

EFFICIENCY AND EQUITY OF EMISSION TRADING WITH ENDOGENOUS ENVIRONMENTAL TECHNICAL CHANGE

by

Paolo Buonanno
(Fondazione ENI Enrico Mattei)

Carlo Carraro
(University of Venice and Fondazione ENI Enrico Mattei)

Efrem Castelnuovo
(Fondazione ENI Enrico Mattei)

Marzio Galeotti
(University of Bergamo and Fondazione ENI Enrico Mattei)

Abstract. In this paper we use a simple climate model with endogenous environmental technical change, obtained by integrating Nordhaus and Yang (1996)'s RICE with the model proposed in Goulder and Mathai (1998), to analyse the efficiency and equity of different policy options. In particular, we aim at: (i) identifying the new effects arising from the endogenisation of technical change; (ii) assessing the pros and cons of the introduction of ceilings to emission trading; (iii) quantifying the distributional effects of climate policy scenarios. Our results show that the costs of complying with the Kyoto protocol are lower when environmental technical change is endogenous, even in the presence of emission trading. Moreover, the introduction of endogenous technical change leads to an equilibrium in which the demand for permits is higher, but supply is also higher, because developing countries invest in R&D to increase the amount of permits they can sell in the market. As a consequence of these two effects, the price of permits is lower. As for ceilings, our analysis provides little support in favour of quantitative restrictions on emission trading. Even if the introduction of ceilings increases the R&D efforts of buyer countries and fosters technological innovation, the overall effect on abatement costs and economic growth is negative. The reason is that the benefits from technological innovation are lower, even in the long run, than the costs of adopting a more expensive approach to climate change control. Finally, even equity is not positively affected by ceilings. We show that flexibility mechanisms in the presence of endogenous technical change increase equity and that the highest equity levels are achieved without ceilings, both in the short and in the long run.

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1. Introduction

In the last year, there have been many attempts to quantify the costs of implementing the Kyoto agreement under different policy options, i.e. with or without different degrees of introduction of the so-called “flexibility mechanisms” (Emission Trading, Joint Implementation, CDM).¹ Despite their high variability, all estimates show that the Kyoto flexibility mechanisms sensibly reduce the costs of compliance. Shogren (1999) notes that “it is estimated that any agreement without the cost flexibility provided by trading will at least double the U.S. costs, ... the key is to distribute emissions internationally so as to minimise the costs of climate policy”. Manne and Richels (1999) state that “losses in 2010 are two and one-half times higher with the constraint on the purchase of carbon emission rights; international co-operation through trade is essential if we are to reduce mitigation costs”. These are just a couple of examples of the many models that reach the same conclusion: emission trading, and more generally the application of the flexibility mechanisms, can reduce overall mitigation costs without reducing the effectiveness of the climate policy (see also Rose and Stevens, 1999; Bosello and Roson, 1999; Hourcade, Ha-Duong, and Lecocq, 1999; Tol, 1999). Notice that the same conclusion can also be achieved independently of the specific climate model which is adopted. Chander, Tulkens, Van Ypersele, and Willems (1999) show that the application of simple economic principles is sufficient to prove the following results:

- flexibility mechanisms reduce total compliance costs;
- the largest cost reduction is achieved when no constraint is imposed on the trading system (e.g. no ceilings);²
- there exists a system of transfers such that this cost reduction benefits all countries.

However, the theoretical conclusions by Chander *et al.* (1999) are achieved within a static model and it is not clear whether they can be generalised to the case in which investment, stock pollution, R&D and technical change are accounted for. In particular, the issue of technical change is very controversial and not yet sufficiently studied.

Some arguments which support the introduction of ceilings on emission trading are indeed based on the role of technical change. It is argued (e.g. in Hourcade *et al.*, 1999; Schleicher, 1999) that the widespread

¹ Many of these papers are gathered in OECD (1998) and in Carraro (1999).

² Article 17 of the Kyoto Protocol calls for emissions trading to be only “supplemental to domestic actions for the purpose of meeting quantified emissions limitation and reduction commitments under Article 3”. To make it operational, it has been suggested that quantitative constraints (ceilings) on imports of emissions reduction be introduced.

adoption of flexibility mechanisms reduces the incentives to carry out environmental R&D, thereby reducing the effectiveness and increasing the costs of abatement options in the long run. Moreover, the incentives to R&D induced by the presence of ceilings on the use of flexibility mechanisms may spill-over onto other sectors, thus speeding up the “engine of growth”, and reducing the impact of climate change control on long-run per-capita income and welfare.

This argument is not completely convincing. For example, Convery (1999) notices that “to the extent that constraints are placed on carbon trade, the costs of compliance will be increased.....the negative effects would spill over also to the countries likely to export carbon credits, since the volume of their sales and the price they get will be lower because of lower demand induced by higher costs of mitigation measures taken at home by the EU and the U.S.A.. All countries lose, and emissions reduction commitments in subsequent periods will be made more expensive and therefore less likely to be significant. Since the gains from trade experienced by Russia and Ukraine will be reduced, it will also reduce the prospects for trade gains from potential entrants from the developing countries in the future”. Bohm (1999) asserts that “forcing countries to produce more of the emissions reduction quantity commodity at home than it wants to is like forcing cold Nordic countries to grow some minimum share of bananas before it is allowed to import bananas from countries that have a comparative advantage in banana production.....Supplementarity will not only make present Annex B countries less likely to accept more stringent future commitments, it will also make it harder to get new countries to join the set of Annex B countries”.

Hence, another argument in favour of free adoption of the flexibility mechanisms is that they will encourage the accession of new countries to the group (coalition) of those who have already decided to accept quantified limits to their GHGs emissions.

In this paper, we do not study the validity of this second argument, which is next on the agenda of future research concerning the modelling of the endogenous formation of climate coalitions (see Carraro, 1998 for a theoretical overview of this issue). We rather focus here on arguments regarding the link between climate policies and technical change.

In particular, we try to provide an answer to the following questions:

- Does endogenous technical change modify the effectiveness and the costs of different ways of implementing the flexibility mechanisms to reduce GHGs emissions in Annex 1 countries?
- Does policy-induced R&D and its impacts on technical change and the emissions/output ratio help to achieve the Kyoto targets? Is R&D a complement or a substitute with respect to emissions trading, i.e. do countries reduce their R&D efforts when trading is allowed for?

- If this is the case, are the benefits from free emission trading more than compensated for by the losses induced by lower R&D efforts?
- Which is the impact on equity of different policy options? Is it true that emission trading will favour developing countries, thus increasing equity, as argued in Nordhaus and Boyer (1999)³ or does emission trading favour mainly Annex 1 countries, because it reduces their abatement costs, thus reducing equity?

In order to answer these questions we take the well-known RICE model of integrated assessment (Nordhaus and Yang, 1996) and incorporate it in a modified version of the endogenous environmental technical change (ETC) model proposed by Goulder and Mathai (1998) (see also Nordhaus, 1997). In this latter model, firms choose their optimal R&D efforts which increase the stock of technological knowledge. This stock enters the production function as one of the production factors and, at the same time, affects the emission-output ratio. Thus, the idea is that more knowledge will help firms increase their productivity and reduce their negative impact on the environment. This ETC model can easily be introduced into the RICE model.

Using our “ETC-RICE” model we are able to solve the game played by the six regions in which the world is divided when deciding the optimal level of four instruments: fixed investments, R&D expenditures, rate of emission control, and the amount of permits which each country wants to buy or sell. The game is played under some regulatory constraints: with or without ceilings on trading, with the possibility to trade only among Annex 1 countries or under global trade, with or without environmental R&D incentives.⁴

In order to construct a benchmark for our analysis, the ETC-RICE model has been calibrated in such a way as to reproduce the same Business As Usual (BAU) scenario as that of Nordhaus and Yang (1996)’s RICE model where technical change is present, albeit only exogenously, and has an impact on the emission-output ratio.

The structure of the paper is as follows. After a brief presentation of the changes introduced in RICE and of the calibration technique, we compare the results of two models. In the first ETC-RICE model, which we call the model with exogenous environmental technical change, each country optimally sets its R&D level and as a consequence the stock of knowledge, but this choice does not affect the emission-output ratio, which evolves exogenously in accordance with Nordhaus and Yang’s assumptions. In the second ETC-RICE model, with endogenous environmental technical change, a change of the stock of knowledge also modifies the emission-output, which therefore depends on the optimal R&D chosen by each country. Hence, in both models technical change is partly endogenous, because R&D is optimally chosen and depends on all relative prices, including the price of permits. But only in the second model, does a change of relative prices, e.g. the price of permits, affect the environmental features of the technology adopted in each country. Hence, only in

³ Nordhaus and Boyer (1999) actually claim that the Kyoto protocol, even if implemented through emission trading, will be excessively costly to the US and extremely beneficial to developing countries.

⁴ This last case is not implemented in the present version of the paper.

the second case can we talk of endogenous environmental R&D or of induced environmental technical change.

By comparing the results obtained with the above two models, we are able to understand the new effects of alternative policy options induced by the endogenisation of environmental technical change. In particular, we would like to test the following propositions:

- The costs of implementing Kyoto are lower when emission trading is adopted and are even lower when endogenous ETC is allowed for.
- If R&D and emission trading are substitutes, the price of permits is lower, because countries reduce their emissions through R&D and thus demand less permits. Hence, the level of trading is also lower than in the case with exogenous technical change.
- Permit-selling countries carry out excessive R&D in order to have more permits to sell in the market. As a consequence, more R&D is carried out at the world level, which implies that total emissions are lower because R&D reduces the emission abatement ratio.
- When ETC is endogenous, the equity index is lower because emission-related transfers to developing countries are lower (as a consequence of the lower permit price and demand).

The second part of the paper is devoted to analysing the role of ceilings. The RICE model with endogenous environmental technical change enables us to compare the effects of policy scenarios in which increasing restrictions to emission trading are introduced. In particular, we would like to check whether:

- When ceilings are introduced all countries increase their R&D effort.
- This increased R&D effort has a positive impact on factor productivity and this impact more than compensates for the increased abatement costs for developed countries induced by the trade restrictions. Hence, for these countries the total costs of implementing Kyoto is lower for stricter ceilings (alternatively, there is an optimal ceiling value which minimises the total cost).
- In the long run, technical change induced by stricter ceilings fosters economic growth and yields a higher GNP level.
- With ceilings, the implementation of Kyoto is more equitable because developed countries increase their abatement through domestic policies and do not buy developing countries "environmental resources" at low price.

As shown in the following sections, this paper supports only some of the above propositions. The main results are summarised in the concluding section, which also outlines directions of further research.

2. Endogenous Technical Change Modelling

Most models used to assess the effects of policies designed to control GHGs emissions adopt an exogenous representation of technical change. Traditional energy economy models include an Autonomous Energy Efficiency Improvement (AEEI) factor, which typically consists of an exogenously set parameter. Of course, this is quite unsatisfactory. The need for a “new generation” of climate models which endogenise the linkages between economic variables (policy variables, in particular) and technical progress is widely recognised and now strongly advocated (see Weyant, 1997; Carraro, 1998). However, there are currently only a few attempts to introduce these linkages in existing models, especially in models of integrated assessment.

Some early attempts were made in the econometric general equilibrium model for the U.S.A. economy of Jorgenson and Wilcoxon (1990), where environmental policy decisions affecting relative prices determine an endogenous change in total factor productivity, and in the applied general equilibrium model for Germany of Conrad and Henseler-Unger (1986) and Conrad and Ehrlich (1993), where substitution possibilities are more feasible with the most recent capital vintages and the adoption of new, “cleaner” vintages depends on climate policies. However, more recently, several models have been developed. One main difficulty faced by modellers when they try to endogenise technical change is the non-observability of this variable. This is why old-fashioned models used a deterministic trend as a proxy of technical change. And this is why that is the starting point of some *ad hoc* attempts to model technical change. For example, in Boone *et al.* (1992), Carraro and Galeotti (1996) and Dowlatabadi and Oravetz (1997), technical progress is still represented by a variable which is added to the main equations of the model. However, this variable is no longer a deterministic function of time. It is rather a stochastic function of time, in which other economic effects are also accounted for.⁵

The problem with this approach is its *ad hoc* nature. There is no explicit solution of firms’ optimisation problem that determines the optimal amount of R&D and investments in the corresponding types of capital. Therefore, links between these variables are mainly statistical and lack a clear economic interpretation.⁶ Similar considerations apply to those energy-environment-economy models that purport to explicitly represent energy supply technologies. Here a common modelling device is the use of “backstop technologies”, assumed to be available at a future date in infinite supply at a high price relative to current energy prices (Nordhaus, 1973). While this approach endogenises the switch to a different technology,

⁵ Another recent interesting development of the literature on induced technical change is constituted by the attempt to represent it as a learning-by-doing process. The model by Grübler and Messner (1996) is based on the concept of learning curves and describes future costs and performance improvements of new technologies as a function of accumulated R&D, and learning and experience gained in diffusion of new technologies.

⁶ An exception is the proposal by Newell, Jaffe and Stavins (1998). Here the model is more sophisticated and represents the economic structure of innovation decisions. However, the problem lies in the necessity of defining a statistical *ad hoc* model to generate the time series to be used in estimating the structural model of technological innovation. Hence, the model is still somewhat *ad hoc*, even if the problem is confined to the estimation procedure.

and thus the time of its adoption, the price level at which this occurs continues to be exogenously determined.

More recently, some contributions have endogenised the process of technical change with the help of structural models of R&D efforts and innovation. These are typically generated as the solution of a firm's dynamic optimisation problem (along with other relevant decision variables), but in which the parameters describing their functional structure are calibrated rather than estimated (see Goulder and Schneider, 1996, and Goulder and Mathai, 1998). In this way, it is relatively easy to simulate a model of R&D and innovation, even if the price to be paid is to postulate a set of parameter values that cannot easily be tested. The use of R&D as a policy variable is also a feature of the R&DICE model of integrated assessment succinctly described in Nordhaus (1997).

In Goulder and Mathai (1998)'s partial equilibrium model of knowledge accumulation, the firm chooses time paths of abatement and R&D efforts in order to minimise the present value of the costs of abating emissions and of R&D expenditures subject to an emission target. The abatement cost function depends both on abatement and on the stock of knowledge which increases over time via R&D investment.⁷ In a similar vein, Nordhaus (1997) lays out a model of induced innovation brought about by R&D efforts. In particular, technological change displays its effects through changes in the emissions-output ratio. This aspect is then embedded in the non-regional version of the author's RICE integrated assessment model for climate change policy analysis (Nordhaus, 1993).

In the present paper, we propose a model of endogenous technical change inspired by the ideas contained in both Nordhaus (1997) and Goulder and Mathai (1998) and accordingly modify Nordhaus and Yang (1996)'s regional RICE model. Doing so requires input of a few new parameter values, some of which we try to estimate using information provided by Coe and Helpman (1995), while the remaining parameters are calibrated so as to reproduce the BAU scenario generated by the RICE model with exogenous technical change. We extend the integrated assessment model thus obtained to allow for trading of emission permits and analyse several policy options looking at their efficiency and equity implications.

Let us briefly describe our model of endogenous technical change and the estimation/calibration procedure.

⁷ A second problem studied by Goulder and Mathai (1998) assumes that the rate of change of the knowledge stock is governed by abatement efforts themselves. This form of technological change is termed learning by doing. The analysis we conduct in the present paper can be easily adapted to this case as well, although we have selected R&D-driven technological change as it appears to be more popular in the literature.

The RICE model proposed by Nordhaus and Yang (1996) is one of the most popular and manageable integrated assessment tools for the study of climate change. It is basically a single sector optimal growth model suitably extended to incorporate the interactions between economic activities and climate. There is one such model for each macro region into which the world is divided (U.S.A., Japan, Europe, China, Former Soviet Union, Rest of the World). Within each region a central planner chooses the optimal paths of fixed investment and emission abatement that maximise the present value of per capita consumption. Output (net of climate change) is used for investment and consumption and is produced according to a constant returns Cobb-Douglas technology that combines the inputs from capital and labour with the level of technology. Population (taken to be equal to full employment) and technology levels grow over time in an exogenous fashion, whereas capital accumulation is governed by the optimal rate of investment. There is a wedge between output gross and net of climate change effects, which depends upon the amount of abatement (rate of emission reduction) as well as the change in global temperature. The model is completed by three equations respectively representing emissions (which are related to output and abatement), carbon cycle (which relates concentrations to emissions), and climate module (which relates the change in temperature relative to 1990 levels to carbon concentrations). Each country plays a non-cooperative Nash game in a dynamic setting, which results in a Open Loop Nash equilibrium (see Eyckmans and Tulkens, 1999). This is a situation where in each region maximises its utility subject to the individual resource and capital constraints and the climate module for a given emission (i.e. abatement) strategy of all the other players.⁸

It is useful to reproduce here the RICE resource and production function constraints as well as the emission relationship. Letting $n=1, \dots, 6$ and $t=1, \dots, T$ identify each macro region and time period respectively (in the model each period spans ten years), we have:

$$Q(n,t) = A(n,t)L(n,t)^{1-\theta} K_F(n,t)^\theta \quad (1)$$

where Q is gross output, A the level of technology, L is population, and K_F is the stock of fixed capital which accumulates according to the usual recursive law:

$$K_F(n,t+1) = I(n,t) + (1-d_F)K_F(n,t) \quad (2)$$

with I being the rate of investment and d_F the rate of capital depreciation. Output net of climate change effects, Y , is used for consumption C and investment purposes:

$$Y(n,t) = \Omega(n,t)Q(n,t) = C(n,t) + I(n,t) \quad (3)$$

⁸ As there is no international trade in the model, regions are interdependent through climate variables.

where Ω is the climate factor which, as said, depends upon the rate of emission reduction m and the change in temperature. Finally, carbon emissions E depend upon the rate of abatement m as well as gross output according to the following relationship:

$$E(n, t) = S(n, t)[1 - m(n, t)]Q(n, t) \quad (4)$$

where S can be loosely defined as the emissions-output ratio. The policy variables of the model are the rates of fixed investment and of emission abatement. For the other variables the model specifies a time path of exogenously given values. Interestingly, this is also the case of the technology level A and of the emissions-output ratio S . Thus we can say that the RICE model contains a specification of exogenous environmental and non-environmental technical change. Obviously those time paths need not coincide in general with the optimal ones. In addition, investment fosters economic growth (thereby driving up emissions) while abatement is the only policy variable used for reducing emissions.

We modify the above equations of the RICE model in order to endogenise the process of technical change. In particular we assume that innovation is brought about by R&D spending which contributes to the accumulation of the stock of existing knowledge. Following an approach pioneered by Griliches (1979, 1984) we assume that the stock of knowledge is a factor of production, which therefore enhances the rate of productivity (see also Weyant, 1997). Besides this channel, however, knowledge also serves the purpose of reducing, *ceteris paribus*, the level of carbon emissions. Thus, in our formulation, R&D efforts prompt both environmental and non-environmental technical progress, although with different modes and elasticities.⁹ More precisely, we modify equations (1) and (4) as follows:

$$Q(n, t) = A(n, t)K_R(n, t)^{b_n} [L(n, t)^{1-g} K_F(n, t)^g] \quad (5)$$

and:

$$E(n, t) = [S_n + c_n \exp(-a_n K_R(n, t))] [1 - m(n, t)] Q(n, t) \quad (6)$$

In (5) the stock of knowledge has a region-specific elasticity equal to b . Note that to the extent that this coefficient is positive, the output production process is characterised by increasing returns to scale, in line with current theories of endogenous growth. Also, note that while we allow for R&D-driven technological progress, we maintain the possibility that technical improvements can also be determined

⁹ Obviously, we could have introduced two different types of R&D efforts, respectively contributing to the growth of an environmental knowledge stock and a production knowledge stock. Such undertaking however is made difficult by the need of specifying variables and calibrating parameters for which there is no immediately available and firm information in the literature.

exogenously (the path of A is the same as in RICE). In (6) knowledge reduces the emissions-output ratio with an elasticity of α , which also is region-specific; the parameter C is a scaling coefficient, whereas S_n is the value to which the emission-output ratio tends asymptotically as the stock of knowledge increases without limit. The stock accumulates in the usual fashion:

$$K_R(n, t+1) = R \& D(n, t) + (1 - d_R)K_R(n, t) \quad (7)$$

where $R \& D$ are the expenditures in research and development and d_R is the rate of knowledge depreciation. We finally recognise that some resources are absorbed by R&D spending. That is:

$$Y(n, t) = C(n, t) + I(n, t) + R \& D(n, t) \quad (8)$$

In summary, our formulation introduces R&D as a further policy variable of the model which on the one hand contributes to output productivity and, on the other hand, affects the emission-output ratio, and therefore the overall level of pollution emissions.

As for parameter calibration and data requirements for the newly introduced variables, we proceed as follows. Firstly, coefficients already present in the original RICE model are left unchanged. Next, for each region we calibrate the coefficient β in the production function (5) so as to obtain in the year 2000 a value of the R&D-output ratio equal to that of 1990. R&D figures for 1990 were taken from Coe and Helpman (1995), while the 1990 stock of knowledge for the U.S.A., Japan, and Europe comes from Helpman's Web page. Here for the other three macro-regions, 1990 values of the knowledge stock have been constructed by taking the ratio knowledge/physical capital of the three industrialized regions and multiplying it by the 1990 physical capital stock of the other regions as given in the RICE model.¹⁰ The regional parameters α and χ in equation (6) are OLS estimated using time series of the emissions-output ratio and of the stock of knowledge (the sample runs from years 1990 to 2120, i.e. it consists of ten years of data). The data for the former variable are those used by Nordhaus and Yang (1996), while those for the latter variable are recovered from a BAU simulation conducted using an emissions-output ratio $S(n, t)$ as in the original RICE model.¹¹ The asymptotic values S_n are computed by simulating the pattern of the exogenous emissions-output ratio considered by Nordhaus and Yang (1996) for 1,000 periods: the values of the last period are then taken as asymptotes. Finally, the rate of knowledge depreciation is set at 5%, following a suggestion contained in Griliches (1979). The relevant quantitative information is presented in Table 1.

¹⁰ Helpman's Web page is at the URL <http://www.economics.harvard.edu/faculty/helpman/data.html>.

¹¹ More specifically, for each region we regress $\ln[S(n, t) - S_n]$ against an intercept and $K_R(n, t)$. The antilog of the intercept provides an estimate of C_n while the slope coefficient produces an estimate of α_n .

Table 1: Coefficients of the ETC-RICE Model

	a_n	b_n	d_R	c_n	s_n	$K_R(n, 1990)$
U.S.A.	0.195440	0.04355	0.05	0.019369	0.00971	1.24200
Japan	0.522430	0.04550	0.05	0.005270	0.00600	0.27773
Europe	0.296490	0.03180	0.05	0.007659	0.00699	0.75520
China	0.618650	0.01080	0.05	0.112771	0.00904	0.03145
FSU	1.197400	0.01660	0.05	0.095579	0.00935	0.07269
ROW	0.072926	0.00927	0.05	0.022409	0.00845	0.39343

Note: The stock of knowledge is expressed in trillions of 1990 U.S. dollars.

For each of the policy options described below we consider model simulations specifying both an exogenous and an endogenous environmental technological change process. In other words, for each policy option two versions of the model are simulated using either equation (4) or (6) respectively.¹² This allows an assessment of the role and impact of endogenous environmental technical change.

Simulations of the model under the two aforementioned hypotheses on the nature of technical change represent our BAU (Business As Usual) scenario, where no constraint on emissions is imposed. As said, the calibration is such that a unique BAU scenario is yielded by the two versions of the model. The principal use of our ETC-RICE model in the present paper is to study the main implications of the Kyoto protocol, and in particular the role of the flexibility mechanisms contained therein. To this end, we further extend the RICE model in order to incorporate the possibility for the world's regions to trade pollution permits among themselves. This calls for additional modifications of the equations considered above as well as a redefinition of the process leading to an Open Loop Nash Equilibrium.

We first introduce in our ETC-RICE model a constraint that sets a limit to the amount of emissions each Annex 1 macro region is allowed to produce under the provisions of the Kyoto protocol. We represent this as follows:

$$E(n, t) = \text{Kyoto}(n) \tag{9}$$

Note that (9) holds only for the signatory countries. In particular U.S.A., Japan, Europe, and Former Soviet Union (FSU) must reduce their emissions, over the period 2008-2012, to 7%, 6%, 8%, and 0%

¹² Note that we maintain the specification of the production process (5) where the state of the technology evolves partly exogenously and partly endogenously. Thus we never replicate the working and results of the original RICE model.

below their 1990 level respectively. We take 2010 as an approximation of the above mentioned five year period.

Simulations of the model with constraint (9) effective represent a first policy option that we consider, which we term simply as “Kyoto”. Note that China and Rest of the World are not subject to the restriction in (9) while the FSU is subject to a zero percent reduction target. In the BAU and Kyoto scenarios, policy variables are the amount of investment and of R&D expenditures, as well as the rate of pollution abatement.

In order to reduce the costs of complying with the limits to emissions, the Protocol introduces the possibility for Annex 1 countries to exchange pollution permits: countries with lower abatement costs will sell permits in an international market, while countries with high costs will buy permits. In equilibrium, net purchases are zero at the price of permits which equalises marginal abatement costs across regions. In order to introduce this flexibility mechanism in our model, we modify equations (8) and (9) as follows:

$$Y(n,t) = C(n,t) + I(n,t) + R \& D(n,t) + p(t)NIP(n,t) \quad (10)$$

$$E(n,t) = Kyoto(n) + NIP(n,t) \quad (11)$$

According to (10), resources produced by the economy must be devoted, in addition to consumption, investment, and research and development, to net purchases of emission permits. Equation (11) states that a region’s emissions may exceed the limit set in Kyoto if permits are bought, and vice versa in the case of sales of permits. Note that $p(t)$ is the price of a unit of tradable emission expressed in terms of the numéraire output price. Moreover, there is an additional policy variable to be considered in this case, i.e. net demands for permits NIP .

Under the possibility of emission trading, the sequence whereby a Nash equilibrium is reached must be revised as follows. Each region maximises its utility subject to the individual resource and capital constraints, now including the Kyoto constraint, and the climate module for a given emission (i.e. abatement) strategy of all the other players and a given price of permits $p(\theta)$ (in the first round this is set at an arbitrary level). When all regions have made their optimal choices, the overall net demand for permits is computed at the given price. If the sum of net demands in each period is approximately zero, a Nash equilibrium is obtained; otherwise the price is revised in proportion to the market disequilibrium and each region’s decision process begins again.

The above modification of the model enables us to analyse different ways of implementing emission trading. Hence, a third policy option, in addition to the BAU and Kyoto scenarios, that we consider is

when there is an active market of emission permits limited to Annex 1 countries. Under this case, a country can affect its level of emission by exchanging permits in the market. We call this scenario Et-A1, for Emission Trading among Annex 1 countries, in order to distinguish it from a further possibility where all countries, including those with no institutional limits to emissions, participate in the market for permits. We call this latter option Et-All. In this latter policy option, countries which do not have quantity commitments within the Kyoto Protocol are allowed to sell emissions if their actual emission levels are below their BAU level.

Some have argued that full access to a market of emission permits provides no incentive to individual countries to undertake domestic actions to cope with the environmental problem. This leads to the possibility of imposing a ceiling on the emission right that can be imported. We model and study this aspect by simulating the ETC-RICE model under the additional “ceilings” constraint:

$$NIP(n,t) = CEIL(n,t)[E_{BAU}(n,t) - Kyoto(n)] \quad (12)$$

where E_{BAU} is the level of regional emissions obtained from the BAU simulation of the model and $CEIL$ is the percentage ceiling to participation in emission trading. In the present paper we consider four additional ET (Emission Trading) policy options, setting the ceiling to either 15% or 33% and having only Annex 1 or All countries exchanging polluting rights.¹³ The eight policy options analysed in this paper are summarised in Table 2 below.

A final important feature of this paper is its focus both on efficiency and on equity of the different policy options described above. Efficiency will be measured in terms of abatement costs and total costs of complying with Kyoto, the latter including both the costs of abatement and the costs (benefits) from buying (selling) permits. We will also consider impacts on GNP growth, R&D efforts, emission control, and emission price. Equity will be measured by an equity index IE which, following Bosello and Roson (1999), compares an “equally distributed level of consumption” $EINC$ with the actual average consumption per head. More precisely, the equity index is:

$$IE(t) = EINC(t) / \left[\sum_n s(n,t) PVC(n,t) \right] \quad (12)$$

where:

$$EINC(t) = \exp \left[\sum_n s(n,t) \ln PVC(n,t) \right] \quad (13)$$

and where s is the region's share in the world population and PVC is the present discounted value of regional consumption. This is the maximised value of the objective functions generated by the model simulations. The index EI ranges between zero and one: the closer to unity, the more equitable the distribution.

3. Efficiency and Equity Effects of Induced Technical Change

Given the ETC-RICE model, we analysed the eight policy options described above and summarised in Table 2. From the optimisation runs, we could derive the optimal time paths of the control variables, and their impacts on the endogenous variables, in the period 2010-2100. In particular, we focused on those variables that could enable us to test the propositions presented in the introduction. Let us start by analysing the role of the endogenous technical change.

Table 2: Policy options

		<i>Flexibility (Ceiling)</i>							
		0		15%		33%		100%	
<i>Coalition Structure</i>	No coalitions	X							
	· · ·								
	Annex 1 regions	X		X		X		X	
	· · ·								
	All Regions			X		X		X	

¹³ For this policy option we simulate the model only under endogenous environmental technical change.

Our first proposition was:

Costs of implementing Kyoto are lower when emission trading is adopted and are even lower when endogenous ETC is allowed for.

We use two definitions of costs. In the first one, we consider only the domestic abatement costs, whereas in the second one we also consider the costs (gains) arising from the exchange of tradable permits. Assuming exogenous environmental technical change, Figure 1 shows the total abatement cost (for all world regions) as we move from the situation in which there is no trade of permits (named Kyoto), to the situation in which only Annex 1 countries trade (Et-A1), to the case in which all countries are allowed to trade (Et-All). Figure 2 shows the total cost (again for all world regions) in the same cases, where the total cost is the sum of the total abatement cost and the total cost (gain) from buying (selling) permits. Finally, Figure 3 shows the difference between the total abatement cost when environmental technical change is endogenous and when it is exogenous. Figure 4 shows these differences for the total cost.

Figure 1: Total Abatement Cost with Exogenous Environmental Technical Change

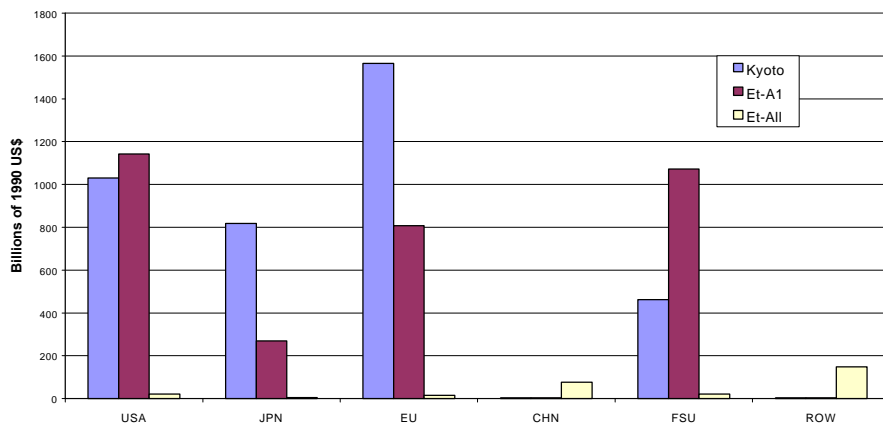


Figure 2: Total cost with Exogenous Environmental Technical Change

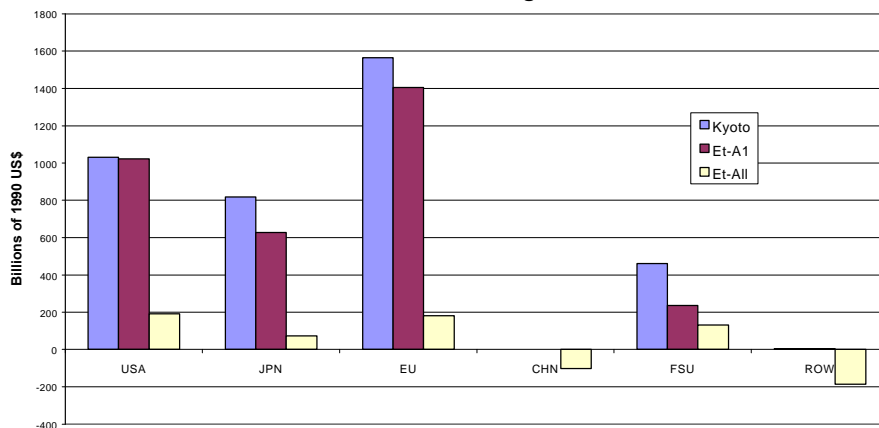


Figure 3: Endogenous vs. Exogenous technical change: differences in Total Abatement Cost (period 2010-2100)

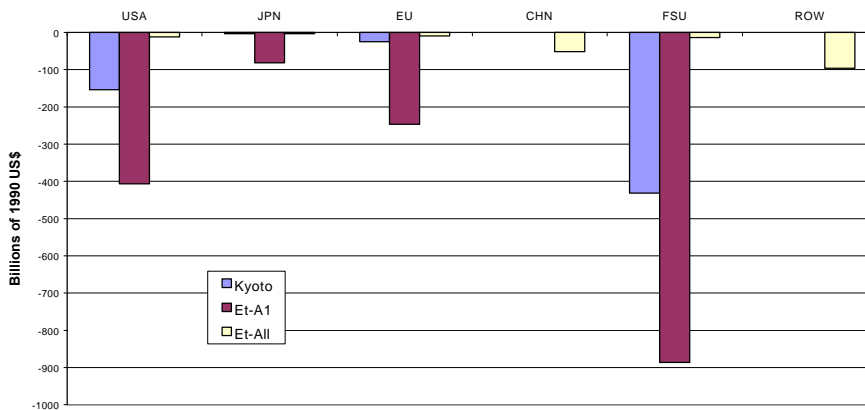
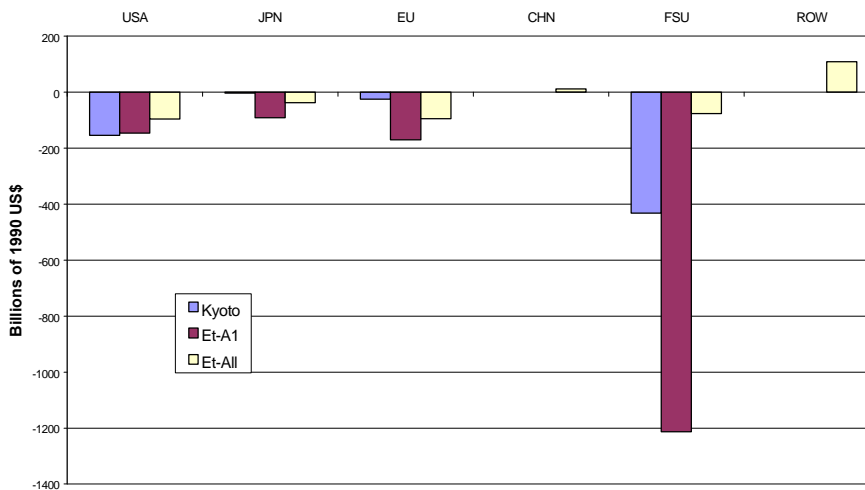


Figure 4: Endogenous vs. Exogenous technical change: differences in Total Cost (period 2010-2100)



It is easy to see that:

- Both the total abatement cost and the total cost decrease as more countries are allowed to trade. The lowest cost is achieved in the case of global trade (Et-All). These results are consistent with most findings in the recent literature on the Kyoto protocol (e.g. OECD, 1998).
- Both the total cost and the abatement cost are lower when environmental technical change is endogenous. Note that the highest benefit, in terms of abatement costs, from endogenising environmental technical change, is achieved when only Annex 1 countries are allowed to trade. This suggests that countries can actually exploit the incentive to innovate when their firms are not excessively penalised by high compliance costs. Indeed, one might think that the impact of environmental technical change is highest when emission trading is not allowed for. This intuition is not supported by our analyses, as will be further shown later on. When total cost is considered, the situation is less clear. For example, the

U.S.A. decreasingly benefits from the incentive to carry out environmental technical change as more countries trade their permits. This is also true for China, whereas the EU and Japan achieve the highest benefit when only Annex 1 countries trade. The situation of the FSU is peculiar. This is the region which derives the highest benefit from the endogenisation of environmental technical change when permits are traded only among Annex 1 countries. As we will see below, one reason is that countries of the FSU are the only sellers of permits in the Et-A1 case. Hence, they have a strong incentive to further reduce their emissions to sell permits in the market. Another reason is that they have lower marginal abatement costs; hence, their own R&D has a large impact on abatement costs.

We can therefore conclude that the first proposition is supported by our policy exercises. The second proposition was:

If R&D and emission trading are substitutes, the price of permits is lower, because countries reduce their emissions through R&D and thus demand less permits. Hence, in the case with endogenous environmental technical change, the level of trading is also lower.

This proposition is only partly true. The fact that emission trading and R&D are substitutes, at least for countries which have to choose between buying permits and carrying out R&D, can easily be seen from Figures 5-7. They show the amount of R&D and import of permits in the different policy scenarios. Note the strong negative correlation between import of permits and R&D, which supports the conclusion that these two control variables are substitutes.

Figure 5: USA - NIP and R&D Correlation

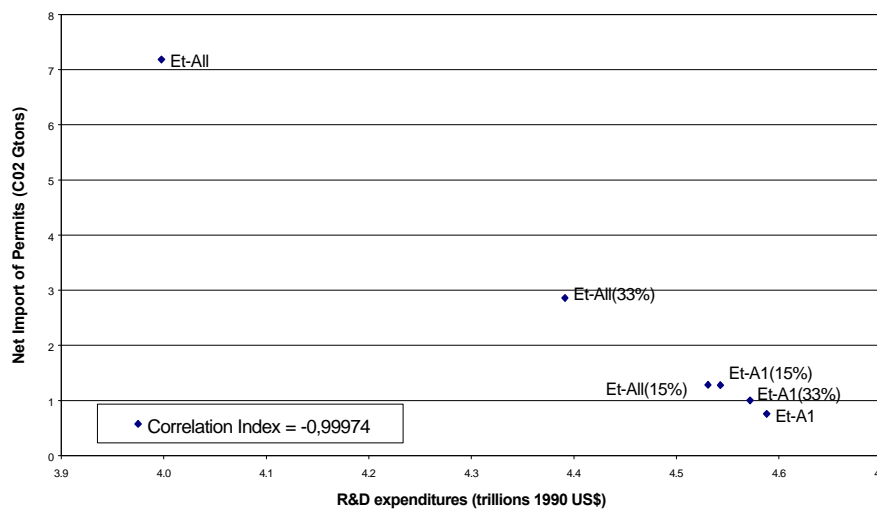


Figure 6: JPN - NIP and R&D Correlation

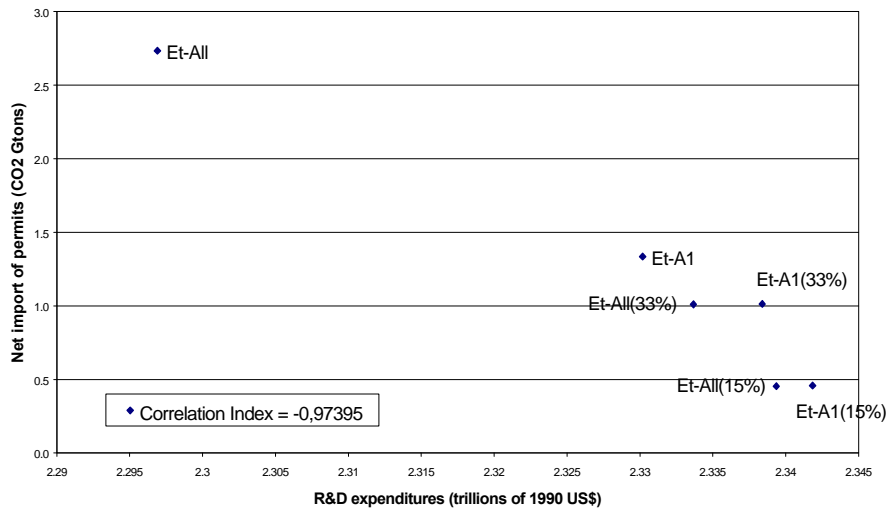
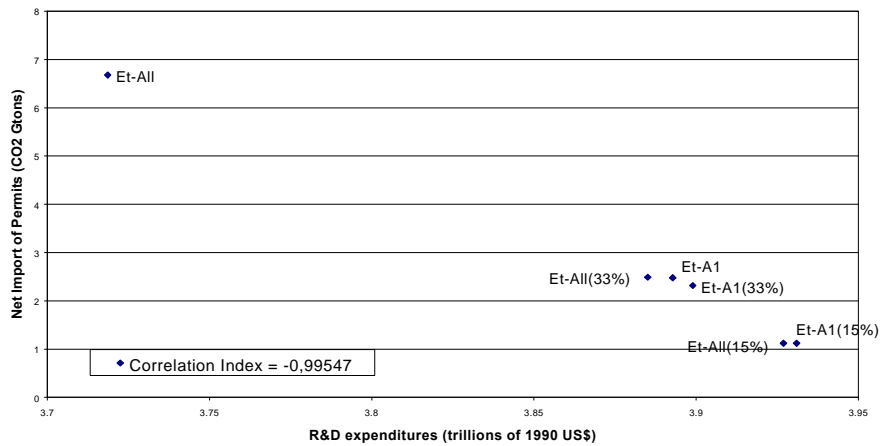


Figure 7: EU - NIP and R&D Correlation



The consequence is that the price of permits is indeed lower when ETC is endogenous, both if only Annex 1 countries trade (Figure 8) and when all countries trade (Figure 9). The reasons, however, are not only those identified in the proposition. R&D actually increases (Figure 10), in particular when no trade is allowed. However, the demand for permits does not decrease for the EU and Japan and decreases for the U.S.A. only when all countries trade permits (Fig. 11). A possible explanation is that the supply of permits also increases when ETC is endogenous (this is what the next proposition states and our results support it). As a consequence, the price of permits is lower, but the exchanged quantity slightly increases (see Figure 12). The proposition should therefore read:

If R&D and emission trading are substitutes, the price of permits is lower in the case with endogenous environmental technical change, both because countries reduce their emissions through R&D, and thus demand less permits, and because the supply of permits increases.

Figure 8: Et-A1 Price of Permits: Exogenous vs. Endogenous

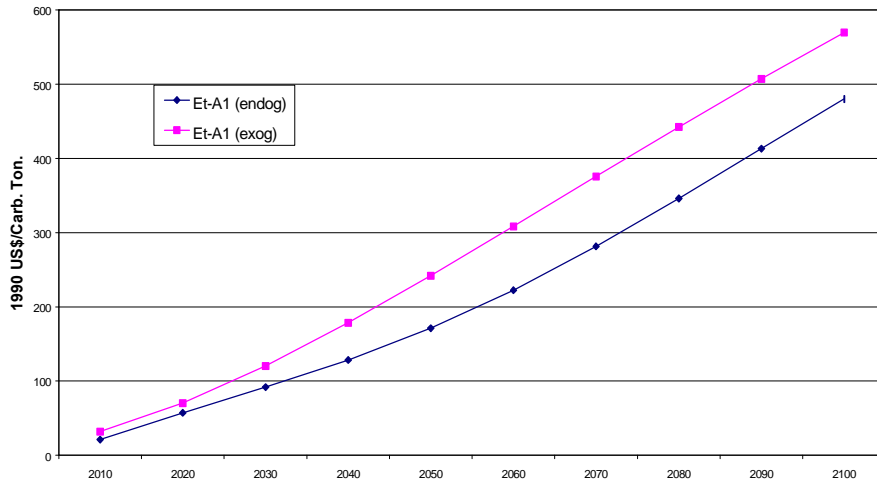


Figure 9: Et-All Price of Permits: Exogenous vs. Endogenous

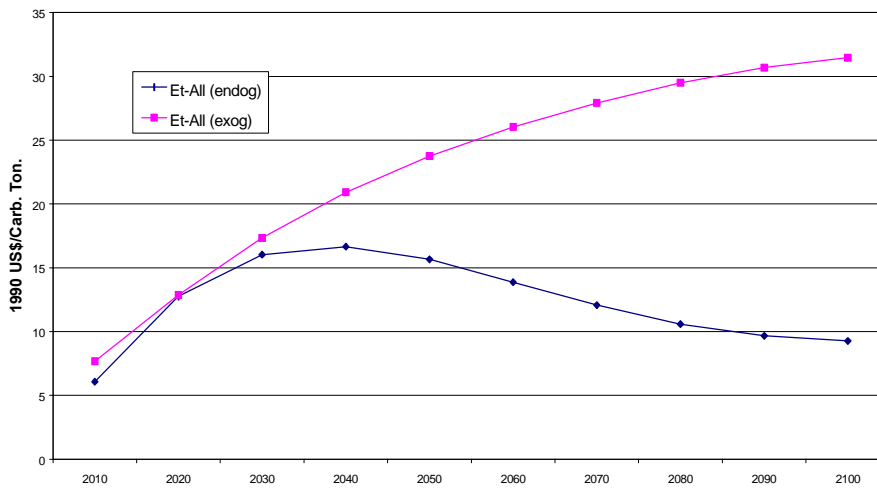
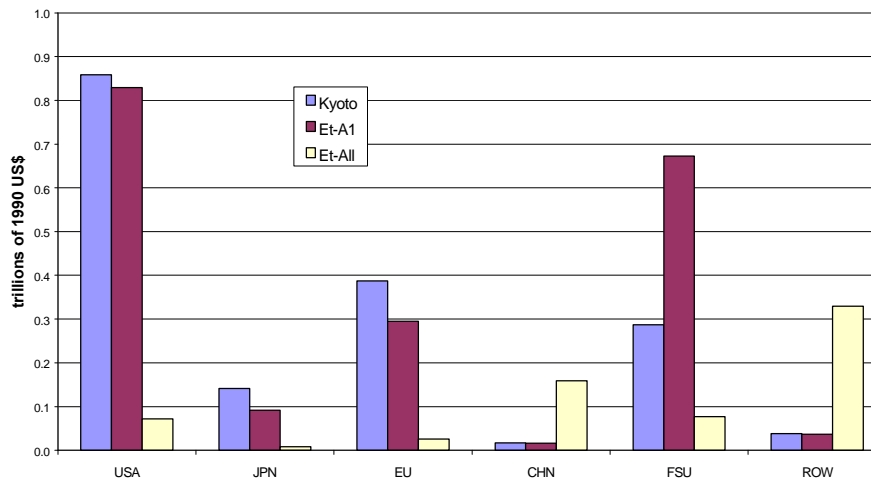


Figure 10: Endogenous v. Exogenous technical change: differences in Total R&D expenditures (period 2010-2100)



**Figure 11: Endogenous v. Exogenous technical change:
differences in Total Net Import of Permits
(period 2010-2100)**

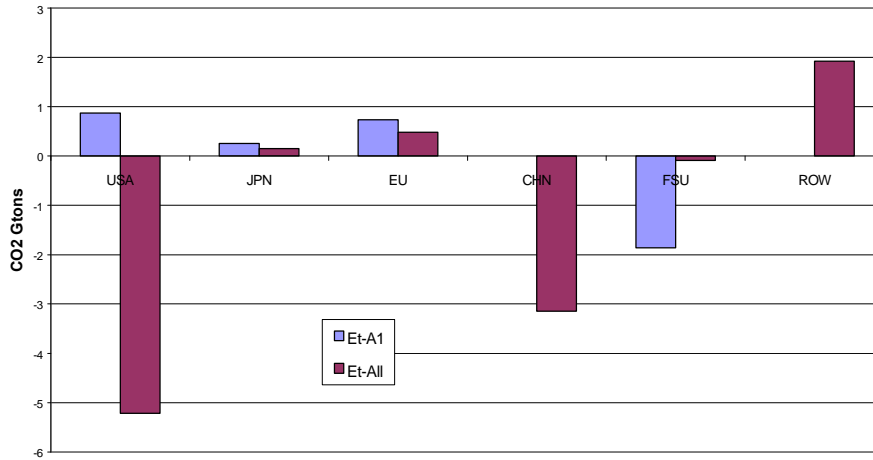
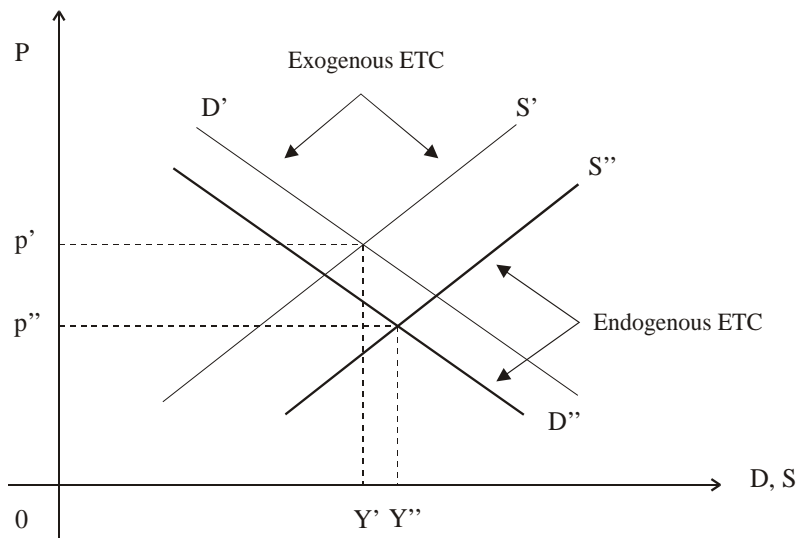


Figure 12: Permit market. Demand and supply shifts.



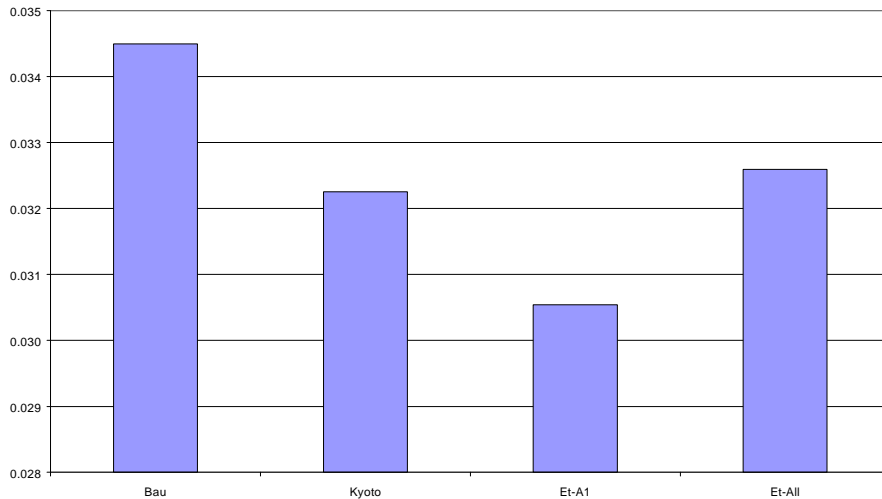
The supply of permits indeed increases because:

Permit-selling countries carry out excessive R&D in order to have more permits to sell in the market. As a consequence, more R&D is carried out at the world level, which implies that total emissions are lower because R&D reduces the emission-abatement ratio.

This proposition is confirmed by Fig. 11, which shows that sellers of permits increase their R&D expenditure. When only Annex 1 countries trade, the FSU sharply increases its R&D expenditure and sells

more permits. When all countries trade, both China and ROW strongly increase their R&D expenditure. The impact is a lower emission-output ratio at the world level (see Figure 13).

**Figure 13: World Emission-Output Ratio
(Average 2000-2100)**



Finally, let us consider the impact on equity of the endogenous environmental technical change. Our proposition was:

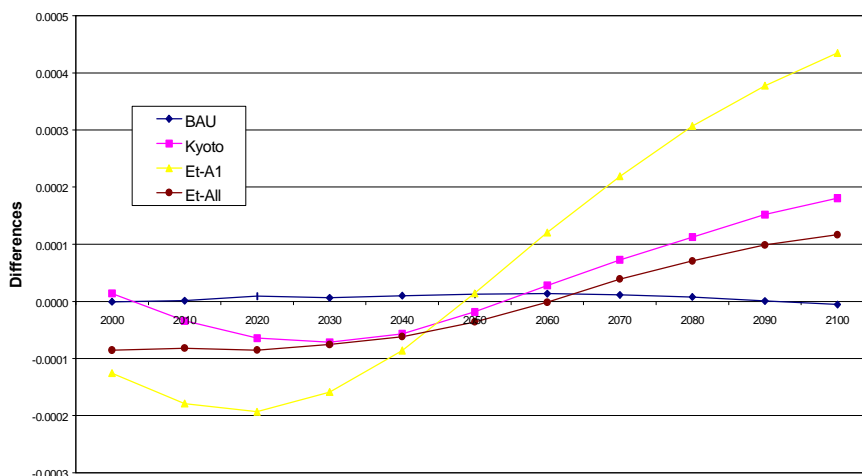
When ETC is endogenous, the equity index is lower because emission-related transfers to developing countries are lower (as a consequence of the lower permit price and demand).

We have already seen that the price is lower, but the exchanged quantity is usually larger. Hence the proposition should be modified as follows:

When ETC is endogenous, the equity index is lower because the total value of emission-related transfers to developing countries is lower (the effect of the lower price dominates the effect of the increased quantity)

This proposition is actually supported by our simulation runs only in the short-run, as shown by Figure 14. In the long-run, the equity index is larger with endogenous technical change. This implies that the adoption of flexibility mechanisms can actually increase equity, at least in the long run (a different result was obtained by Bosello and Roson, 1999). The explanation is as follows. When R&D is exogenous, developing countries increase their supply of permits to exploit the benefits arising from selling their permits. This effect becomes relevant only after a few decades, i.e. in the short run the price effect dominates the quantity effect, but in the long run the ranking of the two effects is reversed

Figure 14: Equity Index: Endogenous vs. Exogenous (differences)



4. Efficiency and Equity of Ceilings on Emission Trading

This section of the paper is devoted to analysing the role of ceilings. The ETC-RICE model enables us to compare the effects of policy scenarios in which increasing restrictions on emission trading are introduced. Our first proposition was:

When ceilings are introduced, all countries increase their R&D effort.

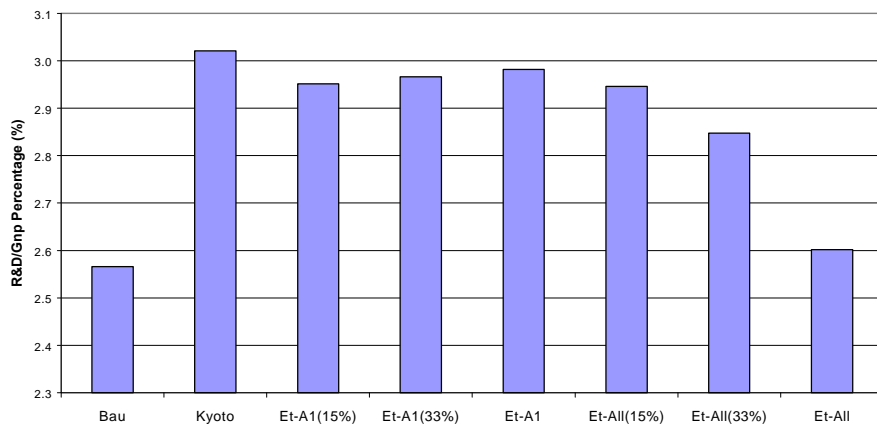
This proposition is in fact confirmed by our numerical analysis as far as developed countries are concerned, but the behaviour of the other world regions is quite different (see Figures 15-20). In the U.S.A., Japan and the EU, the lowest R&D effort, as measured by the per cent ratio between R&D expenditure and GNP, is produced in the Business-As-Usual scenario and when all countries are allowed to trade without any restrictions. The ratio then increases when Annex 1 countries are allowed to trade without ceilings, and further increases in the presence of ceilings. The R&D effort is highest in the Kyoto scenario, which corresponds to a 0% ceiling (all abatement is carried out through domestic measures). Hence, these results support the conjecture of those who are in favour of ceilings, namely that these would stimulate R&D expenditure (but the effects on costs and growth will be presented below).¹⁴

In the other world regions, the R&D effort depends on the role of these regions in the permit markets. For example, the FSU carries out the largest R&D effort in the case in which Annex 1 countries trade without

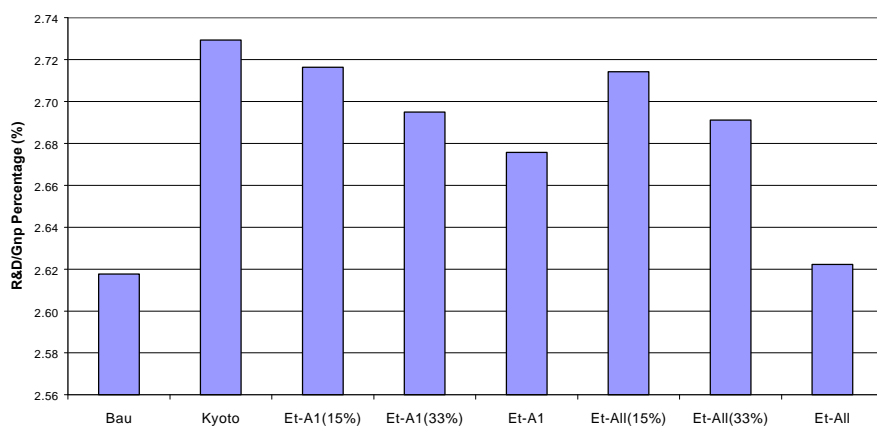
¹⁴ However, those countries for which the ceiling is not binding purchase more permits at a cheaper price and undertake less domestic abatement as well as less R&D effort. This is the case for instance of the U.S. in the Et-A1 (33%) policy option. On the other hand, Japan and Europe have to make more domestic efforts and R&D investment when ceilings are imposed as these are always binding. These results are consistent with those presented in Ellerman, Jacoby, and Decaux (1998).

ceilings. The reason is that this is the most favourable situation for the FSU, because the demand for permits is high and the FSU is the only seller. Hence, they increase R&D to reduce their own emission levels, thus increasing the amount of permits that can be sold in the market. When ceilings are introduced, the demand for permits is lower and the FSU's R&D effort is consequently reduced. It becomes even lower when all countries are allowed to trade. In this case, the FSU is no longer the unique seller, nor the one with the lowest abatement costs. Hence, China and the Rest of the World sharply increase their R&D effort to exploit the benefits arising from selling permits. This R&D effort is obviously reduced in the presence of ceilings. The conclusion is that in general ceilings are likely to increase R&D expenditure (relative to GNP) in OECD countries, but they reduce it in the FSU, China, and other developing countries, where the greatest stimulus to carry out R&D comes from the possibility to trade emission permits without restrictions.

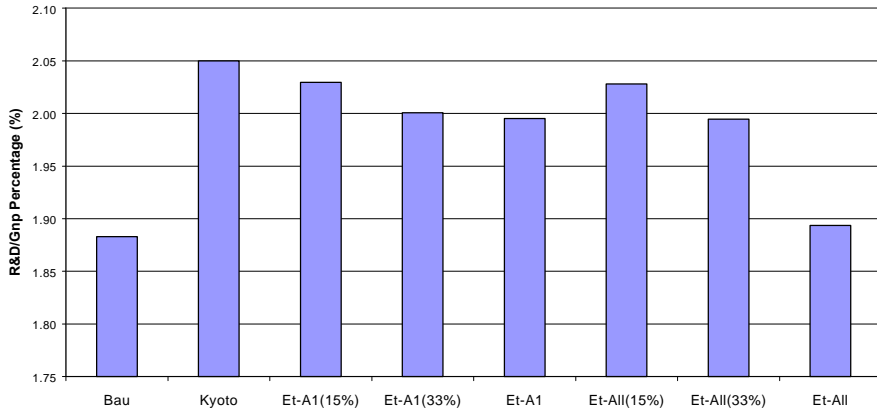
**Figure 15: USA R&D/Gnp Percentage: Average
(period 2010-2100)**



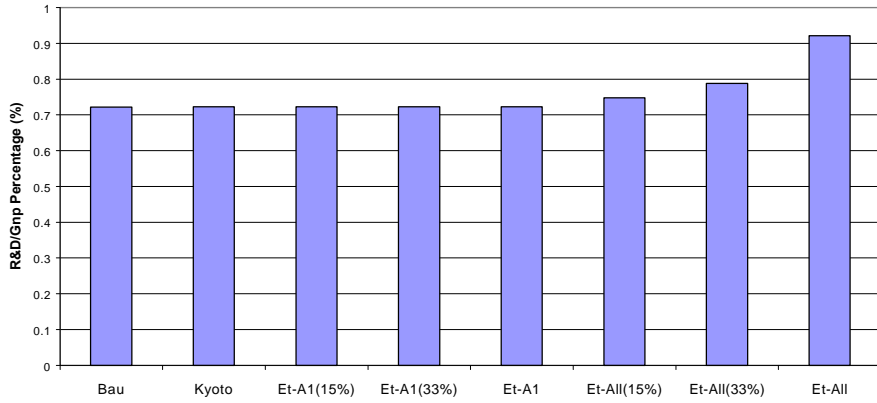
**Figure 16: JPN R&D/Gnp Percentage: Average
(period 2010-2100)**



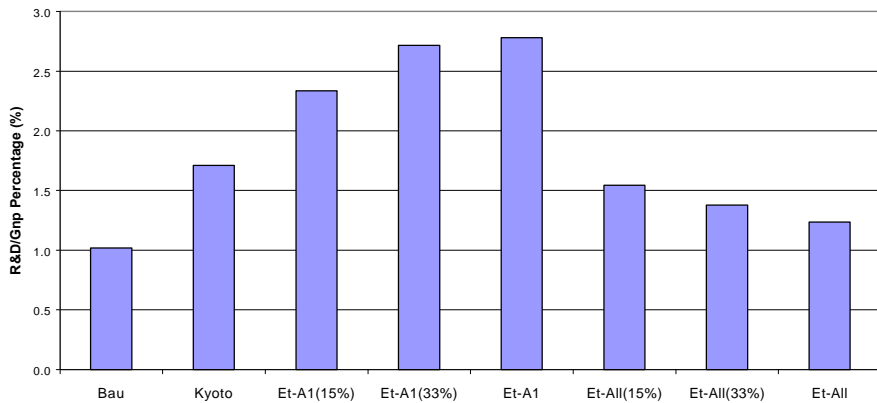
**Figure 17: EU R&D/Gnp Percentage: Average
(period 2010-2100)**



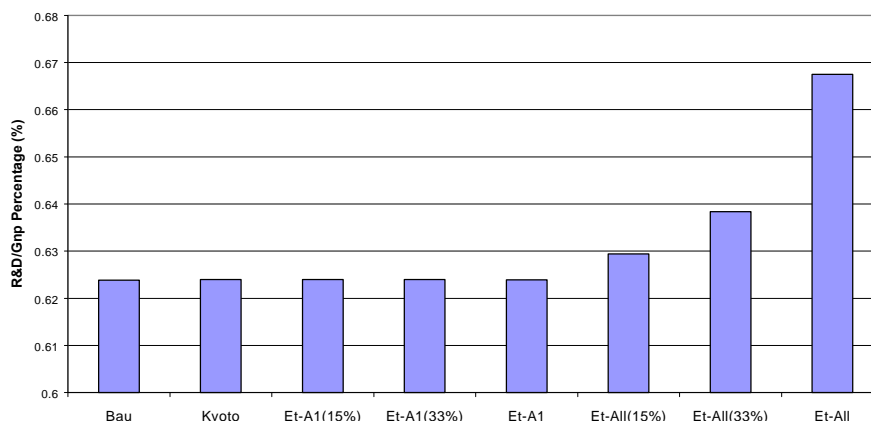
**Figure 18: CHN R&D/Gnp Percentage: Average
(period 2010-2100)**



**Figure 19: FSU R&D/Gnp Percentage: Average
(period 2010-2100)**



**Figure 20: ROW R&D/Gnp Percentage: Average
(period 2010-2100)**



The second proposition was:

This increased R&D effort has a positive impact on factor productivity and this impact more than compensates for the increased abatement costs for developed countries induced by the trade restrictions.

Hence, for these countries the total cost of implementing Kyoto is lower for stricter ceilings (alternatively, there is an optimal ceiling value which minimises the total cost).

Let us now analyse whether the increased R&D effort in the presence of ceilings reduces the total cost of complying with the Kyoto commitments. The above proposition is not supported by our results (see Figures 21-26). In all OECD regions, the highest cost is achieved in the case in which all abatement is carried out domestically and there is no trade (the Kyoto scenario), whereas the lowest cost is achieved when all world countries are allowed to trade without restrictions (the U.S.A. is a partial exception). The presence of ceilings generally increases costs, with the exception of the U.S.A. where a 33% ceiling in the case of global trade may be slightly beneficial (but the ceiling is binding only in the first decade). The situation of the U.S.A. is explained again by the fact that, for countries where the ceiling is not binding, its introduction is beneficial because it reduces the equilibrium prices without affecting the quantity demanded in that country.

In the developing countries the cost is lowest when they can fully exploit the benefits of emission trading. For China and the Rest of the World in the case of global trade, for the FSU in the case of Annex 1 trade.

Figure 21: USA Total cost/Gnp Percentage

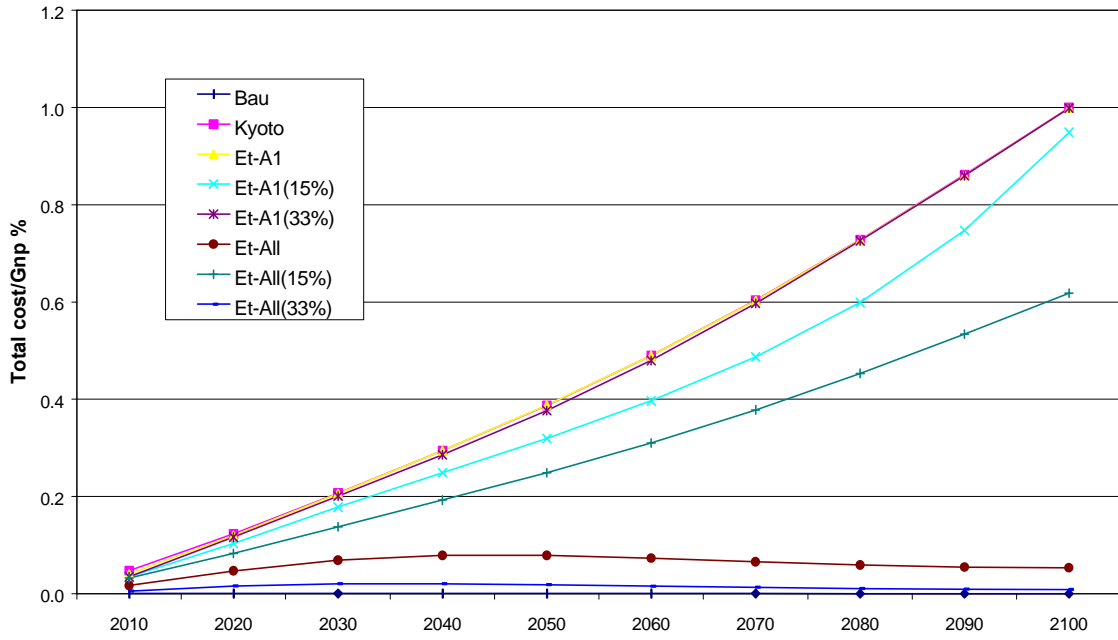


Figure 22: JPN Total cost/Gnp Percentage

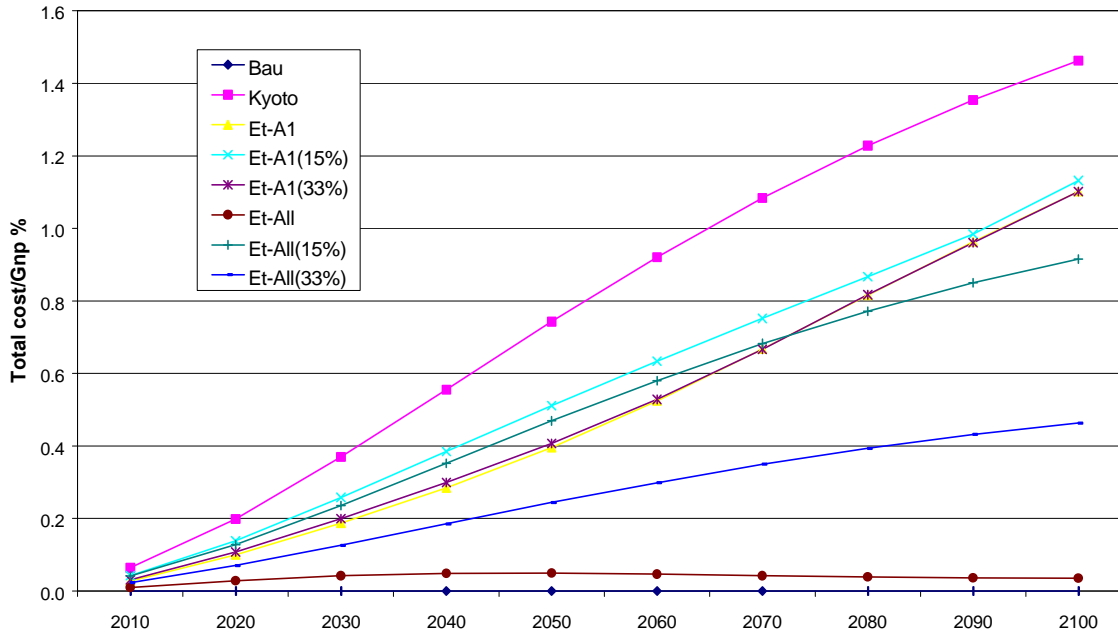


Figure 23: EU Total cost/Gnp Percentage

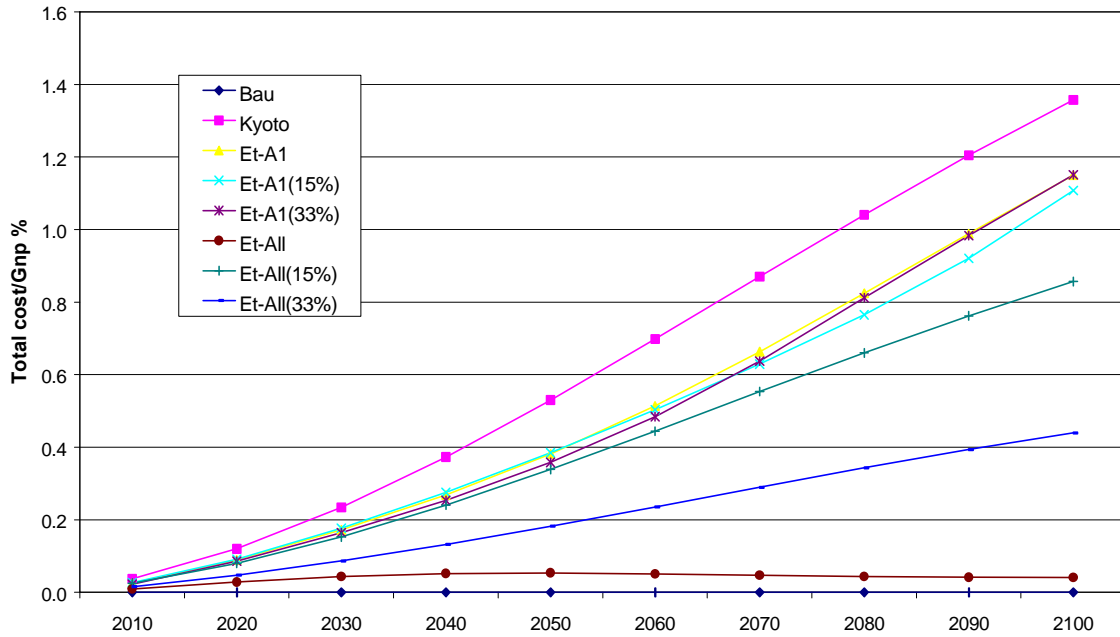


Figure 24: CHN Total cost/Gnp Percentage

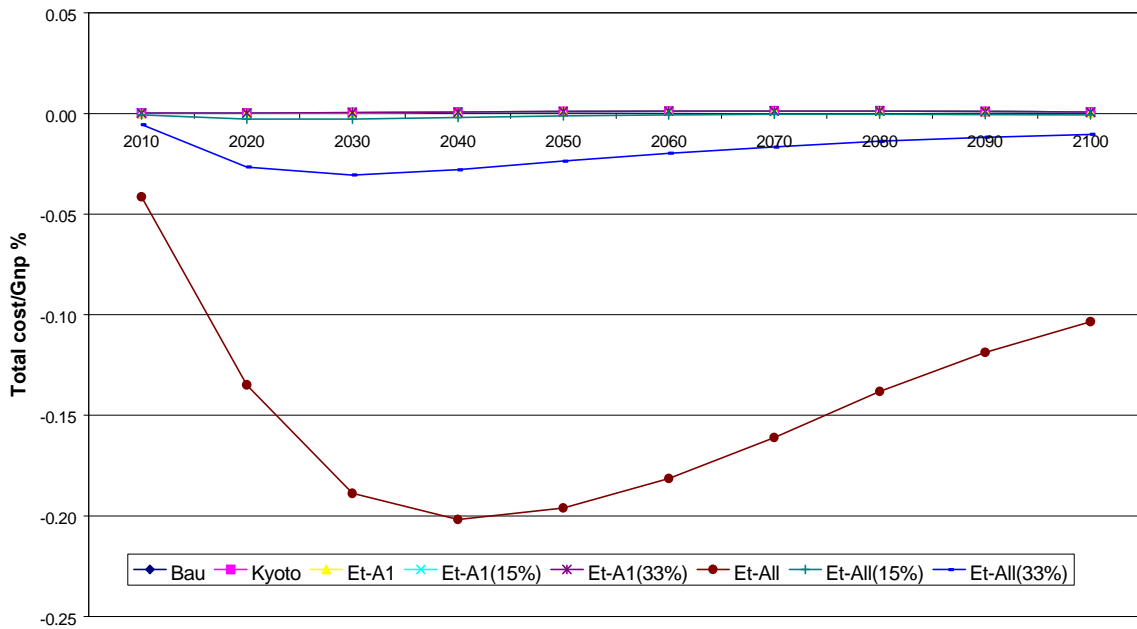


Figure 25: FSU Total cost/Gnp Percentage

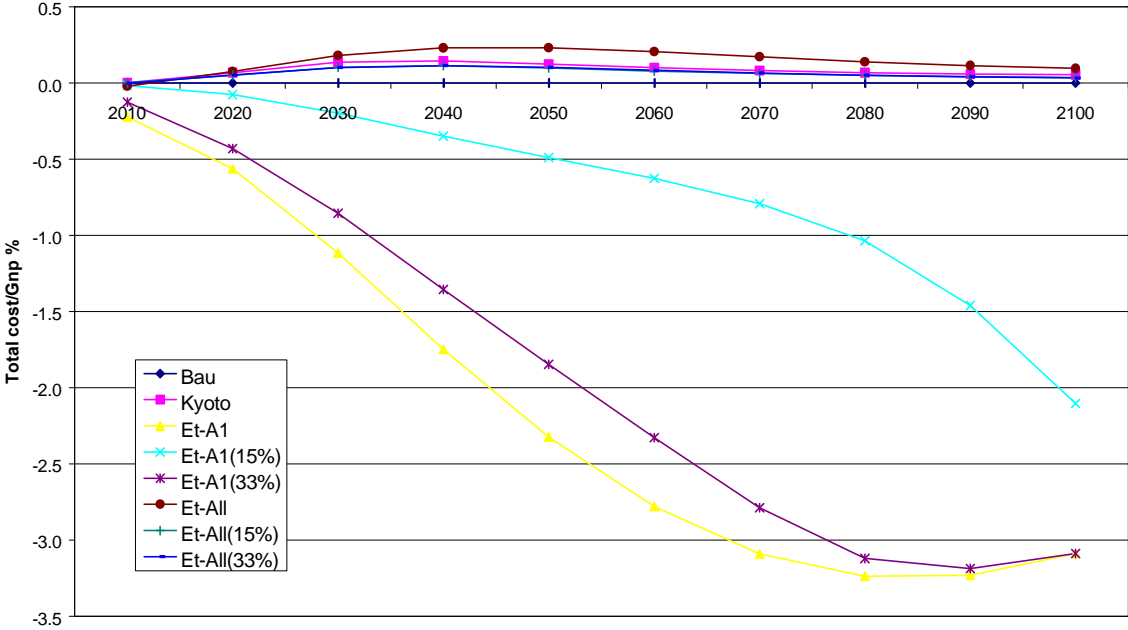
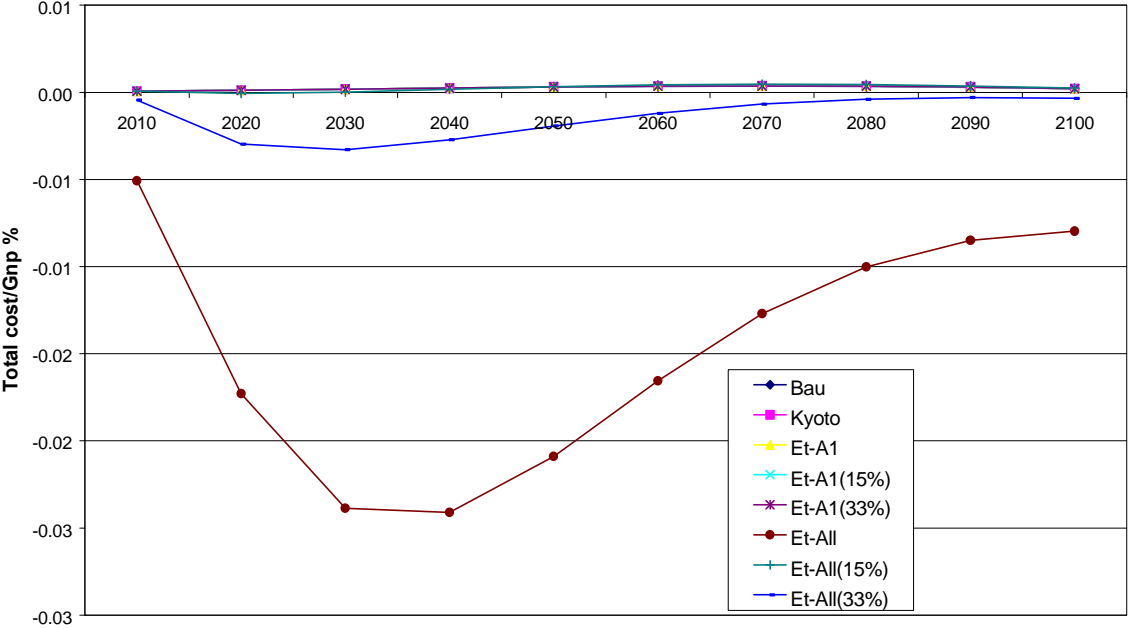


Figure 26: ROW Total cost/Gnp Percentage



The conclusions are different, and probably more puzzling, when analysing our third proposition.

*In the long run, technical change induced by stricter ceilings
fosters economic growth and yields a higher GNP level.*

In this case, the goal was to see whether the long-run effects of the increased R&D effort could stimulate economic growth, thus providing an economic benefit that could compensate the cost of complying with the Kyoto protocol. The argument is closed to the so-called Porter Hypothesis: environmental regulation, and the related costs, induces firms to undertake R&D and introduce innovation, thus achieving a competitive advantage that increases profits in the long run.

Our model can provide a partial macroeconomic assessment of this argument, but unfortunately provides little support for it. Indeed, for OECD regions, the only policy scenario in which the long-run GNP is above its BAU value is the Et-All scenario, where all countries trade permits without restrictions (see Figure 27-29). In all other cases, the GNP is below the BAU values and achieves the lowest value in the Kyoto scenario, where all abatement is carried out domestically. However, there are cases in which ceilings are beneficial. Consider the U.S.A.. If trade is allowed only among Annex 1 countries, ceilings have a beneficial impact on long-run GNP, particularly the stricter 15% ceiling. But in the case of global trade, ceilings have a negative impact on long-run GNP (Figure 27).

The situation is different for Japan and the EU, for which ceilings reduce long-run GNP both in the case of trade among Annex 1 countries and in the case of global trade. In China and in the Rest of the World the highest long-run GNP is also achieved when all countries trade without restrictions. In these regions, ceilings reduce long-run GNP, but may be beneficial in the short run (see Figures 30 and 32).

The situation of the FSU is more complicated (see Figure 31). The reason is that the FSU largely benefits from being the only seller in the Annex 1 trade scenario, but this benefit tends to disappear in the long run. Hence, in last two decades of our optimisation period, the Kyoto scenario seems to provide the largest difference between GNP and its BAU value. The second- and third-best long-run options are those in which a 15% ceiling is introduced (with global and Annex 1 trade, respectively).

Figure 27: USA Gnp: Differences

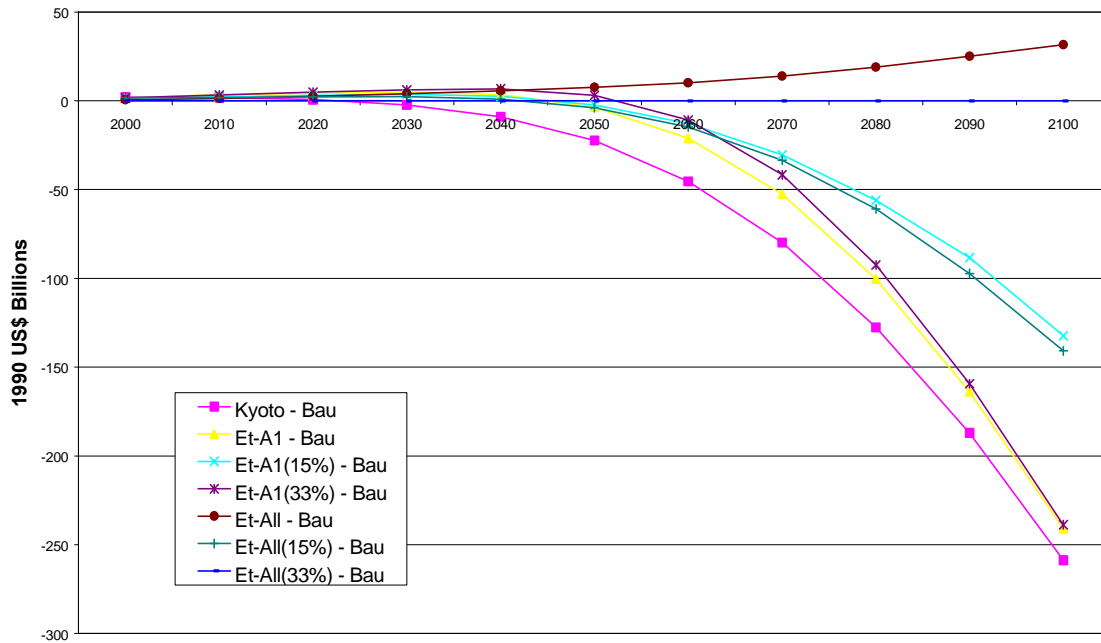


Figure 28: JPN Gnp: Differences

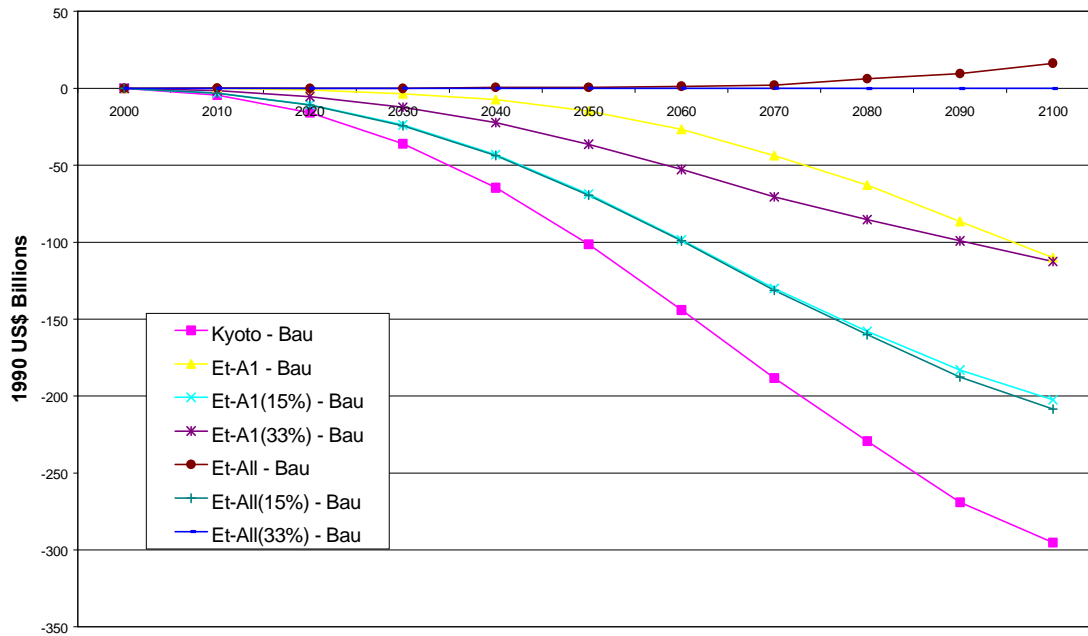


Figure 29: EU Gnp: Differences

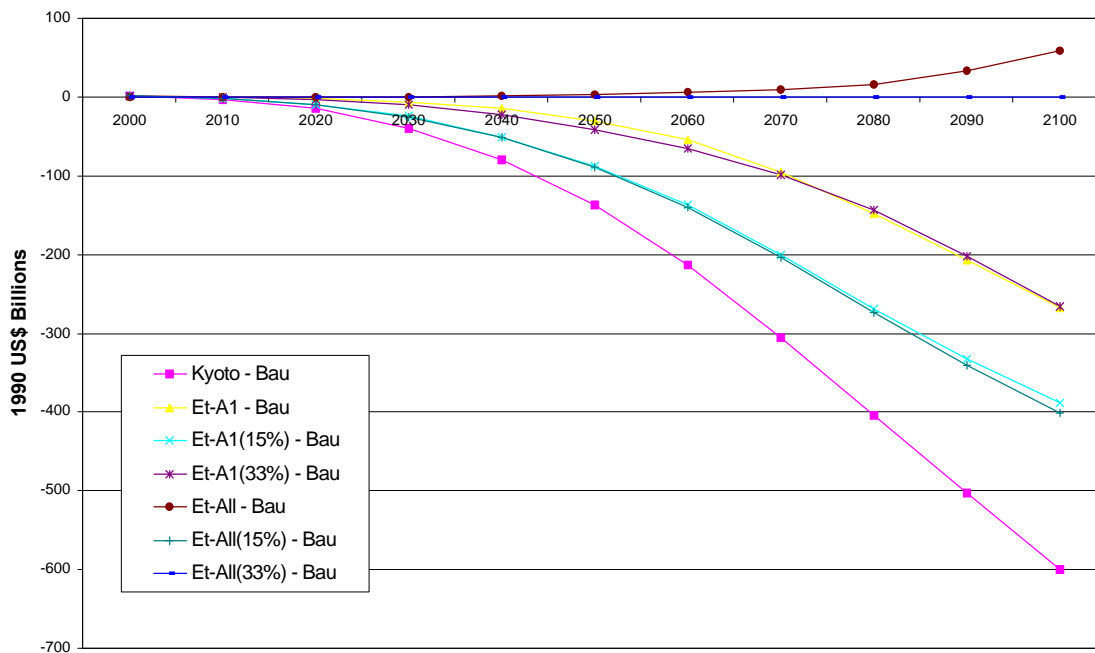


Figure 30: FSU Gnp: Differences

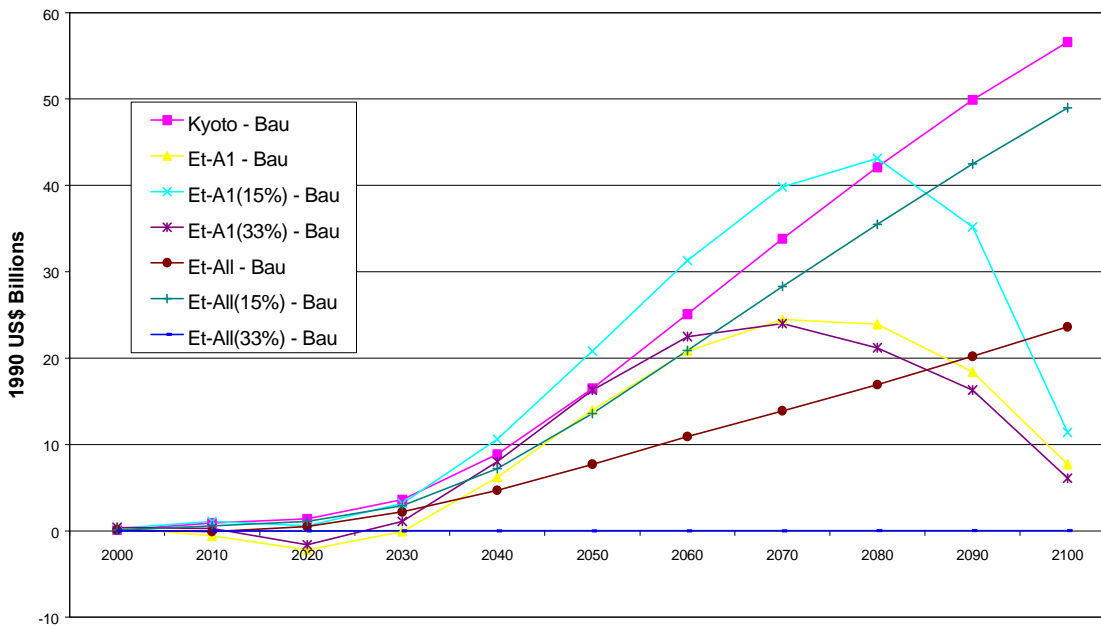


Figure 31: CHN Gnp: Differences

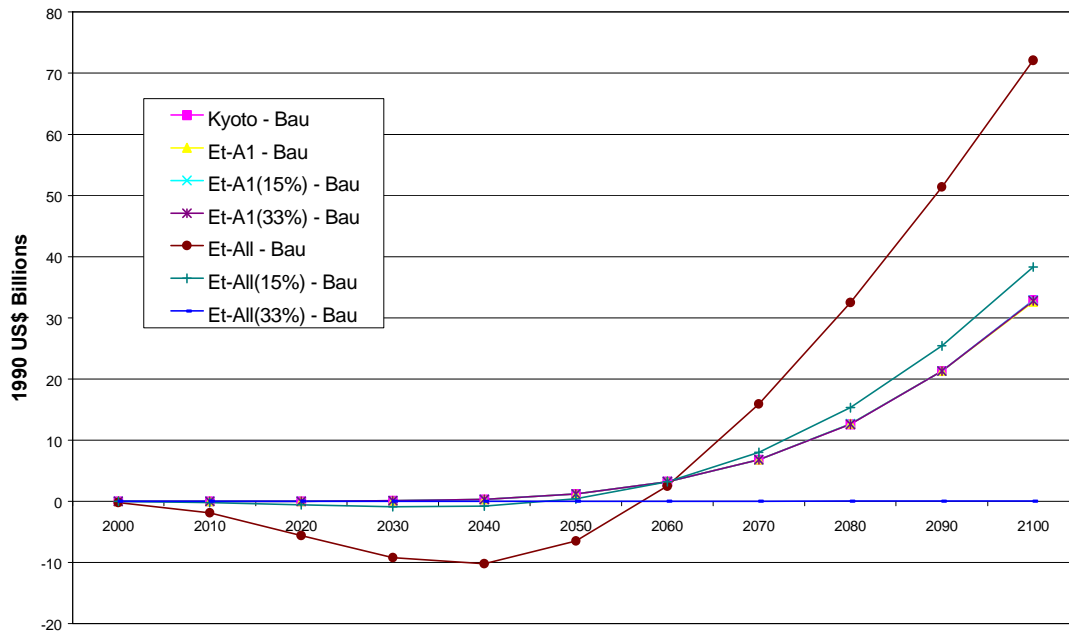
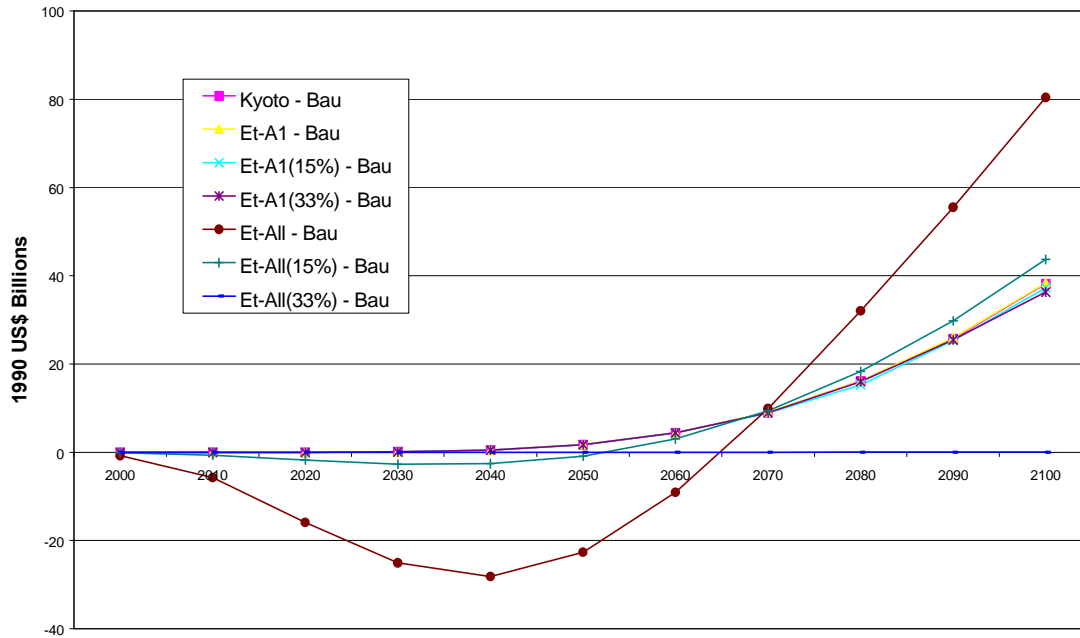


Figure 32: ROW Gnp: Differences



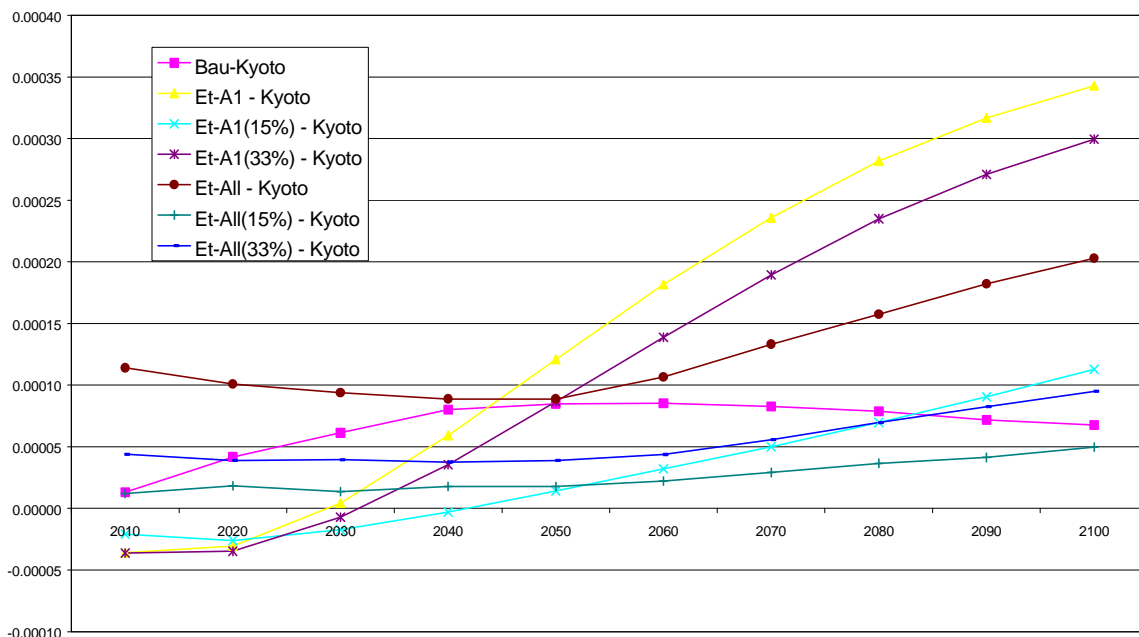
Finally let us focus again on equity. One of the arguments in favour of ceilings is that they would yield a more equitable outcome by preventing developed countries from exploiting developing countries natural resources. This argument is summarised by the proposition below.

*With ceilings, the implementation of Kyoto is more equitable,
because developed countries increase their abatement through domestic policies
and do not buy developing countries environmental resources at low prices.*

Again we must distinguish short-run from long-run effects on equity. As shown by Figure 33, the long-run most equitable policy scenario is the one in which trade is allowed among Annex 1 countries without ceilings. Second is the case with a 33% ceiling (almost never binding), and then comes the case with global trade without ceilings. Hence we can conclude that our results do not support the above proposition, because in the long run the highest level of equity is achieved when no ceilings are introduced (or, equivalently, ceilings are not binding). This is true also in the short run, where the most equitable policy option is the one in which all countries trade without ceilings.

Hence, even as far as equity is concerned there seems to be no support for propositions which emphasise potential benefits of quantitative restrictions to emissions trading.

Figure 33: Equity index: differences



5. Conclusions

In this paper we have used a simple climate model with endogenous environmental technical change, obtained by integrating Nordhaus and Yang (1996)'s RICE with the model proposed in Goulder and Mathai (1998), to analyse the efficiency and equity of different policy options. In particular, we had three goals:

- to identify the new effects arising from the endogenisation of technical change;
- to assess the pros and cons of the introduction of ceilings for emission trading;
- to quantify the distributional effects of climate policy scenarios.

As far as the first goal is concerned, we highlighted some significant new effects. In particular, we showed that the cost of complying with the Kyoto protocol is lower when environmental technical change is endogenous, even when emission trading is allowed. Moreover, the introduction of endogenous technical change leads to an equilibrium in which the demand for permits is higher, but supply is also higher, because developing countries invest in R&D to increase the amount of permits they can sell in the market. As a consequence of these two effects, the price of permits is lower.

As for ceilings, our analysis provide little support for quantitative restrictions on emission trading. Even if the introduction of ceilings increases the R&D efforts of buyer countries and foster technological innovation, the overall effect on abatement costs and economic growth is negative. The reason is that the benefits from technological innovation are lower, even in the long run, than the costs of adopting a more costly approach to climate change control. In other words, firms benefit more from a low impact of climate policies on their costs than from the stimulus to innovation that these policies induce.

Finally, even equity is not positively affected by ceilings. We have shown that flexibility mechanisms in the presence of endogenous technical change increase equity, and that the highest equity levels are achieved without ceilings, both in the short and in the long run.

Albeit useful as a first attempt to compare policy options in which technical change plays a crucial role, these results must be considered as preliminary. Indeed, we plan to carry out further research work in two main directions:

- the implementation of the model of endogenous technical change proposed in this paper in other climate models (MERGE, ICAM, IAM, etc.)
- the generalisation of the model of endogenous technical change to account for international spillovers, decreasing returns of R&D, public incentives to R&D, and related issues.

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