Fondazione Eni Enrico Mattei

Endogenous Induced Technical Change and the Costs of Kyoto

Paolo Buonanno*, Carlo Carraro** and
Marzio Galeotti***

NOTA DI LAVORO 64.2001

SEPTEMBER 2001

CLIM – Climate Change Modelling and Policy

*LSE and Fondazione Eni Enrico Mattei
**University of Venice and Fondazione Eni Enrico Mattei
***University of Bergamo and Fondazione Eni Enrico Mattei

Fondazione Eni Enrico Mattei
Corso Magenta, 63, 20123 Milano, tel. +39/02/52036934 – fax +39/02/52036946
E-mail: letter@feem.it
C.F. 97080600154

ENDOGENOUS INDUCED TECHNICAL CHANGE AND THE COSTS OF KYOTO

by

Paolo Buonanno
(LSE and Fondazione ENI Enrico Mattei)

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

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

December 2000; Revised May 2001

Abstract. Many predictions and conclusions in the climate change literature have been made and drawn on the basis of theoretical analyses and quantitative models that are either static or that allow for simple forms of changes in technology, often along exogenously given time paths. It is therefore not clear *a priori* whether those conclusions and policy recipes still hold in the more realistic case of endogenously evolving technologies. In this paper, a quantitative tool with the features of an endogenous growth model is presented, which also accounts for the possibility that technical change can be induced by environmental policy measures. Both the output production technology and the emission-output ratio depend upon the stock of knowledge, which accumulates through R&D activities. R&D is thus an additional policy variable that comes into play along with pollution abatement and capital investment. Two versions of this climate model are studied, one with endogenous technical change but exogenous environmental technical change (i.e. no induced technical change) and the other with both endogenous and induced technical change. Hence, in both models technical change evolves endogenously as far as the production technology is concerned, but endogenous environmental (or induced) technical change is only accounted for in the second version. Finally, a third version of the model also captures technological spillover effects. As an application, the three versions of the model are simulated allowing for trade of pollution permits as specified in the Kyoto Protocol and assessing the implications in terms of cost efficiency, economic growth and R&D efforts of the three different specifications of technical change.

Keywords: Climate Policy, Environmental Modelling, Integrated Assessment, Technical Change.
JEL Classification: H0, H2, H3.

Paper presented at the Workshop on “Economic Modelling of Environmental Policy and Endogenous Technical Change”, Amsterdam, November 16-17, 2000. This paper is part of the research work being carried out by the Climate Change Modelling and Policy Unit at Fondazione ENI Enrico Mattei. The authors are grateful to Francesco Bosello, Barbara Buchner, Efrem Castelnuovo, Ger Klaassen, Michele Moretto, Roberto Roson, Richard Tol, and Sergio Vergalli for helpful discussions and suggestions. They are also grateful to Z. Yang who kindly provided the RICE model software. Financial support from the EU DG Research on Environment and Climate Programme through the CLIMNEG project (ENV4-CT98-0810) is gratefully acknowledged.

Non-Technical Abstract

Many predictions and conclusions in the climate change literature have been made and drawn on the basis of theoretical analyses and quantitative models that are either static or that allow for simple forms of changes in technology, often along exogenously given time paths. It is therefore not clear *a priori* whether those conclusions and policy recipes still hold in the more realistic case of endogenously evolving technologies. In this paper, a quantitative tool with the features of an endogenous growth model is presented, which also accounts for the possibility that technical change can be induced by environmental policy measures.

The main goal of this paper is to compare the effects of three different ways of modelling technical change in a simple integrated assessment model. The first step of our analysis is the modification of Nordhaus and Young's RICE model to include an additional policy variable - Research and Development - whose optimally chosen level increases the stock of knowledge over time. This in turn affects output productivity, on the one hand, and reduces emissions per unit of output, on the other one. Increased output productivity has been used here to account for sectoral technological spillovers within each region. The presence of a stock of world knowledge affecting both productivity and emission-output ratios is used to account for international technological spillovers, i.e. the international diffusion of technical change.

This leads to three formulations of the RICE model with endogenous technical change. In the first one, technical change is endogenous and enters the production function through the domestic stock of knowledge, thus inducing endogenous growth. In the second one, there is an additional effect of the domestic stock of knowledge on the emission-output ratio. This yields a model with induced technical change, i.e. environmental policies directly affect the incentives to carry out R&D. In the third formulation, the outcome of domestic R&D spills over the other regions' productivity and emission-output ratio.

The paper shows that the modelling of R&D has significant effects on the outputs of the model. In particular, using the analysis of the costs of complying with the Kyoto Protocol as a case study, it is shown that: (i) the presence of induced technical change reduces the costs of complying with Kyoto, both by increasing R&D efforts - because R&D is used strategically to reduce emissions and to increase the supply of permits - and by reducing the price of permits; (ii) the presence of spillovers becomes relevant only in the presence of induced technical change. However, in this latter case, spillovers reduce the incentive to carry out R&D, thus increasing the price of permits. Overall abatement costs do not increase because of the positive effect of a globally diffused R&D on the emission level.

These results are useful to illustrate the fact that the modelling of technical change is relevant and that differences in model structures have significant effects on the equilibrium policy and state variables. However, the proposed formulations of the endogenous technical change are still preliminary and more research is needed both in the definition of the appropriate theoretical structure and on the empirical assessment of the relevant parameters.

Keywords: Climate Policy, Environmental Modelling, Integrated Assessment, Technical Change.

JEL Classification: H0, H2, H3.

ENDOGENOUS INDUCED TECHNICAL CHANGE AND THE COSTS OF KYOTO

1. Introduction

Many studies have recently quantified the costs of implementing the Kyoto agreement according to various policy options, i.e. with or without different degrees of introduction of the flexibility mechanisms.[1] Despite their high variability – due mainly to differences in the structure of the models used to perform the policy studies – all estimates show that the Kyoto flexibility mechanisms significantly reduce the costs of compliance without reducing the effectiveness of climate policy (see the papers collected in Carraro, 2000). However, this conclusion is, more often than not, reached on the assumption that technology evolves over time in an exogenous fashion.

This remark applies for example to the empirical models used to assess the role of ceilings in emission trading. However, most arguments offered in support of the introduction of limits to trading are based on the view that the widespread adoption of flexibility mechanisms reduces the incentives to carry out R&D, thereby reducing the effectiveness and increasing the costs of abatement options in the long run. Moreover, the incentives for R&D induced by the presence of ceilings on the use of flexibility mechanisms may spill over into other sectors, thus speeding up the "engine of growth", and reducing the impact of climate change control on per capita income and welfare in the long-run. Furthermore, the stimuli to technical and social innovation in rich countries will sooner or later be transferred to poor countries via trade in goods and services and knowledge transmission.[2] All of these considerations demonstrate that a convincing analysis of climate policy design - particularly of the role of emission trading and of the ceilings issue - requires a careful specification of technical change and of its spillover effects.

This is important not only because of the impact of technical change on GHGs emissions, but more generally because of the role of technical change and related spillovers in determining the evolution of an economic system. Recent theoretical work by Romer (1986, 1990) and Lucas (1988) has shown that aggregate technological externalities within countries may help explain many of the observed patterns of growth across countries. Furthermore,

---

[1] Some of these papers are gathered in OECD (1998) and in Carraro (1999, 2000).

[2] On the other hand, this "spillover" view is contrasted with the argument that more technical innovation by developed countries would correspondingly reduce that of developing countries, and the net result is not clear (OECD, 1999).

several studies (Nadiri, 1993; Griliches, 1992; Mohnen, 1994; Coe and Helpman, 1995) have shown the quantitative importance of spillovers also across countries.

For these reasons, in this paper a modelling approach is presented in which both endogenous and induced technical change are taken into account. Endogenous growth is captured by assuming that sectoral spillovers within countries and human capital induce increasing returns to scale. Induced technical change is captured by assuming that R&D investments also affect the emission-output ratio. In particular, the well-known RICE model of integrated assessment (Nordhaus and Yang, 1996) is adapted in such a way that the stock of knowledge is introduced in the production function and a modified version of the endogenous environmental technical change (ETC) model, originally proposed by Goulder and Mathai (2000) (see also Nordhaus, 1999), is tested.[3]

In this modified version, the central planner in each country chooses the optimal R&D effort which, in turn, increases 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.

The main goal of the paper is to assess the impacts of different specifications of technical change. Kyoto and the assessment of its economic costs is used as a case study. This enables an assessment of the significance of endogenising technical change, and in particular the determination of its impacts on the emission-output ratio (both with and without international spillovers).

Using the "ETC-RICE" model, the policy game played by the six regions in which the world is divided is solved. Each region chooses 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. In order to construct a benchmark for this 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 in which technical change is present, albeit only exogenously, and has an impact on the emission-output ratio.

---

[3] There are two updated versions of RICE currently available: RICE98 (Nordhaus and Boyer, January 28, 1999) and RICE99 (Nordhaus and Boyer, October 25, 1999). Their new features include: (i) introduction of backstop technologies (only in RICE98); (ii) introduction of a new production input called carbon energy (in both RICE98 and RICE99), the carbon equivalent of energy consumption;) a revised treatment of energy supply, which is no longer seen as inexhaustible; 4) extended climate module including a three-reservoir model calibrated to existing carbon-cycle models; 5) an increased number of world regions (respectively thirteen in RICE98 and eight in RICE99). Moving away from RICE entails a considerable recalibration effort, which we plan to pursue in the next future.

The paper begins with a brief review of the literature on induced technical change in order to set the scene for our specific modelling proposal (see Section 2). In Section 3, the changes introduced in the RICE model are presented, starting from the basic version and leading up to the more comprehensive formulation with international knowledge spillovers. In the first ETC-RICE model, (i.e. the model with endogenous technical change but exogenous environmental technical change), each country optimally chooses the amount of R&D 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, (i.e. with induced technical change), a change in the stock of knowledge also modifies the emission-output ratio. This therefore depends on the optimal R&D chosen by each country, which is in turn dependent on relative prices and hence also on climate policies. Finally, international spillovers of knowledge are introduced in the third version of the ETC-RICE model, with the stock of world knowledge affecting both production and emission technologies.

In section 4, the optimal strategic combination for each country is computed using the three specifications of technical change described above. As a specific example, emission trading is studied both amongst Annex 1 countries only (ET-A1) and amongst all countries (ET-All) under the Kyoto Protocol. The cases of endogenous versus endogenous & induced technical change are compared, both with and without spillovers. For completeness the no trade case is also included, which is simply and somewhat imprecisely labelled as "Kyoto". A few concluding remarks and directions for further research close the paper.

2. A Cursory Review of Endogenous Technical Change Modelling

In early models used to assess the effects of policies designed to control polluting emissions, technical change had an exogenous representation which is by now quite unsatisfactory. This is also true for some celebrated models of integrated assessment, such as Nordhaus and Yang (1996)'s RICE model, where the technology does evolve over time, but in an exogenous fashion. And this is also true for most models used in recent assessments of the costs of complying with the Kyoto Protocol (see the recent IPCC TAR, Chapter 8 for an overview).

2.1 Backstop Technologies

One way of considering energy-saving technical progress often exploited in top-down modelling is through the adoption of a backstop technology. This is a discrete event which takes place in a given, exogenously determined, year and which is assumed to be resource unconstrained. This approach is largely linked to the personal assumptions of the modeller and "precludes analysis of technological innovation over time" (Wilson and Swisher, 1993, p.253). However, this approach can help integrating bottom-up information in top-down analyses. Consider, for example, the GREEN model (Burniaux, Martin, Nicoletti, and Oliveira Martins, 1992) that allows for three backstop options: a carbon-based synthetic fuel, and two carbon-free possibilities. The main hypotheses concern prices and timing of diffusion: the prices are exogenous and the backstop technologies, once they are assumed to come on stream, are available in all regions in unlimited quantities at constant marginal costs. The key variable of this approach is the relative price of the technological substitution options which is exogenously imposed at current levels; moreover, the technological innovation possibilities are assumed to be fixed at the present level of knowledge for the entire simulation path.

Subsequently there have followed a number of attempts aiming to endogenise the linkages between economic variables (policy variables, in particular) and technical progress. An example is represented by recent applied general equilibrium models relying on the concept of vintage capital (Conrad and Ehrlich, 1993, for example). Here substitution possibilities are more feasible with the most recent capital vintages. Thus, the adjustment to relative price shocks does not only depend on the elasticity of substitution but also on the capital replacement rate. This is a novelty with respect to previous modelling approaches because technical change shows its effects on the firms' cost structure through a parametrisation of each vintage's cost functions.

2.2 Stochastic Time Trends

The main difficulty faced by modellers when trying to endogenise technical change is the non-observability of this variable. For this reason, earlier models used a deterministic time trend as a proxy of technical change. This has been the starting point of some *ad hoc* attempts to model technical change. For example, in Boone, Hall, and Kemball-Cook (1992), Carraro and Galeotti (1996) and Dowlatabadi and Oravetz (1997), technical progress is represented by a time variable which is added to the principal equations of the model. However, this variable is not a deterministic function of time; it is rather a stochastic function of time, in which other economic effects are also accounted for. In Boone, Hall, and Kemball-Cook (1992) the dynamics of the time trend representing technical change is inferred by looking at the dynamics of factor demands (a similar approached was proposed by Gao, 1994 and Slade, 1989). In contrast, in Carraro and Galeotti (1996) it is inferred from the dynamics of the capital stock. It is assumed that the capital stock can be broken down into two parts: the energy-saving/environment-friendly capital stock and the energy-consuming one. Each year a new vintage of the capital stock becomes operational. In this way new capital is added to each of the two components. The characteristics of this new capital depend on a number of economic variables, which affect a firm's decision to install energy-saving capital.

The problem with the above approaches is their *ad hoc* nature. There is no explicit solution to the firm's optimisation problem that determines the optimal amount of R&D and investment in the corresponding types of capital. Therefore links between these variables are mainly statistical and lack a clear economic interpretation.[4]

2.3 Structural Models of Technical Change

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), except in models where the parameters describing their functional structure are calibrated rather than estimated (Nordhaus, 1999; Goulder and Schneider, 1999; Goulder and Mathai, 2000). In this way, it is relatively easy to simulate a model of R&D and innovation, even if the price to be paid is the postulation of a set of parameter values that cannot easily be tested.

In the model of knowledge accumulation of Goulder and Mathai (2000), a central planner 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. A second model studied by the

---

[4] An exception is the proposal by Newell, Jaffee and Stavins (1999). 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.

authors 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”.[5]

Another recent development of the literature is constituted by models based on the concept of learning curves (see Grubler and Messner, 1996) describing 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. Thus, technological learning depends on previous, accumulated investments in R&D, and it is therefore termed “learning by searching”. The model presented in this paper falls under this category.

In a vein similar to Goulder and Mathai (2000), Nordhaus (1999) 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, 1994).

A very recent model which stands halfway between bottom-up and top-down strategies is due to Van der Zwaan, Gerlagh, Klaassen, and Schrattenholzer (1999). A macroeconomic (top-down) model is expanded with learning curves previously used in energy systems (bottom-up) models. Technological change is represented through a learning curve describing decreasing non-carbon energy prices as a function of cumulative installed capacity. In Gerlagh and van der Zwann (2000), the authors compare several scenarios with taxes on the carbon and subsidies on the non-carbon technology.

2.4 Technological Spillovers

There is a further dimension of technical change that ought to be incorporated in climate models: new technologies are developed by the most innovative firms and are not immediately available to all. Factors that influence the rate and timing of diffusion are of fundamental importance in assessing the ultimate effectiveness of the innovation.

Modelling this factor is obstructed by certain characteristics of empirical environmental models. In general, top-down models do not provide the degree of sector disaggregation that would be required for analysis at the level of the firm, while bottom-up studies do not consider strategic market behavior that may delay the diffusion of innovation.

---

[5] The analysis we conduct in the present paper can be adapted to this case as well, although we have selected R&D-driven technological change as the industrial organisation literature has been traditionally interested in technological innovation prompted by R&D and because it provides an additional policy variable relative to the case of abatement driven knowledge accumulation.

There are however some attempts to model spillovers and diffusion. One such example can be taken directly from the empirical literature on endogenous growth (see, for example, Mankiw, Romer, and Weil, 1992; Ciccone, 1996). Here, the production function is specified in order to account for positive R&D externalities. These externalities are the mechanism through which endogenous growth takes place.

Summing up the literature briefly summarised above, it can be concluded that at least three factors should be taken into account when modelling technical change in climate models: (i) first, the relationship between technical change and economic growth; (ii) second, its relationship with environmental policy variables on the one hand, and with the emission-output ratio on the other hand; (iii) third, the spillover effects, both at the national and international level.

In the following sections we aim to assess the relevance of these factors when analysing the costs of implementing the Kyoto Protocol.

3. Model Description

The issue of endogenous technical change is tackled in this paper by following the ideas contained in both Nordhaus (1999) and Goulder and Mathai (2000) and accordingly modifying Nordhaus and Yang's (1996) regional RICE model of integrated assessment. As specified below, doing so requires the input of a number of additional parameters, some of which have been estimated using information provided by Coe and Helpman (1995), while the remaining parameters were calibrated so as to reproduce the Business-As-Usual (BAU) scenario generated by the RICE model with exogenous technical change.

This model, called ETC-RICE, is an extended version of RICE, which is one of the most popular and manageable integrated assessment tools for the study of climate change (see, for instance, Eyckmans and Tulkens, 1999). It is basically a single sector optimal growth model which has been extended to incorporate the interactions between economic activities and climate. One such model has been developed for each macro region into which the world is divided (USA, Japan, Europe, China, Former Soviet Union, and 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, which 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, the size of which is dependent upon the amount of abatement (rate of emission reduction) as well as the change in global temperature. The model is completed by three equations 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) respectively.

In our extension of the model, technical change is no longer exogenous. Instead, the following factors are included: first, endogenous technical change affecting factor productivity is introduced. This is done by adding the stock of knowledge in each production function and by relating the stock of knowledge to R&D investments. Second, induced technical change is introduced, by allowing the stock of knowledge to affect also the emission-output ratio.[6] Finally, international technological spillovers are also modelled.

Within each version of the model, countries play a non-cooperative Nash game in a dynamic setting, which yields an Open Loop Nash equilibrium (see Eyckmans and Tulkens, 1999, for an explicit derivation of first order conditions of the optimum problem). This is a situation in which, in each region, the planner maximises social welfare subject to the individual resource and capital constraints and the climate module, given the emission strategy (in the base case) and the R&D expenditure strategy (in the ETC case) of all other players.[7]

---

[6] The R&DICE98 model used by Nordhaus (1999) is a modification of its DICE98 model. The DICE98 model is the global version of RICE98 (see footnote 3 above). Relative to DICE98, the changes in R&DICE98 are the following: (i) capital, labor and interest rate are set as exogenous: this implies an exogenously determined output level; (ii) output is used for consumption, investment, (carbon) energy and R&D spending; (iii) emissions depend upon output times the emission-output ratio whose rate of growth is affected by the amount of R&D. As will become clear shortly, our ETC-RICE model differs in several respects: (i) out model has six world regions, (ii) output is fully endogenous, (iii) output production is affected by R&D through the stock of knowledge (non environmental endogenous technical change), (iv) the level of emission-output ratio, rather than the rate of change, is affected by the stock knowledge, and hence by R&D; (v) we have no additional carbon energy input.

[7] As there is no international trade in the model, regions are interdependent through climate variables. In the model world countries play a non-cooperative game. One interesting application which is next in our research agenda is to run a scenario in which regions cooperate either on technology or in emission reduction or in both policies.

3.1. The Standard Model without Induced Technical Change

As said above, it is assumed for the purpose of this model 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), it is assumed that the stock of knowledge is a factor of production, which therefore enhances the rate of productivity (see also the discussion in Weyant, 1997; Weyant and Olavson, 1999).[8] Thus, in this formulation, R&D efforts prompt non-environmental technical progress, but with different modes and elasticities. More precisely, the RICE production function output is modified as follows:

$$Q(n,t) = A(n,t)K_R(n,t)^{\beta_n}[L(n,t)^{\gamma}K_F(n,t)^{1-\gamma}] \tag{1}$$

where Q is output (gross of climate change effects), A the exogenously given level of technology and K_R, L, and K_F are respectively the inputs from knowledge capital, labour, and physical capital.

In (1) the stock of knowledge has a region-specific output elasticity equal to β_n $(n=1,\ldots 6)$. It should be noted that as long as this coefficient is positive, the output production process is characterised by increasing returns to scale, in line with current theories of endogenous growth. This implicitly assumes the existence of cross-sectoral technological spillovers within each country (Romer, 1990). In addition, it should be noted that while allowing for R&D-driven technological progress, we maintain the possibility that technical improvements can also be determined exogenously (the path of A is the same as that specified in the original RICE model). The stock accumulates in the usual fashion:

$$K_R(n,t+1) = R\,\&\,D(n,t) + (1-\delta_R)K_R(n,t) \tag{2}$$

where $R\&D$ is the expenditure in Research and Development and δ_R is the rate of knowledge depreciation. Finally, it is recognised that some resources are absorbed by R&D spending. That is:

---

[8] In a similar vein, the model for Austria proposed by Kratena and Schleicher (1999) has induced technical change modelled as a stock of knowledge which affects both production and consumption activities (along with stock of fixed capital and of durables respectively). In turn the stock of knowledge accumulates through both R&D investment and learning by doing (which, unsatisfactorily, the authors proxy with current gross output).

$$Y(n,t) = C(n,t) + I(n,t) + R\,\&\,D(n,t) \tag{3}$$

where Y is output net of climate change effects (specified just as in the RICE model), C is consumption and I gross fixed capital formation.

At this stage the model maintains the same emissions function as Nordhaus' RICE model which will be modified in the next section:

$$E(n,t) = \sigma(n,t)[1-\mu(n,t)]Q(n,t) \tag{4}$$

where σ can be loosely defined as the emissions-output ratio, E stands for emissions and μ for the rate of abatement effort. The policy variables included in the model are 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 for technology level A and of the emissions-output ratio σ. Thus, the model presented so far assumes no induced technical change, i.e. an exogenous environmental technical change, and a formulation of productivity that evolves both exogenously and endogenously. In the model, investment fosters economic growth (thereby driving up emissions) while abatement is the only policy variable used for reducing emissions.

3.2. Accounting for Induced Technical Change

In the second step of our model formulation, endogenous environmental technical change is accounted for. It is assumed that the stock of knowledge – which in the previous formulation was only a factor of production - also serves the purpose of reducing, *ceteris paribus*, the level of carbon emissions. Thus, in the second formulation, R&D efforts prompt both environmental and non-environmental technical progress, although with different modes and elasticities.[9] More precisely, the RICE emission-output relationship is modified as follows:

---

[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 sound information in the literature.

$$E(n,t) = [\sigma_n + \chi_n \exp(-\alpha_n K_R(n,t))][1-\mu(n,t)]Q(n,t) \qquad (4')$$

In (4'), knowledge reduces the emissions-output ratio with an elasticity of α_n, which is also region-specific; the parameter χ_n is a scaling coefficient, whereas σ_n is the value to which the emission-output ratio tends asymptotically as the stock of knowledge increases without limit. In this formulation, R&D contributes to output productivity on the one hand, and affects the emission-output ratio - and therefore the overall level of pollution emissions - on the other one.

3.3. Accounting for Knowledge Spillovers

Previous formulations do not include potential spillover effects produced by knowledge, and therefore ignore the fact that both technologies and organisational structures diffuse internationally. Modern economies are linked by vast and continually expanding flows of trade, investment, people and ideas. The technologies and choices of one region are and will inevitably be affected by developments in other regions.

Following Weyant and Olavson (1999), who suggest that the definition of spillovers in the induced technical change context be kept plain and simple - in light of a currently incomplete understanding of the problem - disembodied, or knowledge, spillovers are modelled (see Romer, 1990). They refer to the R&D carried out and paid for by one party that produces benefits to other parties which then have better or more inputs than before or can somehow benefit from R&D carried out elsewhere. Therefore, in order to capture international spillovers of knowledge, the stock of world knowledge is introduced in the third version of the ETC-RICE model, both in the production function and in the emission-output ratio equation. Equations (1) and (4') are then revised as follows:

$$Q(n,t) = A(n,t) K_R(n,t)^{\beta_n} WK_R(n,t)^{\varepsilon_n} [L(n,t)^{\gamma} K_F(n,t)^{1-\gamma}] \qquad (1')$$

and:

$$E(n,t) = [\sigma_n + \chi_n \exp(-\alpha_n K_R(n,t) - \theta_n WK_R(n,t))][1-\mu(n,t)]Q(n,t) \qquad (4'')$$

where the stock of world knowledge:

$$WK_R(j,t) = \sum_{j \neq i} K_R(i,t) \qquad (5)$$

is defined in such a way as not to include a country's own stock.

3.4. Accounting for Emission Trading

As stated in the Introduction, the goal of this paper is to assess the relevance of the specification changes proposed in the previous sub-sections. Therefore, the three versions of the ETC-RICE model described above are used to quantify the costs of implementing the Kyoto Protocol under different assumptions on the use of the so-called "flexibility mechanisms". In particular, we would like to compare the case in which emission trading is not allowed with those in which trading takes place amongst Annex 1 countries, and then amongst all world countries. When running the model in the presence of emission trading, two additional equations are considered:

$$Y(n,t) = C(n,t) + I(n,t) + R\,\&\,D(n,t) + p(t)NIP(n,t) \qquad (3')$$

which replaces equation (3) and:

$$E(n,t) = Kyoto(n) + NIP(n,t) \qquad (6)$$

where *NIP(n,t)* is the net demand for permits and *Kyoto(n)* are the emission targets set in the Kyoto Protocol for the signatory countries and the BAU levels for the non-signatory ones. According to (3'), resources produced by the economy must be devoted, in addition to consumption, investment, and research and development, to net purchases of emission permits. Equation (6) 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 permits expressed in terms of the *numeraire* output price. Moreover, there is an additional policy variable to be considered in this case, which is net demand for permits *NIP*.

Under the possibility of emission trading, the sequence whereby a Nash equilibrium is reached can be described 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(0)* (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 as a function of the market disequilibrium and each region's decision process starts again.

Finally, the model can be used to simulate the effects of restrictions on emission trading, in which case an additional constraint has to be introduced. Namely:

$$NIP(n,t) \leq CEIL(n,t)[E_{BAU}(n,t) - Kyoto(n)] \tag{7}$$

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 Buonanno, Carraro, Castelnuovo, and Galeotti (2000b) three restricted ET (Emission Trading) policy options are studied, with ceilings set equal to either 0% (no trading), 15% or 33% and having either only Annex 1 or All countries exchanging pollution rights.

3.5. Parameter Calibration

In terms of parameter calibration and data requirements for the newly introduced variables, the following procedure was adopted. Firstly, coefficients already present in the original RICE model were left unchanged. Next, for each region, the coefficients β_n and ε_n in the production function (1') were calibrated so as to obtain a value of the R&D-output ratio in the initial year (1990) equal to the historical value. R&D figures for 1990 were taken from Coe and Helpman (1995), while the 1990 stock of knowledge for the USA, Japan, and Europe comes from Helpman's Web page.[10] Finally, for the three remaining macro-regions 1990 values of the knowledge stock were constructed by taking the ratio between knowledge and physical capital of the three industrialised regions and multiplying it by the 1990 physical capital stock of these other regions as given in the RICE model.

The regional parameters α_n and χ_n in the emission equation (4') were OLS estimated using time series of the emissions-output ratio and of the stock of knowledge (the sample runs from years 1990 to 2120 with ten year spans, i.e. it consists of ten years of data). Specifically,

---

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

for each region we regressed $ln[\sigma(n,t)-\sigma_n]$ against an intercept and $-K_R(n,t)$. The antilog of the intercept provided an estimate of χ_n, while the slope coefficient produced an estimate of α_n. The data for the former variable were taken from Nordhaus and Yang (1996), while those for the latter were taken from a BAU simulation conducted using the original emissions-output ratio $\sigma(n,t)$ of the RICE model.

The asymptotic values σ_n were 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 of such simulations were then taken as asymptotes. The world knowledge parameter θ_n in (4”) was calibrated. Finally, the rate of knowledge depreciation was set at 5%, following a suggestion contained in Griliches (1979).

Weyant (1997, p.53) correctly points out that “there does not exist good information on a number of key parameters such as those that determine the magnitude of spillover knowledge from investments in R&D. Good information on how knowledge enters the production function with capital and other inputs is also not currently available. I think the most difficult challenge of dealing with induced technological change is obtaining good empirical estimates for key parameters”. Bearing this important cautionary note in mind, the parameter values used in the policy analyses which will be presented in the next section are shown in the following Tables 1 and 2.

Table 1: Coefficients of the ETC-RICE Model (without Spillovers)

	α_n	β_n	δ_n	χ_n	σ_n	$K_R(n,1990)$
USA	0.195	0.043	0.05	0.019	0.009	1.242
Japan	0.522	0.045	0.05	0.0050	0.006	0.277
Europe	0.296	0.031	0.05	0.007	0.006	0.755
FSU	1.197	0.016	0.05	0.095	0.009	0.072
China	0.618	0.010	0.05	0.112	0.009	0.031
ROW	0.072	0.009	0.05	0.022	0.008	0.393

Note: The stock of knowledge is expressed in trillions of 1990 U.S. dollars. FSU stands for Former Soviet Union, ROW for Rest of the World.

Table 2: Coefficients of the ETC-RICE Model (with Spillovers)

	α_n	β_n	ε_n	χ_n	θ_n
USA	0.177	0.029	0.0131	0.019	0.0005
Japan	0.470	0.019	0.0019	0.006	0.0004
Europe	0.244	0.021	0.0059	0.008	0.0005
FSU	0.910	0.015	0.0004	0.117	0.0025
China	0.521	0.010	0.0001	0.139	0.0026
ROW	0.068	0.009	0.0013	0.025	0.0008

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

4. Endogenous Induced Technical Change and the Costs of Kyoto

In order to quantify the additional effects of introducing first induced technical change and then international knowledge spillovers, the well-known problem of assessing the costs of complying with the Kyoto Protocol is used as a case study. In particular, the impact on the costs of Kyoto of emission trading is studied when exchange takes place both amongst Annex 1 countries only (Et-A1) and amongst all countries (Et-All). For completeness, the no trade case, labelled rather imprecisely as "Kyoto", is also included. For each optimisation run the time paths of the control variables (abatement, fixed investment, R&D expenditures, net demand for permits) are obtained and their impacts on the endogenous variables (emissions, GNP, consumption, and so on) over the period 2010-2100 (the well-known "Kyoto forever" scenario) computed.[11]

---

[11] In this paper we do not address the issue of "ceilings" to emission trading: we refer the reader to Buonanno, Carraro, Castelnuovo, and Galeotti (2000b) for the analysis of this problem using the model presented here.

4.1 Technical Change and Total Costs

The overall costs of complying with the Kyoto Protocol under different policy options and for different specifications of technical change are presented in Table 3. The notion of costs considered here is the sum of abatement costs, R&D spending and, whenever applicable, outlays/receipts due to purchasing/selling pollution permits.[12] For ease of presentation we only display average figures over the simulation period 2010-2100.

The general picture that emerges from the table is consistent across model specifications. First of all, the Kyoto scenario entails the highest overall costs as no emission reduction can be traded away and emission limits cannot be overcome. The possibility of emission trading leads to a reduction in compliance costs for all Annex 1 countries when trade is restricted as in the Et-A1 scenario, and for all countries under global trade (Et-All case).

There are a couple of exceptions to this rule. The first one is the case of the FSU in the two versions of the model with induced technical change. Notice that FSU total costs increase in the global trade scenario with respect to the ET-A1 scenario. This situation can be explained by the fact that, under Et-A1 trading, the FSU sells permits, thus receiving a relevant financial transfer. Under global trading, China and ROW become the main sellers of permits. Moreover, supply increases and the price of permits becomes lower. Hence, financial transfers to the FSU are much smaller under global trading and the total costs increase.

A second case concerns China and ROW and depends on the strategic use of R&D. As shown below, sellers of permits have an incentive to invest in R&D to increase their supply of permits and the related revenue. This incentive and the non-cooperative framework through which decisions are taken, may lead some countries - notably sellers of permits - to over invest in R&D. This may induce an excess supply of permits and a too low price in the market for permits. The consequence is that total costs for seller countries under global trading – total costs include the cost of R&D investments – may increase as shown in Table 3 for China and ROW in the ETC+ITC case. Notice that the incentive to over-invest in R&D is lower in the presence of spillovers, because of the well-known free-riding inventive. As a consequence, the effect described above is smaller and global trading induces a reduction of total costs even for China and ROW in the model versions with spillovers.

---

[12] Abatement costs in the RICE model are given by the product between a country's optimal rate of abatement μ and its GNP.

Table 3: Total Compliance Costs under Alternative Specifications of Technical Change and for Alternative Policy Options

Specification of Technical Change	*Policy Option*	*USA*	*Japan*	*Europe*	*FSU*	*China*	*ROW*
ETC	Kyoto	0.480	0.308	0.512	0.080	0.044	0.356
	Et-A1	0.478	0.293	0.500	0.056	0.044	0.356
	Et-All	0.412	0.242	0.387	0.050	0.033	0.335
ETC+ITC	Kyoto	0.550	0.321	0.549	0.066	0.045	0.360
	Et-A1	0.546	0.292	0.513	0.002	0.045	0.360
	Et-All	0.409	0.239	0.380	0.050	0.050	0.379
ETC+ITC with Spillovers	Kyoto	0.575	0.296	0.583	0.091	0.058	0.412
	Et-A1	0.591	0.279	0.558	0.047	0.058	0.412
	Et-All	0.446	0.224	0.408	0.067	0.046	0.393

Note: the figures reported are expressed in 1990 trillion USD and are averages over the period 2010-2100. ETC refers to the model with only environmental technical change; ETC+ITC also incorporates induced technical change; ETC+ITC with Spillovers is self-explanatory.

We can also consider the results of Table 3 from the viewpoint of alternative models of technical change. When induced technical change is allowed for, R&D is used also to lower the emission-output ratio. In this case, spending in domestic abatement can be replaced by investments in R&D activities. The net impact on total compliance costs of this substitution effect of induced technical change cannot be predicted a priori. Costs turn out to be higher for all countries under Kyoto and Et-A1 regimes, the only exception being the FSU. Costs are instead lower under global trading, but only for the three industrialised regions. Considering the role of knowledge spillovers, our a priori is that free riding induces countries to undertake less R&D relative to the absence of this type of externality. This entails more domestic abatement activities and therefore costs. Again, however, the net effect on compliance costs is not a priori defined and the results show that for all countries, with the single exception of Japan, costs go up when spillovers are part of the picture.

These results suggest that in almost all countries total costs tend to be lower whenever R&D - rather than domestic abatement (through regulation, taxation, etc.) - is used to reduce emissions. However, this also depends on the trading scheme which is adopted. Hence, a clearer understanding of the dynamics of total costs under different specifications of technical change and/or under different scales of trading can be obtained only by looking at the different components of total costs. As a consequence, we now move to consider the individual components of total compliance costs in more detail.

4.2 Technical Change and Abatement Costs

Figures 1 and 2 show the difference in abatement costs between the RICE model with endogenous technical change, on the one hand, and with endogenous plus induced technical change on the other, both without and with spillovers respectively. In general, the costs of domestic action are lower when environmental technical change is endogenous (the bars show the difference between costs in the ETC and costs in the ETC-plus-ITC model specifications).

The difference in costs is especially pronounced with the opening and extension of the emission trading market, for Annex 1 regions under Et-A1 and for Non Annex 1 regions under Et-All regimes. The reason is that, as previously said, in the presence of induced technical change, R&D can be used strategically in the game amongst the six world regions. When permits can be traded only amongst Annex 1 countries, FSU's optimal strategy is to increase R&D (see Figure 5) in order to sell more permits into the market. The increased sales of permits increase the FSU's income and welfare. The increased supply of permits also reduces the price of permits (see Figure 3), thus providing larger benefits to those countries which demand more permits, namely Europe and Japan.

The situation is different when trading is allowed amongst all world countries (in this case, remember that non-Annex 1 countries' emission targets coincide with their BAU emission paths). The incentive for FSU to carry out strategic R&D disappears, because it is no longer the only supplier of permits. By contrast, China has an incentive to increase its R&D (see Figure 5). However, marginal costs in China are lower than in the FSU, thus inducing smaller incentives to increase R&D. R&D in China increases (see Figure 5) but R&D in the FSU largely decreases. Hence the benefits (in terms of reduced costs) provided by induced technical change are smaller.

FIGURE 1: ENDOGENOUS VERSUS ENDOGENOUS PLUS INDUCED TECHNICAL CHANGE: DIFFERENCES IN ABATEMENT COSTS

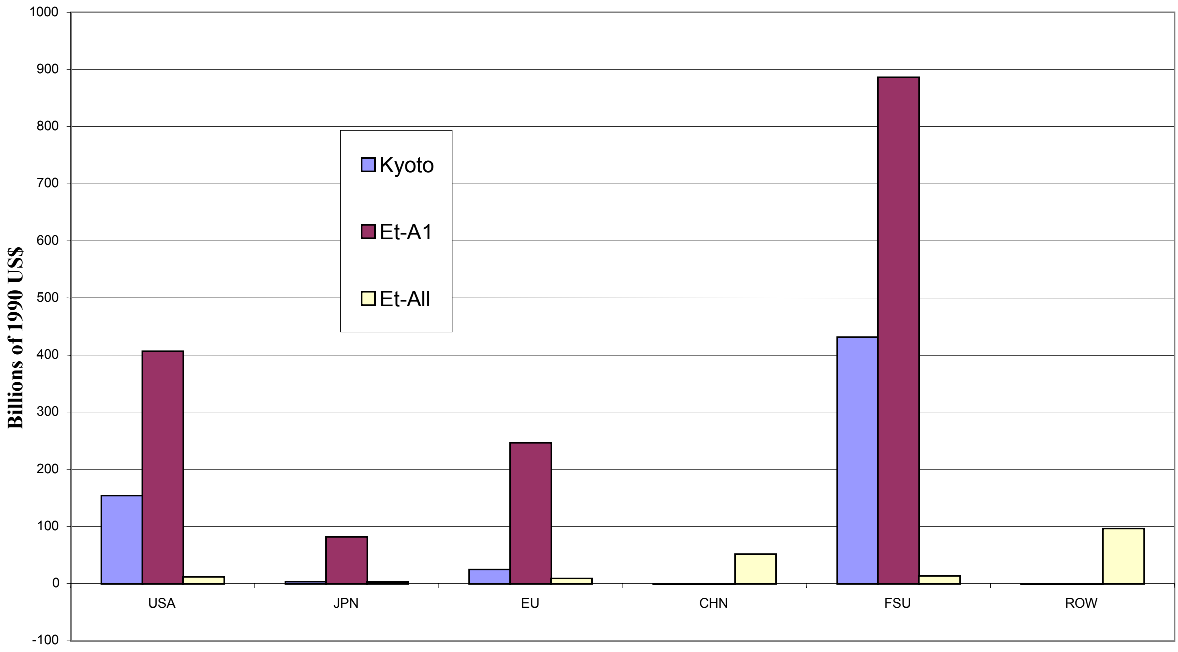
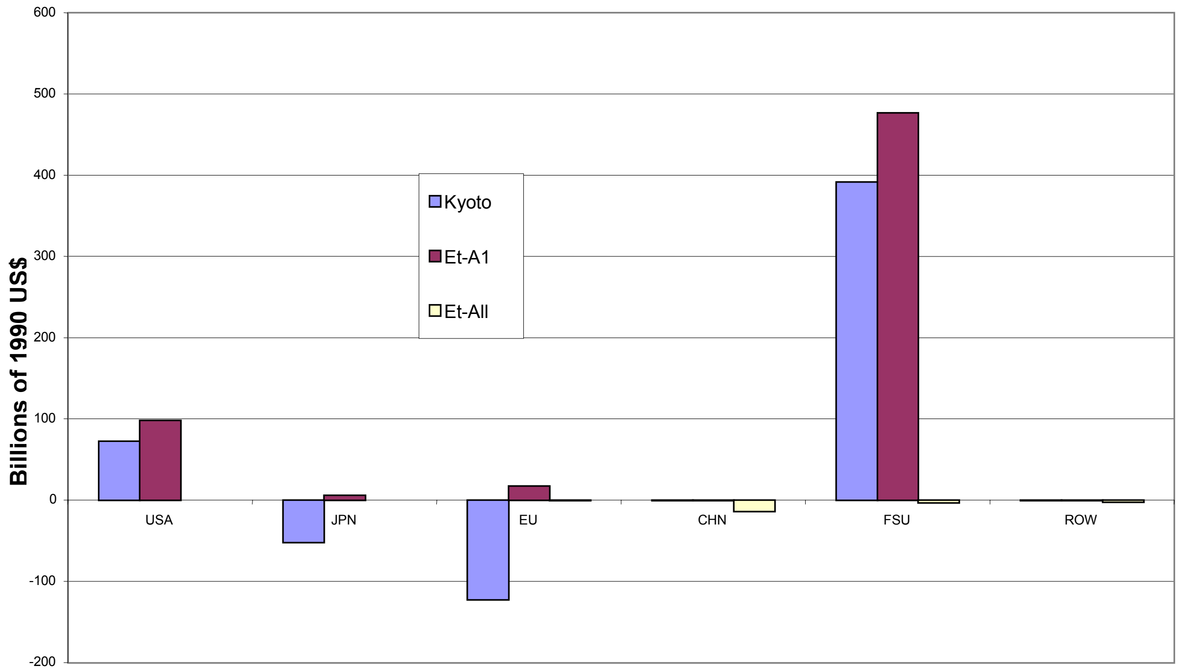


FIGURE 2: ENDOGENOUS VERSUS ENDOGENOUS PLUS INDUCED TECHNICAL CHANGE WITH SPILLOVERS: DIFFERENCES IN ABATEMENT COSTS



The incentives to carry out strategic R&D are even smaller when there are knowledge spillovers. Indeed, in the presence of spillovers, the well-known free-riding incentive leads all countries to reduce their R&D efforts. This has two effects. On the one hand, the emission-output ratio increases, thus increasing the amount of emissions that need to be abated either through domestic policy and measures or through permit purchases; on the other hand, the supply of permits becomes smaller, thus increasing their price and the costs for countries which need to buy permits to comply with their abatement obligations.

It should also be noted that, in the presence of spillovers, when emission trading is allowed amongst Annex 1 countries, the FSU has almost no incentive to increase its R&D efforts, i.e. the free-riding incentive offsets the incentive to use R&D strategically (see Figure 6). By contrast, the industrialised countries have an incentive to increase their R&D efforts to reduce their demand of permits – because the permit price is higher due to the reduced FSU supply (see Figure 4) – and even to become supplier of permits (in the case of the USA). This is why these countries reduce their overall abatement costs even in the presence of spillovers.

Finally, it should be noted that in the presence of spillovers and global emission trading, abatement costs in almost all regions are practically zero (the exception is the FSU which is no longer the only seller in the trading market). This again is due to the outcome of two effects. Global trading reduces marginal abatement costs, and technological spillovers, while reducing total R&D, have the effect of diffusing R&D worldwide, thereby reducing the emission-output ratio in all regions.

4.3 Technical Change and Trading Costs

Further information is provided in Figures 3 and 4, which illustrate the pattern of the price of permits for cases in which only Annex 1 countries are allowed to trade and in which all countries are allowed to trade respectively. The price of permits is lower under induced technical change, both when only Annex 1 countries trade (Figure 3) and when all countries trade (Figure 4). As has been mentioned above, this is explained by the increased supply and the reduced demand for permits when technical change reduces the emission-output ratio. In addition, it should be noted that spillovers have a very limited effect if environmental technical change is not endogenised. By contrast, in the case of induced technical change with spillovers the price of permits is higher than in the case without spillovers.

The reason is again the strategic use of R&D. Without induced technical change, there is almost no impact of R&D on emissions, and therefore little reason to use R&D

strategically. Spillovers, which affect the incentive to carry out R&D, have almost no impact on the equilibrium outcome. With induced technical change, spillovers largely reduces the incentive to carry out R&D. This increases the required abatement effort and increases the demand for permits, thus raising their price.

FIGURE 3: PRICE OF PERMITS UNDER ET-A1 – ENDOGENOUS VERSUS ENDOGENOUS PLUS INDUCED TECHNICAL CHANGE WITH AND WITHOUT SPILLOVERS

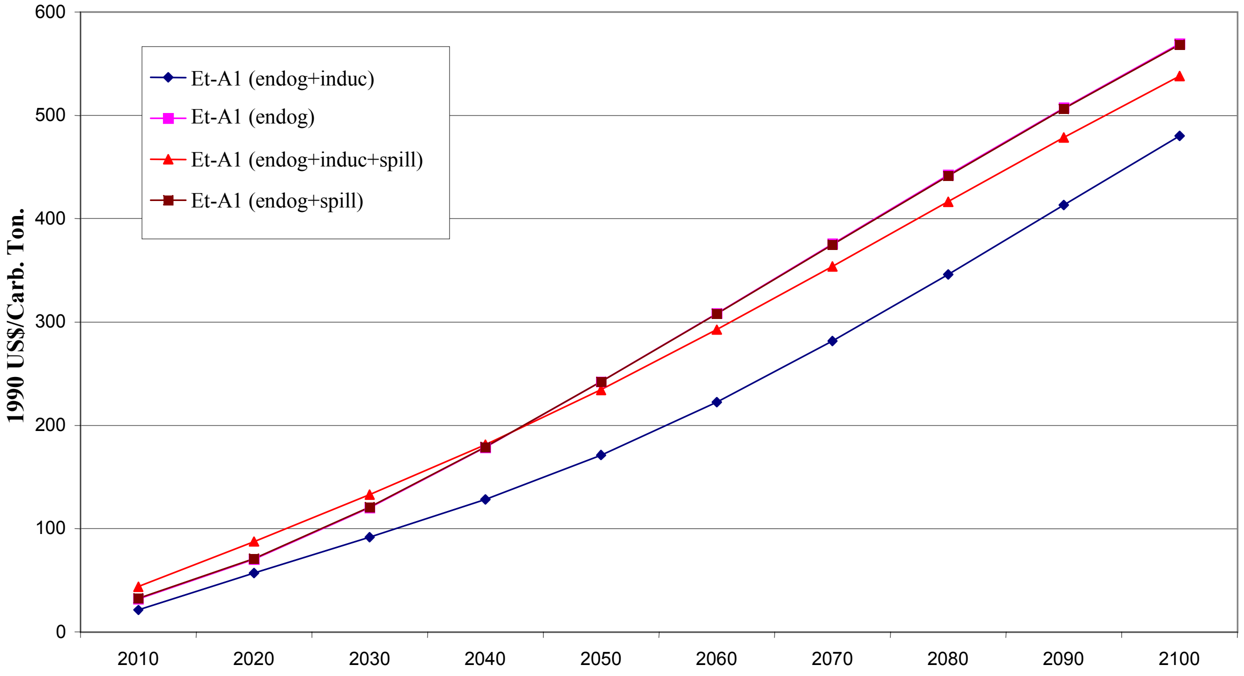
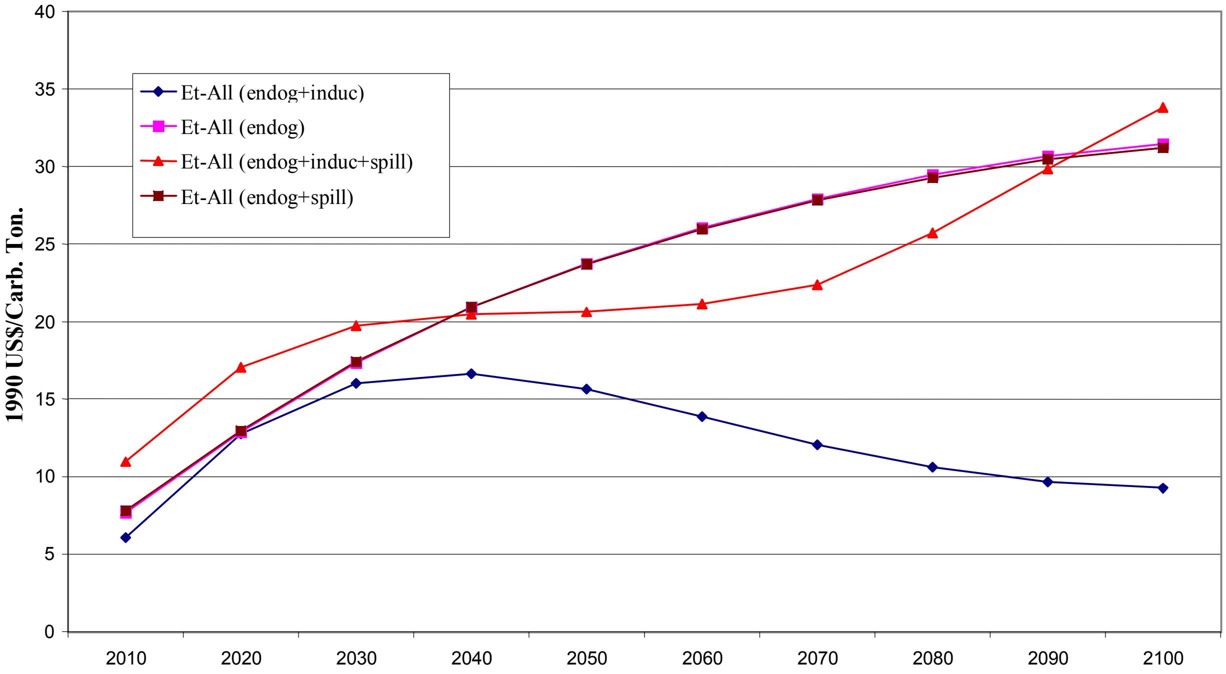


FIGURE 4: PRICE OF PERMITS UNDER ET-ALL – ENDOGENOUS VERSUS ENDOGENOUS PLUS INDUCED TECHNICAL CHANGE WITH AND WITHOUT SPILLOVERS



4.4 Technical Change and R&D Costs

Figures 5 and 6 confirm two previous findings. First, in the EU, US and Japan there is a negative correlation between the extension of the permit market and R&D (this result was also found in Buonanno, Carraro, Castelnuovo, and Galeotti, 2000a). Indeed, when trading becomes global, the lower marginal abatement costs induce lower permit prices and reduce the incentive to carry out R&D. The opposite is true for the other regions which use R&D strategically to increase the amount of permits sold in the market.

Second, the presence of spillovers reduces the incentive to carry out R&D in the FSU, China and ROW, thus giving the US and Japan the opportunity to use R&D strategically to reduce their demand for permits and even to sell permits in the market.

FIGURE 5: ENDOGENOUS VERSUS ENDOGENOUS PLUS INDUCED TECHNCAL CHANGE DIFFERENCES IN TOTAL R&D EXPENDITURES

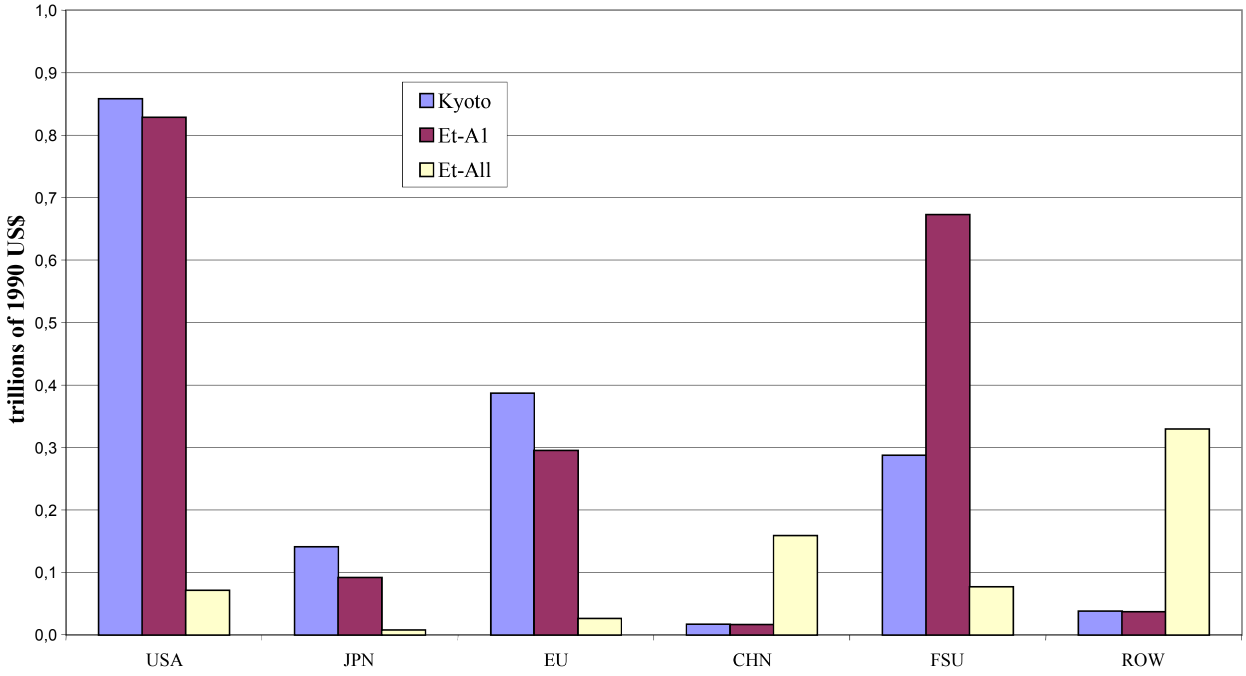
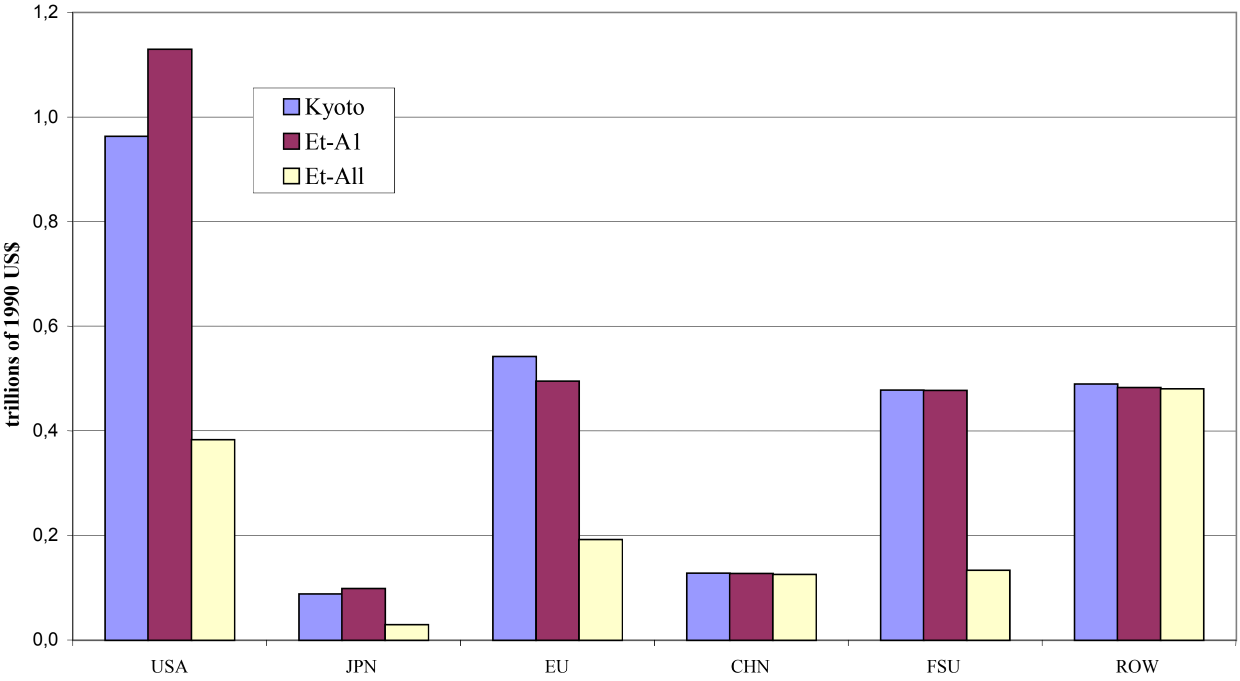


FIGURE 6: ENDOGENOUS VERSUS ENDOGENOUS PLUS INDUCED TECHNICAL CHANGE WITH SPILLOVERS
DIFFERENCES IN TOTAL R&D EXPENDITURES



5. Concluding Remarks

The main goal of this paper was to compare the effects of three different ways of modelling technical change in a simple integrated assessment model. The first step of our analysis was the modification of the RICE model to include an additional policy variable - Research and Development - whose optimally chosen level increases the stock of knowledge over time. This in turn affects output productivity, on the one hand, and reduces emissions per unit of output, on the other one. Increased output productivity has been used here to account for sectoral technological spillovers within each region. The presence of a stock of world knowledge affecting both productivity and emission-output ratios is used to account for international technological spillovers, i.e. the international diffusion of technical change.

This leads to three formulations of the RICE model with endogenous technical change. In the first one, technical change is endogenous and enters the production function through the domestic stock of knowledge, thus inducing endogenous growth. In the second one, there is an additional effect of the domestic stock of knowledge on the emission-output ratio. This yields a model with induced technical change, i.e. environmental policies directly affect the incentives to carry out R&D. In the third formulation, the outcome of domestic R&D spills over the other regions' productivity and emission-output ratio.

The paper has shown that the modelling of R&D has significant effects on the outputs of the model. In particular, using the analysis of the costs of complying with the Kyoto Protocol as a case study, we have shown that:

(i) the presence of induced technical change reduces the costs of complying with Kyoto, both by increasing R&D efforts - because R&D is used strategically to reduce emissions and to increase the supply of permits - and by reducing the price of permits.

(ii) the presence of spillovers becomes relevant only in the presence of induced technical change. However, in this latter case, spillovers reduce the incentive to carry out R&D, thus increasing the price of permits. Overall abatement costs do not increase because of the positive effect of a globally diffused R&D on the emission level.

These results are useful to illustrate the fact that the modelling of technical change is relevant and that differences in model structures have significant effects on the equilibrium policy and state variables. However, the proposed formulations of the endogenous technical change are still preliminary and more research is needed both in the definition of the appropriate theoretical structure and on the empirical assessment of the relevant parameters.

For instance, elements of uncertainty should be introduced in a model in which technical change, whether for productivity or environmental purposes, is endogenous. Moreover, induced technical change has been modelled as a continuous process, whereas a more advanced model should also account for discrete episodes of technological improvements, by explicitly referring to and integrating backstop technologies. Finally, it would be useful to distinguish environmental R&D from other forms of R&D, thus giving each country two policy variables and in this way accounting for potential crowding-out effects.

References

Boone, L., Hall, S. and D. Kemball-Cook (1992), "Endogenous Technical Progress in Fossil Fuel Demand", mimeo, Center for Economic Forecasting, London Business School.

Buonanno, P., C. Carraro, E. Castelnuovo, and M. Galeotti (2000)(a), “Efficiency and Equity of Emission Trading with Endogenous Environmental Technical Change”, in C.Carraro (ed.), Efficiency and Equity of Climate Change Policy, Dordrecht: Kluwer Academic Publishers, 121-162.

Buonanno, P., C. Carraro, E. Castelnuovo, and M. Galeotti (2000)(b), “Emission Trading Restrictions with Endogenous Technological Change”, Fondazione ENI Enrico Mattei Nota di Lavoro N.43-00, forthcoming *International Environmental Agreements*.

Burniaux, J.M, J.P.Martin, G.Nicoletti and J.Oliveira Martins (1992), "The Costs of Reducing CO2 Emissions: Evidence from GREEN", OECD Economics and Statistics Department Working Paper No.115.

Carraro, C. (ed.) (1999), International Environmental Agreements on Climate Change, Dordrecht: Kluwer Academic Publishers.

Carraro, C. (ed.) (2000), Efficiency and Equity of Climate Change Policy, Dordrecht: Kluwer Academic Publishers.

Carraro, C. and M. Galeotti (1996), "WARM: A European Model for Energy and Environmental Analysis", *Environmental Modelling and Assessment*, 1, 171-189.

Ciccone, A. (1996), “Externalities and Interdependent Growth: Theory and Evidence”, mimeo, University of California at Berkeley.

Coe, D.T., and E. Helpman (1995), “International R&D spillovers”*, European Economic Review*, 39, 859-887.

Conrad, K. and M. Ehrlich (1993), "The Impact of Embodied and Disembodies Technical Progress on Productivity Gaps - An Applied General Equilibrium Analysis for Germany and Spain", *Journal of Productivity Analysis,* 4, 317-335.

Dowlatabadi H. and M. Oravetz (1997), “Is There Autonomous Energy Efficiency improvement?”, Department of Engineering and Public Policy, Carnegie Mellon University.

Eyckmans, J. And H. Tulkens (1999), “Simulating with RICE Coalitionally Stable Burden Sharing Agreements for the Climate Change Problem”, *CLIMNEG* Working Paper, CORE, Université Catholique de Louvain.

Gao, X.M. (1994), “Measuring Technological Change Using a Latent Variable Approach”, *European Review of Agricultural Economics*, 21, 113-129.

Gerlagh, R. and B.C.C. Van der Zwaan (2000), “Gross World Product and Consumption in a Global Warming Model with Endogenous Technological Change”, Paper presented at the Workshop on “Economic Modelling of Environmental Policy and Endogenous Technical Change”, Amsterdam, November 16-17, 2000.

Goulder, L.H. and K. Mathai (2000), “Optimal CO_2 Abatement in the Presence of Induced Technological Change”, *Journal of Environmental Economics and Management,* 39, 1-38.

Goulder, L.H. and S. Schneider (1999), "Induced Technological Change and the Attractiveness of CO_2 Abatement Policies", *Resource and Energy Economics*, 21, 211-253.

Griliches, Z. (1979), "Issues in Assessing the Contribution of R&D to Productivity Growth", *Bell Journal of Economics*, 10, 92-116.

Griliches, Z. (1984), R&D, Patents, and Productivity, Chicago: University of Chicago Press.

Griliches, Z. (1992), "The Search for R&D Spillovers", *Scandinavian Journal of Economics*, 94, 29-47.

Grübler, A. and S. Messner (1996), "Technological Uncertainty", in N. Nakicenovic, W.D. Nordhaus, R. Richels, and F.L. Toth (eds.): Climate Change: Integrating Science, Economics, and Policy, CP-96-1, International Institute for Applied Systems Analysis, Laxenburg, Austria, 295-314.

Jorgenson, D.W. and P.J.Wilcoxen (1990), "Intertemporal General Equilibrium Modelling of U.S. Environmental Regulation", *Journal of Policy Modeling* 12, 715-744.

Kratena, K. and S.P. Schleicher (1999), "Emission Reduction Policies and Induced Technological Change: Microeconomic Evidence and Macroeconomic Impacts of the Austrian Kyoto Protocol Package", mimeo, June.

Lucas, R.E. (1988), "On the Mechanics of Economic Development", *Journal of Monetary Economics*, 100, 223-251.

Mankiw, N.G., D. Romer, and D.N. Weil (1992), "A Contribution to the Empirics of Economic Growth", *Quarterly Journal of Economics*, 107, 407-437.

Mohnen, P. (1994), "The Econometric Approach to R&D Externalities", Université du Québec à Montréal, Departement des Sciences Econmiques Cahier N.9408.

Nadiri, M.I. (1993), "Innovation and Technological Spillovers", National Bureau of Economic Research N.4423.

Newell, R.G., A.B. Jaffe, and R.N. Stavins (1999), "The Induced Innovation Hypothesis and Energy-Saving Technological Change", (1999), Quarterly Journal of Economics, 114, 941-975.

Nordhaus, W.D. (1994), Managing the Global Commons: The Economics of the Greenhouse Effect, Cambridge: MIT Press.

Nordhaus, W.D. (1999), "Modelling Induced Innovation in Climate-Change Policy", paper presented at the IIASA Workshop on Induced Technological Change and the Environment, Laxenburg, June 21-22.

Nordhaus, W.D. and Z. Yang (1996), "A Regional Dynamic General-Equilibrium Model of Alternative Climate-Change Strategies", *American Economic Review,* 4, 741-765.

OECD (1998), "Climate Change and Economic Modelling. Background Analysis for the Kyoto Protocol", Proceedings of the Workshop held in Paris, September 17-18.

Romer, P. (1986), "Increasing Returns and Long-Run Growth", *Journal of Political Economy*, 98, S71-S102.

Romer, P. (1990), "Endogenous Technological Change", *Journal of Political Economy*, 94, 1002-1037.

Schleicher, S.P., B. Buchner, and K. Kratena (2000), "Why Cost Minimisation Strategies for the Kyoto Mechanisms May Cause Market Failures", University of Graz, mimeo.

Slade, M.E. (1989), “Modelling Stochastic and Cyclical Components of Technical Change: An Application of the Kalman Filter”, *Journal of Econometrics*, 41, 363-383.

Stavins, R.N. (2000), "Economic Analysis of Global Climate Change Policy: A Primer", mimeo, August.

Van der Zwaan, B.C.C., R. Gerlagh, G. Klaassen, and L. Scrattenholzer (1999), “Endogenous Technological Change in Climate Change Modelling”, forthcoming *Energy Econmics*.

Weyant, J.P. (1997), “Technological Change and Climate Policy Modeling”, paper presented at the IIASA Workshop on Induced Technological Change and the Environment, Laxenburg, June 26-27.

Weyant, J.P. and T. Olavson (1999), “Issues in Modelling Induced Technological Change in Energy, Environmental, and Climate Policy”, *Environmental Modelling and Assessment*, 4, 67-85.

Wilson, D. and J. Swisher (1993), "Exploring the Gap: Top-down Versus Bottom-up Analyses of the Cost of Mitigating Global Warming", *Energy Policy*, March: 249-263.