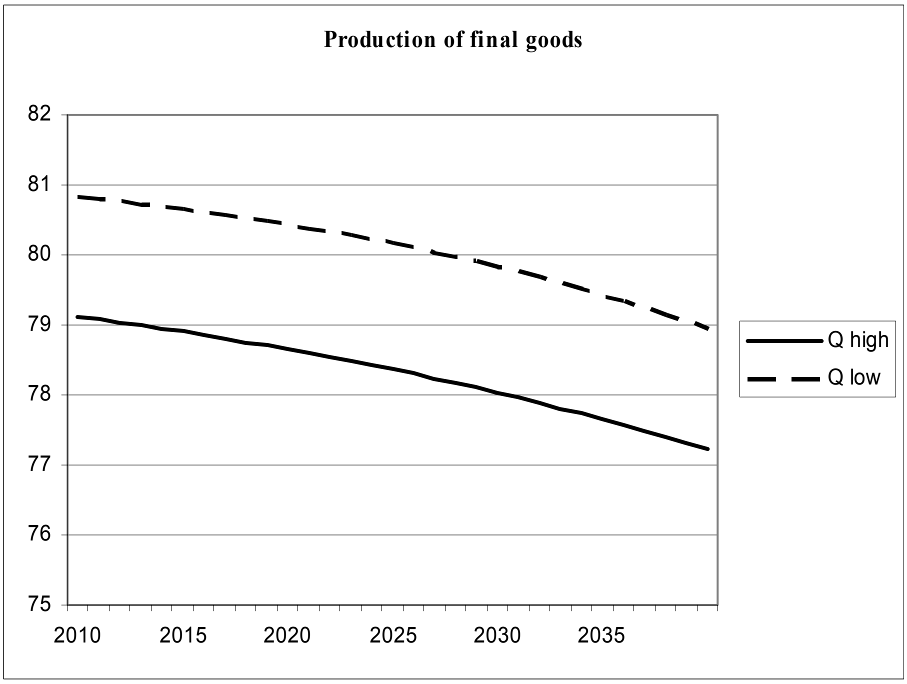
Figure 5. The resource allocation to less polluting energy technology R&D activities (parameter θ_B) under the two scenarios, see Fig. 4 for explanations, base = endogenous technology, no climate constraint, clim= endogenous technology and the climate constraint

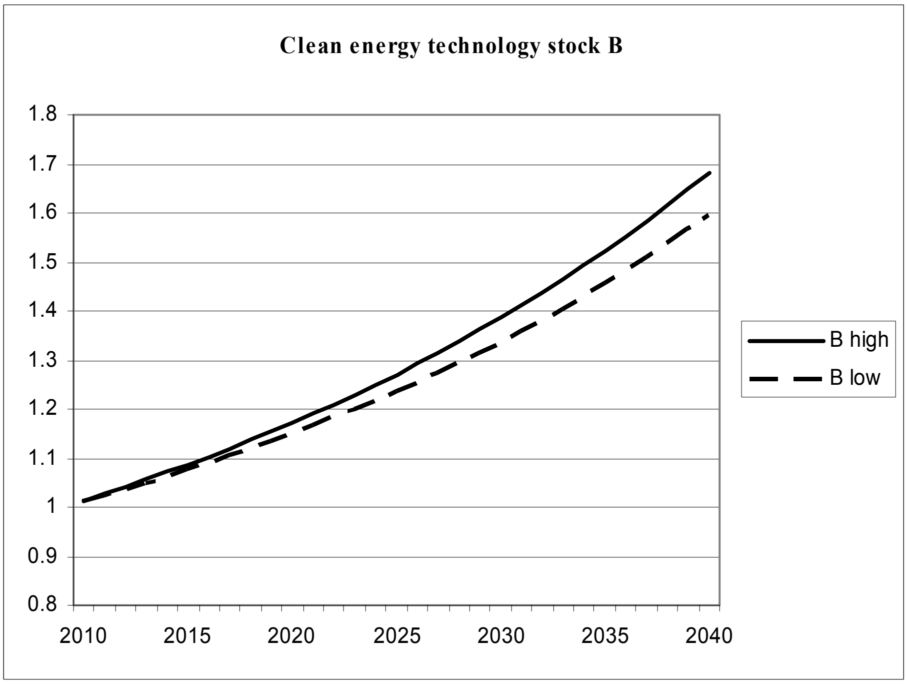


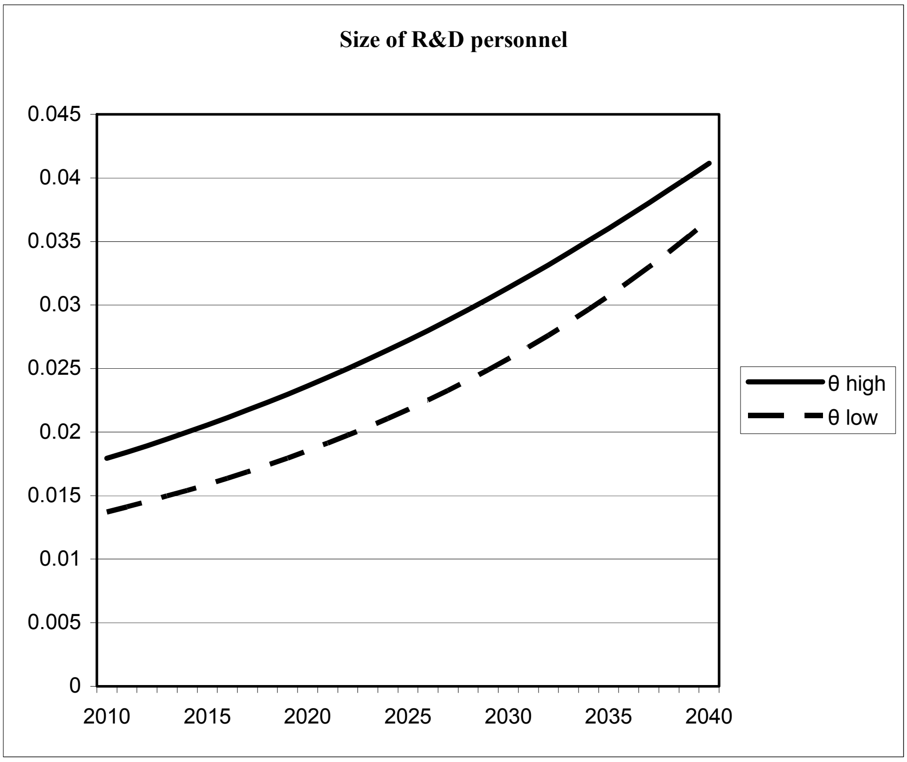
Let us next turn to consider the international purchase of pollution rights P*, which were absent above. Accordingly, we add Equation (20) to the system. The initial price q of pollution is around 0.8 units (i.e. the marginal productivity of P* with P* = 0). We consider two alternatives, where we lower q to be 0.6 (low price) and 0.7 (high), respectively. Now we get the following results, see Fig. 6.

Figure 6. The case under internationally tradable permits for pollution (for explanations, see the text, high = high price of the pollution permit, low = low price on it)









According to the results, the international price of the tradable permit has quite substantial effects. Under a low price of tradable permit, the purchases of them are, of course, higher, and accordingly, domestic production is clearly higher. Under both cases, the path of purchases of pollution rights P* is declining, because the domestic build up of energy technology B is a substitute for P*. The incentive to carry out own R&D in clean energy technology is clearly smaller under a low value of the pollution right.

5. Technology and environmental policy in a market economy

The analysis in Sections 3 and 4 is based on a command economy and the social planner's activities. Next, turn to the case where we consider the market allocations for production of final goods, and technology and environmental tax policies in a market economy. In order to do that, we have to be more articulated than above in describing the technology build up. We follow Zon and Yetkiner (2003), with slight modifications, and build a three sector model for the economy. So, we have three types of firms: final good producers, intermediate good producers and the R&D firms which invent new blueprints for less polluting energy technology. The final goods producing firms face the same production function as above in (6), but with no explicit domestic capital stock, and the energy input defined as in (9) above. We now identify the effective energy saving services stock $\tilde{B}$ to consist of those related to the various blueprints i, $\tilde{B}_i$,

$$\tilde{B} = (\int_0^B \tilde{B}_i^{1-\alpha} di)^{1/(1-\alpha)} , \tag{27}$$

where again B is the number of blueprints of less polluting energy technology invented up to the present time, and $0 < \alpha < 1$. The elasticity of substitution between the various blueprints of energy technology is $(1-\alpha)^{-1}$. The firms in the final goods sector maximise the profit Π_Q,

$$\Pi_Q = Q - WL_Q - \int_0^B p_i \tilde{B}_i di - (1+\tau)P_E^* E \quad , \tag{28}$$

where p_i is the price on services $\tilde{B}_i$. The profit also comprises of the purchases of the energy technology services from the intermediate goods sector and the purchases of energy input, subject to a possible tax on the use of energy. The demand for energy technology is given by differentiation of (28) with respect to $\tilde{B}_i$,

$$(1-\alpha)L_Q^{\alpha}E^{-\alpha}\tilde{B}^{\alpha}\tilde{B}_i^{-\alpha} = p_i \quad , \tag{29}$$

which implies that the price elasticity of demand is approximately 1/α for the less polluting energy services. The intermediate goods sector simply uses raw energy saving capital B_i to produce the respective services,

$$\tilde{B}_i = \kappa_i B_i , \tag{30}$$

where κ is the relevant total factor productivity. The firms in the R&D sector become local monopolies if they are able to develop a new blueprint of energy technology, and they capture the whole profit of the intermediate goods firms. The profit of the intermediate good sector can be written as follows,

$$\Pi_i = p_i\tilde{B}_i - c_{Bi}\tilde{B}_i = \alpha p_i\tilde{B}_i = L_Q\alpha(1-\alpha)^{1/\alpha}c_{Bi}^{1-1/\alpha}(\tilde{B}/E) \quad , \tag{31}$$

where c_B is the unit cost of producing a new item of energy technology, and we have used the first order condition (29). The monopoly profits gradually erode, as new and better energy saving techniques are invented. On the basis of Eq. (30) we can further write $c_i = \kappa_i^{-1}r$. The profit on the existing (old) energy technology erodes at the speed $\hat{\kappa} = \kappa_t / \kappa_{t-1} - 1 > 0$, as new inventions set the effective price of the services, which can be charged on the old technology.

As standard, there is a stock market evaluating the value of the R&D activity in the economy. Let V_B be the market value of the profit stream connected with the latest technology B. R&D sector firms maximise the present value over cost

$$V_B\frac{dB}{dt} - (1-s)W(\theta_B\bar{L}) , \tag{32}$$

where dB/dt measures the number blueprints invented within an infinitesimally small time unit and s is a subsidy on R&D activity by the government, assumed in the standard way to be financed by lump-sum taxes (see e.g. Zon and Yetkiner, 2003).[4] Using the R&D technology specified in (10) above we get for the optimal allocation in the R&D sector, where the labour employed in equilibrium has the same wage in R&D activities as in the production sector,

$$\theta_B \bar{L} = \left[\frac{(1-s)W}{\eta_B B^{\lambda_B} \xi V_B} \right]^{\frac{1}{\xi - 1}} . \tag{33}$$

The stock market evaluates the profits of R&D activity so that the following arbitrage condition holds,

$$V_B = \int_0^\infty e^{-rt} \Pi_{Bt} dt = \frac{\Pi_B}{r + \hat{\kappa}} , \tag{34}$$

where Π_B is that in Eq. (31) with i = B and we have assumed a constant rate of technological advancement $\hat{\kappa}$ in Eq. (30).

In order that the market allocation of labour to R&D activity is the same as that in the social optimum reached under a command economy, produced by the equation system (18) to (26) above, we solve for the optimal subsidy from (33) so that θ_B determined by this equation is the same as above in Section 4. The reason for this subsidy is that there are market failures related to R&D. As Zon and Yetkiner (2003) argue there are, first, the intertemporal spillovers from existing energy technology to future technological inventions. And second, there are monopoly profits related to this activity. The optimal policy is therefore ambiguous a priori.

The optimal purchase of tradable permits can be derived by maximising (6) with respect to P*. Comparing the outcome to Eq. (20), we see that that there is no point in raising revenues through energy taxation, in addition to imposing the environmental constraint on the economy, so that $\tau = 0$.

The household sector optimises its consumption-saving decisions in a manner which does not call for corrective policies, see Alho (1993) more details on this.

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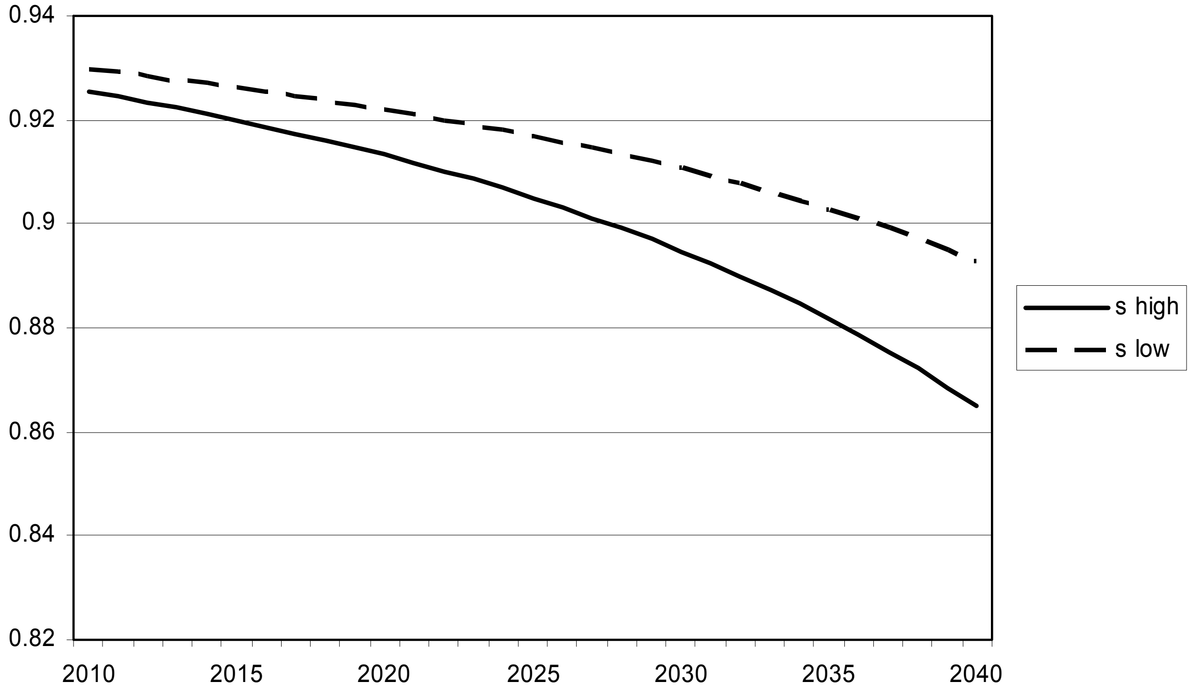
[4] Equivalently, they can be financed by a tax on labour, if labour supply is inelastic.

Let us now turn to the numerical solution for optimal subsidy s from Eq. (33). The results are shown in Fig. 7. We use the same two alternatives for the price q on pollution rights as above in Fig. 6.

Figure 7. The optimal subsidy rate (s) on environmental R&D activity



From the results we see, first, that the optimal rate of subsidy is quite high indeed, on the order of 90 per cent of the wage cost of R&D activity. Secondly, the subsidy is higher in the beginning than later on, as the cost of new technology is lowered ($\hat{\kappa}$ is assumed to be 1 per cent p.a.). We also infer that the need to subsidise R&D is the lower, the higher the price on the tradable emission permit. This reflects the fact that a tighter market for pollution rights in itself leads to a more profitable R&D activity and thereby higher allocation of resources to R&D (see Fig. 6), and, consequently, to a smaller need for government intervention in promoting R&D activity.

6. Concluding remarks

We have in this paper shed some basic insights into the issue of economic growth under climate policies. In comparison to the evidence produced by existing large-scale environmental and economic models, see the pioneering Finnish model Forsström and Honkatukia (2002), and its use by Honkatukia et al. (2005), our basic results roughly correspond in magnitude to those produced by these more extensive methods.

The case of growth under endogenous technology produced results, which in some cases did, and in some respects did not, lead to a markedly different outcome as under the case of exogenous technology. On the other hand, the price of the tradable permit seems to play quite an essential role as to the outcome, as also in Honkatukia et al. (2005). As to policies, we derived the result that the optimal subsidy channelled to R&D activity in clean energy technologies is quite high and covers some 90 per cent of these costs. It should be remarked that our empirical framework omitted the other technological stock, and R&D in it, incorporated in the total factor productivity. Enlarging the numerical model to this case is left to be analysed later on.

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