Does Endogenous Technical Change Make a Difference in Climate Policy Analysis?

A Robustness Exercise with the FEEM-RICE Model

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Summary

Technical change is generally considered the key to the solution of environmental problems, in particular global phenomena like climate change. Scientists differ in their views on the thaumaturgic virtues of technical change. There are those who are confident that pollution-free technologies will materialize at some time in the future and will prevent humans from suffering the catastrophic consequences of climate change. Others believe that there are inexpensive technologies already available and argue the case for no-regret adoption policies (e.g. subsidies). Others again believe that the process of technological change responds to economic stimuli. These economic incentives to technological innovation are provided not only by forces that are endogenous to the economic system, but also by suitably designed environmental and innovation policies. In this paper, we consider and translate into analytical counterparts these different views of technical change. We then study alternative formulations of technical change and, with the help of a computerized climate-economy model, carry out a number of optimization runs in order to assess what type of technical change plays a role (assuming it does) in the evaluation of the impact of climate change and of the policies designed to cope with it.

Keywords: Climate policy, Environmental modeling, Integrated assessment, Technical change

JEL Classification: H0, H2, H3

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1. Introduction

Technological change is a major force in a country's economic growth. Since before the industrial revolution, economies and societies have evolved as a result of technological change. A long sequence of inventions - engines, power generation systems, industrial processes, and appliances – have changed people's lives. Society has moved from a reliance on wind, water, animal power, and wood to reliance first on coal, and then on natural gas and petroleum. Today, many technologies utilize fossil fuels, which has led to the release of large amounts of carbon into the atmosphere, and the scientific consensus is that these emissions will contribute to changing the earth's climate.

Atmospheric concentrations of carbon dioxide (CO_2), a greenhouse gas (GHG), are up by 33% from pre-industrial levels. If these concentrations are to stabilize at, for example, twice the pre-industrial level, per capita global emissions will first need to peak and then decline to (at least) half their 1990 value by the end of the twenty-first century. This would seem challenging enough with current technologies, but, fortunately, technology does not stand still. Technological innovation is increasingly seen as one of the key instruments we possess for reconciling the current fundamental conflict between economic activity and the environment.

No one really believes or is ready to accept that the solution to the climate change problem is to reduce the pace of economic growth. Instead, it is believed that changes in technology will bring about the long sought de-coupling of economic growth from generation of polluting emissions.

Yet, there are contrasting views on this issue . Some maintain a faithful view that technological change, having a life of its own, will automatically solve the problem. In contrast, others express the conviction that the process of technological change by and large responds to impulses and incentives, and it has therefore to be fostered by appropriate policy actions.

Technological change generally leads to the substitution of obsolete and dirty technologies with cleaner ones. It must be borne in mind, however, that technical change is not per se always environment-friendly, as it can lead to the emergence of new sectors and industries with new kinds and degrees of pollution problems, like the generation of new harmful pollutants. There are therefore no substitutes for policy in directing the innovation efforts toward fostering economic growth and helping the environment at the same time.

All the above remarks are reflected in climate models, the main quantitative tools designed either to depict long run energy and pollution scenarios or to assist in climate change policy analysis. Climate models have traditionally accounted for the presence of technical change, albeit usually evolving in an exogenous fashion. More recently, however, models have been proposed where the technology changes endogenously and/or its change is induced as a result of the deliberate choices of agents and government intervention.

Both bottom-up and top-down models, a long standing distinction in energy-economy-environment modeling, have been recently modified in order to accommodate forms of endogenous technical change. As it turns out, the bottom-up approach has mostly experimented with the notion of Learning by Doing (LbD henceforth), while a few top-down models have entertained the notion of a stock of knowledge which accumulates over time via R&D spending (see Galeotti and Carraro, 2003 for a survey).

In this paper, we consider alternative formulations of the process of technical change, in particular those that are endogenous to the economic system. We use a model specifically designed for climate change impact and policy analysis, which accommodates the various specifications. We then assess whether the way in which technological change is modeled makes a difference from the point of view of the impact of climate change on a number of relevant economic and environmental variables. We also consider the consequences for the market of international emission trading, the main flexibility mechanism envisaged by the Kyoto Protocol.

While the sheer number of variables, time periods, regions and scenarios involved mean that results are not easy to summarize, our findings seem to confirm previous evidence according to which induced technical change does not make a big difference, at least when emission reduction targets are those set, for example by the Kyoto-Bonn-Marrakech agreements A greater difference emerges only in the presence of more ambitious emission reduction targets. When the comparison is made between various endogenous and exogenous formulations of technical change, our results suggest that LbD formulations make a bigger difference.

Attention is to be drawn to the fact that not all technical change is good for the environment. This implies that environment-friendly technical change is no substitute for policy. Quite the opposite: our results show that policy, in terms of (more) stringent targets is needed for environment-friendly technical change to kick in.

The remainder of the paper is as follows. Section 2 briefly reviews the main ways of modeling the process of technological change in economic-climate models. Particular attention is paid to endogenous and induced technical change. Section 3 embeds the alternative ideas presented in the previous section into a specific model. Section 4 shows the outcomes of our game-theoretic optimization runs and discusses our results. Concluding comments close the paper.

2. On Modeling Technical Change in Climate-Economy Models

When dealing with (very) long run phenomena, technological change is a factor included in every model that purports to describe the essential elements of human economic activities . Models describing interaction between economic activity and the environment – the climate in particular – *by necessity* incorporate a description of the process of technological change.

2.1. From Exogenous to Endogenous Technical Change

In early and now outdated models used to assess the effects of policies designed to control polluting emissions, technical change was considered to be an exogenous factor. Nevertheless, some celebrated models of integrated assessment, such as Nordhaus and Yang (1996)'s RICE model, assume technology evolves 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).

Let us focus on energy-saving or emission-reducing technical change. One early formulation often exploited in top-down modeling was based on the future adoption of backstop technologies. This is a discrete event which takes place in a given, exogenously determined year and is assumed to be resource unconstrained. The problem with this approach is that it is largely linked to the personal assumptions of the modeler and precludes the analysis of technological innovation over time (Wilson and Swisher, 1993). A prominent example of this was the GREEN model developed at the OECD (Burniaux, Martin, Nicoletti, and Oliveira Martins, 1992), which incorporated three backstop options: a carbon-based synthetic fuel, and two carbon-free energy sources. The main hypothesis concerned prices and the timing of technology diffusion. Prices were exogenous and the backstop technologies, once assumed to come on stream, were 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, possibilities for technological innovation are assumed to be fixed at the present level of knowledge for the entire simulation path.

Subsequently, there followed a number of attempts aimed at endogenizing the linkages between economic variables (policy variables, in particular) and technical progress. The main difficulty faced by modelers was the non-observability of this latter variable. For this reason, earlier models used a deterministic time trend as a proxy of technical change (e.g. Nordhaus and Yang, 1996). This was the starting point of some more recent but *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 was represented by a time variable added to the principal equations of the model. However, this variable was not a deterministic function of time; it was rather a stochastic function of time, in which other economic effects were also accounted for.[1] The problem with these approaches was their *ad hoc* nature. They were not derived from the explicit solution of a firm's optimization strategy designed to determine the optimal amount of R&D and investment in the corresponding type of capital. Therefore, links between these variables were mainly statistical and thus do not lend themselves to clear economic interpretation.

2.2. Modeling Endogenous and Induced Technical Change

While there is little debate over the importance of energy efficiency in limiting greenhouse gas (GHG) emissions, there is an intense debate about its cost-effectiveness and about the government policies that should be pursued to enhance energy efficiency. Analysts have pointed out for years that there is an "energy efficiency gap" between the most energy-efficient technologies available at some point in time and those that are actually in use. On

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[1] In Boone, Hall, and Kemball-Cook (1992) the dynamics of the time trend representing technical change was inferred by looking at the dynamics of factor demands. In contrast, in Carraro and Galeotti (1996) it was inferred from the dynamics of the capital stock. It was 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.

this basis, the debate has centered upon the extent to which there are low-cost or no-cost options for reducing fossil energy use through improved energy efficiency. Jaffee, Newell, and Stavins (2003) note that this debate opposes "technologists" and economists, who hold very different views about the issue.

"Technologists" believe that there are a number of opportunities for low-cost improvements in energy efficiency, and that exploiting these opportunities will require active intervention in markets for energy-using equipment to help overcome barriers to the use of more efficient technologies. This view implies that with appropriate technology and market creation policies, significant GHG emission reduction can be achieved at a very low cost. In essence, their approach is to support energy-efficiency decisions with the goal of overcoming the existing "market barriers" to the penetration of various technologies that enhance this energy efficiency.

To "Economists" only some of these barriers represent real "market failures" that reduce economic efficiency. This view emphasizes that there are tradeoffs between economic efficiency and energy efficiency. It is possible to get more of the latter, but typically only at the cost of less of the former. The economic perspective suggests that GHG emission reduction is more costly than the technologists argue. Therefore, it puts relatively more emphasis on market-based GHG emission control policies, like carbon taxes or tradable carbon permit systems, to encourage the least costly means of carbon efficiency (not necessarily energy efficiency) enhancement available to individual energy users. One possibility is to substitute polluting inputs with less polluting ones within the existing technology conditions. An alternative is for firms to make deliberate choices purporting to develop new and less polluting production methods, i.e. strive to innovate.

In this latter case, the starting point is to ask why firms would want to develop cleaner technologies themselves. At the basis of the "innovative" reason for R&D are the two motivating forces of profitable investment and strategic advantage, against which to consider costs of carrying out R&D, including factors such as appropriability. The alternative to this approach is the idea that the accumulation of knowledge occurs not as a result of deliberate (R&D) efforts, but as a side effect of conventional economic activity. This view is a typical feature of Learning by Doing (LbD) approaches.

In terms of environmental modeling, the bottom-up approach has mostly appealed to the notion of LbD, while a few top-down models have entertained the notion of a stock of knowledge which accumulates over time via R&D spending.

A number of bottom-up models have integrated endogenous technological change that assumes LbD. Examples are MESSAGE (Messner, 1997) and MARKAL (Barreto and Kypreos, 1999), dynamic linear programming models of the energy sector that are generally used in tandem with MACRO, a macro-economic model which provides economic data for the energy sector (Manne, 1981; see also Seebregts, Kram, Schaeffer, Stoffer, Kypreos, Barreto, Messner, and Schrattenholzer, 1999; Manne and Barreto, 2001). These models optimize the choice between different technologies using given abatement costs and carbon emission targets. They feature a learning or experience curve describing technological progress as a function of accumulating experience with production (LbD for manufacturers) and with use (learning-by-using – LbU – for consumers) of a technology during its diffusion. Technological learning has been observed historically for many different industries and is a well-established concept.

In general, the inclusion of endogenous technical change leads to earlier investment in energy technologies, a different mix of technologies and a lower level of overall discounted investment, as compared to exogenous technical change. When examining the optimal timing of CO_2 abatement (Grubler and Messner, 1998) via a set of given concentration stabilization targets, endogenous technical change gives us an optimal trajectory with lower emissions in the near term . The differences are, however, rather small relative to the exogenous case.

Recent developments have considered two-factor learning functions in which there is a separate effect, besides cumulative capacity, of R&D expenditures on the costs of specific energy technologies. Preliminary results do not support this addition, termed “Learning by Searching”: in four out of eight technologies, cumulative R&D expenditures increased, rather than decreased investment costs (Criqui, Klaassen, and Schrattenholzer, 2000; see also Miketa and Schrattenholzer, 2002).

Barreto and Kypreos (2002) introduce a knowledge stock function to model a two-factor learning curve in the ERIS model. Their results are encouraging and point to the importance of R&D efforts (in addition to market deployment) as elements of the technological learning process. Nevertheless, a number of conceptual and practical issues remain to be solved.

In terms of top-down modeling, the focus has been more on R&D induced technical change than on LbD. Models featuring an endogenous technology belong to either one of two categories: computable general equilibrium (CGE) or optimal growth models. An early example belonging to the first group is the MESEMET model (van Bergeijk, van Hagen, de Mooij, and van Sinderen, 1997) for the Dutch economy. Here, public and private R&D both affect the stock of human capital and form a stock of so-called technology capital: these enter the output production process along with the traditional inputs. Besides being limited to a single country, in this particular model only productivity-enhancing technical change is endogenous, as any climate or environmental consideration is absent from the model.

A more directly relevant example is the multi-region, multi-sector integrated assessment model called WIAGEM (Kemfert, 2002). In this recursively dynamic CGE model, R&D spending affects the productivity of the energy input to the production process: more R&D therefore results in increased energy efficiency. The results point to the importance and relevance of allowing for this type of induced technical change. It is to be noticed that R&D enters the model as a flow, whereas most of the other R&D-based model introduce a stock of knowledge.

Besides Nordhaus' RICE, which we review below, the other probably most popular climate model is Manne and Richels (1992)'s MERGE model. Like RICE, MERGE is an intertemporal growth model in which each of the model's regions maximizes the discounted utility of its consumption subject to an intertemporal budget constraint. Each region's wealth includes not only capital, labor, and exhaustible resources, but also its negotiated international share in emission rights. Moreover, in addition to international trade in emission rights, it allows for trade in oil, gas, and energy-intensive goods. The model divides the world into nine geopolitical regions. A distinguishing feature of the model is that it combines a top-down perspective on the remainder of the economy together with a bottom-up representation of the energy supply sector. A distinction is made between electric and non-electric energy. There are several alternative sources of electricity supply, some of them being in operation in the base year (2000), others due to be available later on.

In a very recent version of the model (Manne and Richels, 2002a), one of the previous two electric backstop technologies, the low-cost one, is replaced by a LbD process. Its total costs are initially identical to those of the high-cost backstop, but its learning costs decline by 20% for every doubling of cumulative experience. The authors examine the impact of LbD on the timing and costs of emission abatement under both a concentration and an emission target. On the whole, they find that including LbD does not alter the conclusions of earlier studies that focused on the timing of emission reductions. However, although LbD does not accelerate the timing of the transition to less carbon intensive technologies, it can have a major impact on the overall costs of the transition.

Another recent model which exploits the notion of LbD to endogenize technical change is the DEMETER model proposed by van der Zwaan, Gerlagh, Klaassen, and Schrattenholzer (2002) (see also Gerlagh and van der Zwaan, 2000; Gerlagh, van der Zwaan, Hofkes, and Klaassen, 2000; van der Zwaan and Gerlagh, 2002). A macroeconomic (top-down) model is used to distinguish between two different energy technologies, carbon and carbon-free. The costs of the latter are dependent upon the cumulative capacity installed. Thus the model is expanded with learning curves previously used in energy system (bottom-up) models. The model is a global one and cannot address issues such as emission trading. The authors compare several scenarios with taxes on the carbon and subsidies on the non-carbon technology. During the first decades, they find that carbon taxes reduce energy consumption. At a later stage, however, when the greenhouse gas policies have enhanced the maturing of the carbon-free technology, energy prices decrease and energy consumption reaches values higher than under business-as-usual. Moreover, overall consumption decreases in the first decades, with respect to business-as-usual, because of transition costs, while the availability of a progressively cheaper non-carbon technology increases total consumption in later periods.

The RICE model has been used by Nordhaus (2002) to lay 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 was actually embedded in the non-regional version of the author’s RICE model for climate change policy analysis, called DICE (Nordhaus, 1993). Nordhaus (2002) is often quoted by authors who claim that induced technical change is not very important. What appears to be more relevant is input substitution away from “carbon energy”, relative to R&D-prompted innovation. The former reduces carbon intensity twice as much as the latter. Nordhaus (2002) compares two versions of DICE, the global counterpart of the RICE model. In one case, output-constrained movements along the production isoquant were considered; in the induced innovation version capital is exogenous, i.e. there is no investment and no GNP growth, and a technology with fixed coefficients between carbon energy on the one hand and a capital-labor combination on the other. It remained to be seen how the results would change when, more realistically, optimal economic growth was allowed.

This is what Popp (2003) does. As in Nordhaus, R&D is four times more costly than physical investment, to account for the divergent social and private rates of return associated with R&D. The author also admits the possibility of crowding out (at a rate of 50%). Popp postulates an effective energy input given by a CES combination of purchased energy diminished by an exogenous technical change component and a stock of knowledge based on R&D. There are diminishing returns to R&D when translating into knowledge stock. The author compares a carbon emissions policy scenario under exogenous and endogenous formulations of technical change. A positive effect on welfare results from the induced innovation scenario relative to the exogenous case (on a 1995-2205 horizon), but the impact on the key economic and environmental variables is small. There is a small decrease in emissions under the endogenous model formulation, but no effect on temperature, and a negligible impact on output.

The conclusions of the study is that technical change is no cure-all for climate change. Technological gains do not occur without a policy signal that R&D is profitable. The welfare gains resulting from induced innovation come from cost savings, but the impact on the environment is minimal. Popp's modified DICE model contains a very careful modeling of the R&D/innovation component and of the way it is embedded in the climate model. A limitation of the model is that it is global and its carefully calibrated parameters typically refer to the U.S. economy. In a very recent variation dubbed ENTICE-BR, Popp (2004) extends the ENTICE model to also include an energy backstop technology.

Another interesting model of knowledge accumulation is proposed by Goulder and Mathai (2000), in which a central planner chooses time paths of abatement and R&D efforts in order to minimize 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 that increases over time via R&D investment. By assuming a central planner, this model sidesteps the problem of explicitly modelling innovation incentives and appropriability. A second formulation studied by the authors assumes that the rate of change of the knowledge stock is governed by abatement efforts themselves. This form of technological change is termed LbD.[2]

Both endogenous and induced technical change are taken into account by Buonanno, Carraro, Castelnuovo, and Galeotti (2000, 2001) and Buonanno, Carraro, and Galeotti (2002).[3] In particular, it is assumed that R&D investment accumulates into a stock of knowledge that affects both the production technology (endogenous technical change) and the emission-output ratio (induced technical change). By extending Nordhaus and Yang (1996)'s RICE model, the authors assumed that the stock of knowledge enters the production function as one of the production factors and, at the same time, affects the emission-output ratio, as originally proposed by Goulder and Mathai (2000) (see also Nordhaus, 2002). Thus, the idea is that more knowledge will help firms increase their productivity and reduce their negative impact on the environment. In this modified version, the central planner in each country chooses the optimal R&D effort that, in turn, increases the stock of technological knowledge. The amount of R&D is therefore a strategic variable.

Using the above-described model , labeled "ETC-RICE" or "FEEM-RICE", we are able to solve the policy game played by the six regions in which the world is divided . In the policy game, 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. Two versions of the model were considered: in the first one, with endogenous technical change, the choice of the optimal amount of R&D does not affect the emission-output ratio; in the second one, with induced technical change (i.e. endogenous environmental 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.

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[2] The not so optimistic results deriving from modeling induced technical change are partly due to the assumption of a single technology, according to Gerlagh and Lise (2003). In their partial equilibrium model of energy supply and demand, these authors consider two energy technologies for the production of a carbon-rich and a carbon-poor input. R&D is combined with LbD: R&D-based knowledge is combined with capital and labor in a technology which produces more and more energy input over time, owing to LbD. Two such energy production processes are combined in a VES aggregator function which allows modeling the transition from one technology to the other. Unlike Goulder and Schneider (1999)'s pessimistic conclusions (they also had a model that includes renewables and fossil fuel-based technologies), those authors obtain a "factor-five" result: an emission reduction policy (a carbon tax) targeted to concentrations is five times more effective under the induced technical change formulation than in the no ITC case. The model is partial and global and neglects energy savings as an option to reduce emissions. In that case factor substitution would probably be more important than ITC.

[3] See also Buchner, Carraro and Cersosimo (2002), Buchner, Carraro, Cersosimo and Marchiori (2002), and Castelnuovo, Moretto and Vergalli (2001).

Castelnuovo, Galeotti, Gambarelli, and Vergalli (2002) use the same model, but further extend it to allow for LbD. The notion of “learning curve” is central in this dynamic energy simulation model and reflects the observation that with greater “experience” (cumulative production), there is a pronounced tendency for a decline in the unit costs of novel technologies (such as photovoltaics and wind power), but there is no obvious decline in the unit costs of more conventional methods (such as supercritical coal and natural gas – combined cycle). The newer technologies tend to be higher in unit costs than the conventional ones. If investors base all their decisions on immediate costs, there would be little tendency to support the newer technologies that are currently more expensive. Their cumulative experience is too small, and they could be “locked out” permanently. This is the rationale for public intervention in the market. Leaning-by-doing entails the acceptance of high near-term costs in return for an expected lowering of future costs.

In this extension of the RICE model, the authors follow Romer (1996) in modeling LdB in the simplest way, that is by assuming that learning occurs as a side effect of the accumulation of new physical capital. This entails a production function which exhibits increasing returns to capital. In order to maintain the analogy with the R&D-based version of the model, they also allow for the emission-output ratio to depend upon cumulated capacity, i.e. the sum of past physical investment efforts. It should be apparent that this model specification makes explicit reference to the recently developed theory of endogenous growth which emphasizes the role of knowledge, of physical and human capital, R&D activities, and LbD.

2.3. 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.

Modeling 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 an analysis at the level of the firm, while bottom-up studies do not consider strategic market behavior that may delay the diffusion of innovation.

There are however some attempts to model spillovers and diffusion. One such attempt (Buonanno, Carraro and Galeotti, 2002) can be taken directly from the empirical literature on endogenous growth (see, for example, 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. Recall that in the FEEM-RICE model the agent chooses the optimal R&D effort which increases the stock of technological knowledge. This stock in turn enters the production function as one of the production factors and, at the same time, affects the emission-output ratio. R&D is thus a strategic variable, the idea being that more knowledge helps increase a firm's productivity and reduces the negative impact on the environment. In Buonanno, Carraro, Castelnuovo, and Galeotti (2000) and Buonanno, Carraro, and Galeotti (2002) a further extension of the model has productivity and emission intensity also affected by foreign knowledge, which therefore spills over onto domestic variables.

Barreto and Kypreos (2002) embed learning spillovers in their bottom-up multi-regional MARKAL model. With these spillovers, emission constraints in a given region force the deployment of low-carbon technologies there and affect the technology mix in other regions, even if these regions do not face emission constraints or have the possibility to trade emission permits with the constrained regions. Spillovers across regions allow the unconstrained ones to benefit from the cost reductions of the learning technologies triggered by the carbon reduction limits fulfilled by the constrained regions. The paper analyzes only the impact of learning in electricity generation technologies and full spillover across regions is considered.

3. Model Description

After this brief survey of the recent literature on technological innovation in climate models, let us develop an empirical analysis of different formulations of technical change. In this section, the issue of technical change and of its alternative formulations is discussed with the help of RICE, one of the most popular and manageable integrated assessment tools for the study of climate change. The original version of this model was developed by Nordhaus and Yang (1996). 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 of the six macro regions 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 maximizes the present value of per capita consumption.[4] 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. The model considers only the main greenhouse gas - carbon dioxide (CO_2) .

As stated above, the original version of the model formulates the process of technological change exogenously. There are two sources of technical change: one is productivity-enhancing, the other is emission-reducing. More specifically, the production function incorporates a technology index that increases exogenously over time, so that output increases for given inputs. One the other hand, for a given rate of domestic abatement and a given level of production activity, emissions are reduced by an index that decreases exogenously over time.

In this paper, we extend the RICE model and make technical change no longer exogenous. First, an endogenous technical change affecting factor productivity is introduced. This is done by adding a stock of knowledge to each country's production function. Second, induced technical change is modelled by assuming that the above stock of knowledge also affects the emission-output ratio. In a further extension of the model, 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. This is a situation in which, in

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[4] More precisely, welfare is given by the discounted sum of per-period utilities; these are in turn specified as the log of per capita consumption.

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 knowledge accumulation strategy (in the case of endogenous technical change) of all other players.

3.1. The Standard Model without Induced Technical Change

Formally, in the RICE model technical change enters the following two relationships:

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

and:

$$E(n,t) = \left[1 - \mu(n,t)\right]\sigma(n,t)\,Q(n,t), \qquad 0 \le \mu(n,t) \le 1 \tag{2}$$

where (*n,t*) index countries and time respectively. The first expression is a standard constant returns to scale Cobb-Douglas production function; the second expression is the emission-output relationship. Output is denoted by Q and is obtained by combining the services from the inputs of labor L and of fixed capital K_F. As specified above , the amount of labor corresponds to full employment in the economy, in turn taken to be equal to population. Population in the model evolves exogenously over time. The index A is the level of technology or productivity and grows exogenously over time. Its changes capture the first type of technological change. The rate μ represents the abatement carried out in the country, so that only the unabated portion of the output of economic activities generates harmful emissions. However, the ratio at which this occurs, which is captured by σ in the model, is not constant, but actually decreases over time, again in an exogenous fashion. This is the second type of technological change included in the RICE model.[5]

So far Nordhaus and Yang (1996). In our extension of the RICE model, technical change is no longer exogenous. Specifically, we assume that there exists an endogenously

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[5] In the paper we will use the expression ‘emissions-output ratio’ to indicate the time-varying, idiosyncratic coefficient σ(n,t). In fact, as equation (2) suggests, σ(n,t) is a *conditional* (by-product of the) emissions-output ratio, the domestic-abatement rate μ(n,t) being the conditioning variable. We consider as synonymous the terms ‘emissions-output ratio’ and ‘sigma’.

generated stock of knowledge which affects both factor productivity and the emission-output ratio. The crucial element of the model is the way in which knowledge accumulates. Following Romer (1996), on the one hand, and Goulder and Mathai (2000), on the other, we explore the two principal theoretical options, i.e. we first relate knowledge to R&D investments, and then we allow knowledge to be generated through LbD. In the former case, knowledge is the result of intertemporal optimal accumulation of R&D, where R&D is a strategic variable. In the LbD case, we simply assume that knowledge is approximated by installed capacity. In our model, installed capacity is represented by physical capital, which cumulates through periodic investment. Thus, the LbD approach entails one less choice variable with respect to the R&D approach, but no further claim on resources created is made, aside consumption and physical investment. These are the two main approaches the literature has followed when modelling induced technical change.

Because the focus of the present paper is on the impact of endogenous induced technical change, we will maintain throughout the assumption of an endogenous productivity-enhancing technical change. In other words, our starting point here is a modified production function, relative to (1), where knowledge affects factor productivity. In the case of innovation being brought about by R&D spending, it is assumed that the stock of knowledge is a factor of production, and is part of a country's production technology along with physical capital and labor. Knowledge therefore enhances the rate of productivity (see Griliches, 1979 and 1984). Hence, the FEEM-RICE production function is:

$$Q(n,t) = A(n,t) K_R(n,t)^{\beta_n^R} \left[L(n,t)^{\gamma} K_F(n,t)^{1-\gamma} \right] \tag{3}$$

where K_R is the input from knowledge capital. This stock accumulates as follows:

$$K_R(n,t+1) = R\,\&\,D(n,t) + (1-\delta_R) K_R(n,t) \tag{4}$$

where *R&D* is the expenditure in Research and Development and δ_R is the rate of knowledge depreciation. R&D is of course costly: spending is therefore included in the fundamental identity of sources and uses:

$$Y(n,t) = C(n,t) + I(n,t) + R\,\&\,D(n,t) \tag{5}$$

where *C* is consumption, *I* gross fixed capital formation and *Y* is output net of climate change effects, in accordance with the following expression:

$$Y(n,t) = \Omega(n,t)Q(n,t) \tag{6}$$

with *Ω* being an output scaling factor capturing damages from climate change. More specifically, this term is the damage function which increases with global temperature and decreases with domestic abatement.

In the case of Learning by Doing (LbD), equation (1) has to be modified in a manner that allows for a rise in productivity due to physical capital (installed capacity), without the contribution of K_R in the production function. It is possible to formalize this idea by simply modifying the Cobb-Douglas coefficients, so that returns to scale are increasing, owing to an augmented capital-output elasticity. Thus, equation (1) in the LbD case reads as follows:

$$Q(n,t) = A(n,t)\left[L(n,t)^{1-\gamma} K_F(n,t)^{\gamma}\right] K_F^{\beta^L} = A(n,t)\left[L(n,t)^{1-\gamma} K_F(n,t)^{\gamma+\beta^L}\right] \tag{7}$$

where β^L can be referred to as the learning-by-doing coefficient.

LbD is not the result of deliberate action. It therefore does not place any claim on total resources. It follows that equation (5) reverts back to its original formulation in the RICE model:

$$Y(n,t) = C(n,t) + I(n,t) \tag{8}$$

3.2 Accounting for Induced Technical Change

As said above, besides affecting factor productivity, knowledge also influences the emissions-output ratio. This is referred to as induced technical change. Following the R&D approach, it is assumed that the stock of knowledge, besides being a factor of production, also serves the purpose of reducing, *ceteris paribus,* the level of carbon emissions. Thus, R&D efforts prompt both environmental and non-environmental technical progress. More precisely, consider the RICE emissions-output relationship, whose original version is given in (2).

Accounting for induced technical change, (2) is modified as follows:

$$E(n,t) = \left[\sigma_n + \chi_n^R \exp\left(-\alpha_n^R K_R(n,t)\right)\right]\left[1-\mu(n,t)\right]Q(n,t) \tag{9}$$

where α_n^R is the region-specific elasticity through which knowledge reduces the emission-output ratio, χ_n^R is a scaling coefficient, and 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 emissions-output ratio, and therefore the overall level of pollution emissions, on the other hand.[6]

With a LbD-based knowledge accumulation, equation (2) is simply replaced by the following equation:

$$E(n,t) = \left[\sigma_n + \chi_n^L \exp\left(-\alpha_n^L K_F(n,t)\right)\right]\left[1-\mu(n,t)\right]Q(n,t) \tag{10}$$

where we substitute knowledge capital with physical capital. Hence, physical capital covers the role that knowledge capital has in the R&D approach, i.e. K_F contributes to output productivity on the one hand, and affects the emissions-output ratio, i.e. the overall level of pollution emissions, on the other hand.[7]

3.3. Accounting for Knowledge Spillovers

The previous formulations did not include potential spillover effects produced by knowledge, and therefore ignored the fact that both technologies and organizational 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 view of our currently

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[6] We are well aware of the fact that introducing a single type of R&D investment that serves two purposes is unsatisfactory. However, besides the difficulty of finding suitable data for environmental and non-environmental R&D for six world regions, the most relevant problem is that in the BAU case, when no constraint on emissions is present, there is no incentive in undertaking positive rates of environmental R&D. Therefore, parameter identification would hardly be feasible.

[7] Hence, also with the Learning by Doing formulation, we do not distinguish between possible different sources of knowledge formation (say, non-environmental sources and environmental ones). In doing so, we draw a parallel between the R&D-driven Knowledge case and the LbD-driven one in order to perform sensible comparisons between these two frameworks.

incomplete understanding of the problem - disembodied, or knowledge, spillovers are modelled here (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, we introduce a stock of world knowledge both in the production function and in the emission-output ratio equation. Equations (3) and (9) are then revised as follows:

$$Q(n,t) = A(n,t)K_R(n,t)^{\beta_n} WK_R(n,t)^{\varepsilon_n}[L(n,t)^{\gamma} K_F(n,t)^{1-\gamma}] \tag{11}$$

and:

$$E(n,t) = \left[\sigma_n + \chi_n^R \exp\left(-\alpha_n^R K_R(n,t)\right) - \theta_n WK_R(n,t))\right]\left[1-\mu(n,t)\right]Q(n,t) \tag{12}$$

where the stock of world knowledge:

$$WK_R(j,t) = \sum_{j \neq i} K_R(i,t) \tag{13}$$

is defined in such a way as not to include a country’s own stock. Note that international technology spillovers refer to a country’s R&D activities. It is assumed that the process of learning from doing does not generate beneficial externalities for other countries.

3.4. Parameter Calibration

As for parameter calibration and data requirements for the newly introduced variables, we proceed as follows. First, coefficients already present in the original RICE model are left unchanged. Next, when the R&D driven stock of knowledge is considered as an input of the production function (see equation (3)), we calibrate the coefficient β_n^R for each region so as to obtain, for the year 1990, a value of the R&D-output ratio equal to the actual one. R&D figures for 1990 are 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.[8] For the remaining three macro-regions, 1990 values of the knowledge stock are constructed by taking the average ratio between knowledge and 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. The regional parameters α_n^R and χ_n^R in equation (9) 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). 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 the original emissions-output ratio $\sigma(n,t)$ of the RICE model.[9] The asymptotic values σ_n are computed by simulating the pattern of the exogenous emissions-output ratio in the original Nordhaus and Yang (1996)'s model 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).

Instead, when learning-by-doing is the source of experience in the model, we do not calibrate the capital-output elasticity β. Rather, in this case we arbitrarily fix the value of this elasticity at 1/10 of the capital-output elasticity as in Nordhaus and Yang (1996)' s model. Technically speaking, we do so because it would not be possible to replicate the original Business As Usual scenario without setting the elasticity to zero. Hence, in this way we are basically augmenting the physical capital productivity in order to mimic the LbD effect.[10] Once the value β is imposed on the elasticity parameter, we simulate a BAU scenario with an exogenous emissions-output ratio, in order to collect the time-series for the physical capital. Then we OLS estimate the parameters α_n^L and χ_n^L in equation (10) using the same time series of the emissions-output ratio as in the former OLS regression, while replacing the stock of knowledge with the stock of physical capital (the sample still runs from years 1990 to 2120). Table 1 contains all the new coefficients and initial values introduced in the RICE model

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

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

[10] Given the high level of arbitrariness involved in this operation, Castelnuovo, Galeotti, Gambarelli, and Vergalli (2003) perform a sensitivity test, by admitting in a second stage of the analysis a larger LbD coefficient, which is now set at 3/10 of the original capital-output elasticity.

4. Does the Specification of Technical Change Make a Difference? Evidence from a Kyoto-Marrakech Scenario

As stated in the Introduction, the goal of this paper is to explore the implications of alternative ways of describing how changes in environmental technology take place in the context of models designed for climate policy analysis. In particular, as seen in the previous section, we can consider and contrast four specifications of technical change: (i) an exogenous formulation; (ii) R&D-based induced technical change or "learning-by-researching"; (iii) experience-based induced technical change or "learning-by-doing"; (iv) international knowledge spillovers in the context of R&D-based and LdB based induced technical change.

Because we want to consider whether and to what extent these formulations produce different equilibrium results, the choice of the scenario within which to conduct the optimisation runs is not of crucial interest. In particular, and unlike the bulk of the other contributions in current literature, it is not our aim to consider the consequences of alternative policy scenarios for different variables of interest (on this topic, see Buchner and Carraro, 2003).

This being the case, we have singled out one scenario, which is one of those most often analysed in literature on climate policy. We consider a situation in which the Kyoto Protocol is in effect and trade of emission permits takes place among all Annex B countries with the exception of the U.S. This is basically the Kyoto-Marrakech scenario, which for simplicity is assumed to apply through all the optimisation periods.

As a preliminary step towards an empirical analysis, we must describe how the international permit market is formalized in the model we use. When considering emission trading, two additional equations have to be included. The first one accounts for the new burden that emissions permits represent in the fundamental identity of sources and uses. Hence, equations (5) and (8) have to be respectively replaced by the following:

$$Y(n,t) = C(n,t) + I(n,t) + R\&D(n,t) + p(t)NIP(n,t) \qquad (14)$$

$$Y(n,t) = C(n,t) + I(n,t) + p(t)NIP(n,t) \qquad (15)$$

In addition, the following equation allows for the Kyoto limits to be relaxed through emission trading:

$$E(n,t) \leq Kyoto(n) + NIP(n,t) \qquad (16)$$

The variable *NIP* represents the net demand for permits, while *Kyoto* is the emission target set in the Kyoto Protocol for each one of the signatory countries and the BAU levels for the non-signatory ones. According to (14) and (15), resources produced by the economy must be devoted, in addition to consumption, investment and, in (14), research and development, to net purchases of emission permits. Equation (16) states that a region's emissions may exceed the limit set in Kyoto if permits are bought, and vice versa for the sale 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 the net demand for permits *NI*P.

When emission trading is allowed for, the sequence whereby a Nash equilibrium is reached can be described as follows. Each region maximizes its welfare function subject to individual resource and capital constraints, now including the Kyoto constraint, and to the climate module for a given emission (i.e. abatement) strategy of all the other players and a given price for permits *p(t.)* 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 that 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. The year 2010 is taken to be the first commitment period in the model.

The above mechanism describes only one, perhaps the most important, facet of the flexibility permitted by the Kyoto agreement, the so-called "where flexibility". The Protocol, however, allows countries which trade permits not to sell all their current allowances on the market, but to save an amount for future use. This possibility is commonly referred to as "banking" and applies in particular to the countries of the Former Soviet Union (FSU), which are the ones characterized by a certain amount of "hot air" (emissions that are currently below their 1990 target). After the U.S. – a potential big buyer of permits – decided not to ratify the Kyoto Protocol, it is likely that, with demand diminishing, the price of permits will be very low, possibly approaching zero (Springer, 2003). In this event, it may be convenient for the FSU to supply an amount of permits smaller than its hot air, and bring some allowances forward in time. To model banking activities in an optimal intertemporal way is no easy task. The papers that have considered "when flexibility" have made ad hoc assumptions on the amount of permits that are not sold on the spot market (Babiker, Jacoby, Reilly, and Reiner, 2002; Manne and Richels, 2002b; Springer, 2003).

In our model, we allow for exogenous banking of permits by FSU and assume that a proportion ρ of the difference between emissions and Kyoto target is offered to the market during the first commitment period. That is:

$$NIP(FSU,t)=\rho[E(FSU,t)-Kyoto(FSU)] \tag{17}$$

where ρ measures the amount of banking. In our exercise, we will assume two values for ρ, set at 0.8 and 0.6 respectively. Short of reasonable alternatives, we assume that the FSU uses the banked permits in the second commitment period, thereby increasing its (net) supply of permits. That is:

$$NIP(FSU,t+1)=(1+\rho)[E(FSU,t+1)-Kyoto(FSU)] \tag{18}$$

Another relevant consideration that arises from the probable configuration of the international trading market relates to the fact that the FSU – being the only seller of permits – is likely to hold considerable market power. Especially in view of the U.S. withdrawal, and the consequent very low price that would emerge under competitive conditions, it is reasonable to assume that the FSU will ration its supply of permits, so as to appropriate a portion of buyers' surplus. Like banking, the issue of market power has been taken up by a few papers and the modelling difficulties noted before apply here as well (Böhringer and Löschel, 2001; Babiker, Jacoby, Reilly, and Reiner, 2002; Manne and Richels, 2002b; Springer, 2003).

A simple, admittedly ad hoc way to account for market power by the FSU in our model is to make the same assumption made before in the case of banking (equation (17) but to assume that the amount subtracted at time *t* will not be given back and supplied to the market. Finally, it is obviously possible to account for both banking and market power by the

FSU by assuming, for example, that ρ=0.6 in equation (17) but that (1+ρ)=1.2 in equation (18).

We now turn to the presentation of our simulation results. The horizon we consider reaches far to the year 2100. To show the results, we adopt the exogenous technical change scenario as the reference case. The number of endogenous variables to look at, the length of the time period, the number of regions, and the various scenarios obviously force us to make a choice of the results to show. From this perspective we tried to blend the case of global variables, which we show over the whole time horizon, and regional variables, which we report as average over time for individual regions. The evidence on global variables concerns world GNP (figure 1), CO_2 concentrations (figure 2), temperature (figure 3), and price of permits (table 4, figure 6). Regional variables include welfare (table 2), emissions (table 3), R&D expenditures (figure 4), and emission control rate (figure 5).[11]

The main results can be summarised as follows.

1. World GNP, concentrations, and temperature all grow over time. This is hardly surprising, as the model is one of (optimal) economic growth where the forces promoting economic development, such as fixed investment and R&D spending, are stronger than the environmental forces hindering growth. In this respect, it must be remembered that the emissions of only two regions – EU and Japan – initially, later on of (only) three regions (FSU included) are capped by the climate agreement. The growth of the other regions is only limited by the negative impact that an increased temperature has on GNP.
2. In terms of alternative formulations of the process of technical change, differences are quantitatively small; the difference between exogenous and endogenous specifications are negligible. This is the likely consequences of a scenario characterized by an emission reduction policy that is too weak. With more stringent limits on emissions, differences become more sizeable. In the present setup, there is too little incentive to carry out emissions reducing investments in new technologies.
3. In terms of endogenous technical change specifications, Learning by Doing is a more growth-oriented formulation, while Learning by Researching is more environment-oriented. And this is even more so when knowledge spillovers of domestic R&D efforts onto other regions are considered.

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[11] Figures 5 and 6 clearly refer only to the corresponding scenarios.

4. The most discernible difference across ITC formulations is in the price of permits. The price of the R&D-based ITC scenario is lower than that of the LbD-based case. Also, the price is lower for the endogenous R&D case relative to the exogenous R&D one. This evidence suggests that in a competitive configuration of the permit market, emission-reducing R&D is used strategically. The FSU does most of the R&D in order to keep well below its emission limit so as to have permits to sell in the market. A larger supply for given demand will result in a lower price. The LbD case instead entails no deliberate, and hence, optimal strategies from this standpoint.
5. As for regional emissions, recall that in the model there is a single R&D type that serves two purposes: it increases production and it decreases emission intensity, ceteris paribus. Emissions, however, are given by the product of emission intensity times output. Under the impulse of R&D efforts which lead to a larger stock of knowledge, the latter prevails upon the former, thus leading to increased emissions. Relative to the exogenous case (emission intensity not affected by knowledge), however, differences are small. Interestingly, the above outcome applies to Annex B countries, which demand permits, while the opposite holds for the FSU. Note that this does not occur in the case of LbD, as there is no trade-off between domestic abatement and domestic R&D.
6. Besides "where" flexibility, "when" flexibility appears to be important. As a matter of fact it is unlikely that the FSU – the bigger supplier (and in the scenarios here considered, the only one) of permits – will sell on the market all the difference between allowed and actual emissions . More probably some permits will be banked for later use, or withheld altogether for strategic purposes (to exploit monopoly power). In both cases, the equilibrium price of permits increases by, on average, 20% in the first commitment period. For the reasons already explained above, the increment is more significant in the R&D-based formulation of technical change relative to the LbD case, and when R&D is used strategically in the endogenous specification relative to the exogenous one.

7. Further Model Developments

The main shortcomings of the model formulations shown in the previous section are due mainly to the absence, in the core model, of an explicit energy module. The absence of an energy production factor makes it impossible to capture the effects of technical change on the energy intensity of production. Moreover, the "Learning-by-Researching" and the

"Learning-by-Doing" features of technical change were modeled separately, while it would appear appropriate to include both sources of technical change in the same model. Finally, approximating the stock of experience with physical capital is not very accurate, but the presence of the abatement rate as a control variable made it difficult, if not impossible, to account for cumulated abatement efforts as the force driving the learning process.

A more recent version of the RICE model is currently available (Nordhaus and Boyer, 2000). Among other aspects, the world is divided in eight regions (six before) and a new production input called carbon energy has been introduced, together with a revised treatment of energy supply which is no longer seen as inexhaustible. Using this model as the basis for our developments, in the new FEEM-RICE we are able to focus on two distinct sources of potential technical change: the energy intensity of production and the carbon intensity of energy use. These two aspects allow us to address energy-saving as well as energy-switching issues. In terms of the well known Kaya identity:

$$E_t = \sum_n \left(\frac{E_n}{CE_n} \right) \left(\frac{CE_n}{Y_n} \right) \left(\frac{Y_n}{L_n} \right) L \tag{19}$$

our extended version of the model allows us to endogenise both energy intensity (CE_n/Y_n) and carbon intensity (E_n/CE_n).[12]

The main novelty of our new formulation hinges on a new variable, which we call (with poor inventive) Technical Progress, accounting for both Learning-by-Researching and Learning-by-Doing *at the same time*. As before, we assume that innovation is brought about by R&D spending which contributes to the accumulation of the stock of existing knowledge. In addition to this Learning-by-Researching effect, the model also accounts for the effect of Learning-by-Doing, now modeled in terms of cumulated abatement efforts. Thus, Technical Progress *TP* is defined as follows:

$$TP(n,t) = f[ABAT(n,t), K_R(n,t)] \tag{20}$$

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[12] As in most of the models used in this literature, population is exogenously determined. An important future development would be that of endogenizing demographic changes, including migration flows across regions.

where $K_R(n,t)$ is the stock of knowledge and $ABAT_S$ represents the stock of cumulated abatement. The variable TP is considered to affect both energy intensity (i.e., the quantity of carbon energy required to produce one unit of output) and carbon intensity (i.e., the level of carbonization of primarily used fuels).[13]

This model has been recently analysed and tested. Some preliminary results are shown in Bosetti, Carraro and Galeotti (2004). These results suggest that technical change plays a more relevant role in the climate policy process and that mitigation costs are very different when technical change is endogenous compared to when an exogenous formulation is adopted.

Therefore, the relevance of technical change crucially depends both on how stringent future emission targets are and on the richness of the model specification. Further work into this latter direction is therefore necessary.

8. Concluding Remarks

Technical change is generally considered the key to the solution of environmental problems, in particular global phenomena like climate change. Scientists differ in their views on the thaumaturgic virtues of technical change . There are those who are confident that pollution-free technologies will materialize at some time in the future and will prevent humans from suffering any catastrophic consequences. Others believe that there are inexpensive technologies already available and solicit no-regret adoption policies. Others again believe that the process of technological change responds to economic stimuli. These are provided not only by forces that are endogenous to the economic system, but also by suitably designed environmental and innovation policies.

In this paper, we have suggested breaking down these different views of technical change into analytical counterparts . We have modified a model specifically designed for climate change impact and policy analysis to accommodate various specifications of exogenous and endogenous induced technical change and to analyze their main implications.

With the help of this computerized climate-economy model, we have carried out a number of optimization runs in order to assess whether the way in which technological

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[13] For an extensive description of the new FEEM-RICE model the reader is referred to Bosetti, Carraro and Galeotti (2004); for an application see Bosetti, Galeotti and Lanza (2004).

change is modeled makes a difference from the point of view of the impact of climate change on a number of relevant economic and environmental variables. We also considered the consequences for the market of international emission trading, the main flexibility mechanism envisaged by the Kyoto Protocol.

The overall conclusions that we draw from our results can be summarized as follows. Technical change does not seem to make a big difference, at least when the emission reduction targets are those set by agreements like the Kyoto-Marrakech protocol. More ambitious abatement targets are necessary to induce climate friendly technological innovation. When comparing endogenous and exogenous formulations of technical change, the LbD specifications seem to have a larger impact on the main economic and environmental variables. However, notice that not all technical change is friendly to the environment. And that environment-friendly technical change is no substitute for policy. Quite the opposite: our results show that policy – in terms of (more) stringent targets (or of high carbon taxes) – is needed for environment-friendly technical change to kick in.

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Appendix: The RICE Model

In this appendix we reproduce the remaining equations that make up the whole model. These equations are reported here for the sake of completeness and are the same as the ones found in the original RICE model.

In each region there is a social planner who maximizes the following utility function:

$$\max_{\{C(n,t)\}} \sum_{t=1}^{T} \beta^{t-1} L(n,t) \log[C(n,t)/L(n,t)] \tag{A1}$$

where L represents the exogenously evolving population, C is the absolute level of consumption, and β is the discount factor. By assumption population equals the employed labor force. The discount factor is exogenously given (equal to 3%). The budget constraint is given by an equation like (5) in the main text. Clearly, the capital stock evolves as follows:

$$K(n,t+1) = (1-\delta_K)K(n,t) + I(n,t+1) \tag{A2}$$

where I is the level of investment in physical capital and δ is the rate of depreciation of capital stock. The process is the same as that for *R&*D (see equation (4) in the main text)..

Turning to the climate module of the model, equation (6) in the main text shows the wedge existing between gross output Q and net output Y, justified by the negative effect exerted by the temperature level on the welfare of each region. Changes in temperature are generated by emissions through the equations described hereafter.

First of all, the term $\Omega(n,t)$ in (6) is the above-mentioned damage function with the following representation:

$$\Omega(n,t) = \frac{1 - b_{1,n}\mu(n,t)^{b_2}}{1 + \theta_{1,n}\left(T(t)/2{,}5\right)^{\theta_2}} \tag{A3}$$

where μ is the domestic abatement rate controlled by each region, while T is the global temperature level, and b_1, b_2, θ_1 and θ_2 are parameters.

Equations (2), (9) and (10) in the text describe how emissions are generated by production activity, and depend also on the domestic effort against pollution as well as the environmental technology that each region enjoys. Over time, emissions accumulate and form the carbon concentration stock M:

$$M(t) = \beta \sum_{n} E(n,t) + (1 - \delta_M) M(t-1) \qquad \text{(A4)}$$

where γ is the marginal atmospheric retention ratio of CO_2 emissions and δ_M is the rate of transfer of CO_2 from atmosphere to other reservoirs. The following step describes the relationship between the accumulation of greenhouse gases, the level of temperature, and climate change. The equations regulating the temperature level are:

$$T(t) = T(t-1) + \{\tau_1 [F(t) - \lambda T(t-1)] - \tau_2 [T(t-1) - T^*(t-1)]\} / \tau_3 \qquad \text{(A5)}$$

$$T^*(t) = T^*(t-1) + [T_1(t-1) - T_2(t-1)] / \tau_4 \qquad \text{(A6)}$$

$$F(t) = \eta \log[M(t) / M(0)] / \log(2) + O(t) \qquad \text{(A7)}$$

where T is atmospheric temperature relative to pre-industrial level, T^* is deep ocean temperature relative to pre-industrial level, F represents the radiative forcing from all greenhouse gas concentrations, τ_1, τ_2, τ_3, and τ_4 are parameters of the climate equation, λ is the feedback parameter in the climate model (inverse to the temperature-sensitivity coefficient), η is a parameter enhancing the impact of carbon concentration on the radiative forcing, and O is an exogenously given force.

The base year is 1990 and the model is simulated in 10-year steps.

Table 1: Parameters of the Model

	α_n^R	χ_n^R	α_n^L	χ_n^L	σ_n	β_n^R	β_{low}^L	$\delta_{R,K}$	$K_R(n,1990)$
USA	0.19544	0.01937	0.04267	0.02326	0.0097	0.0435	0.025	0.05	1.2420
Japan	0.52243	0.00527	0.12296	0.00823	0.0060	0.0455	0.025	0.05	0.2777
Europe	0.29649	0.00766	0.04524	0.00993	0.0070	0.0318	0.025	0.05	0.7552
China	0.61865	0.11277	0.02421	0.11084	0.0090	0.0108	0.025	0.05	0.0314
FSU	1.19740	0.09558	0.08072	0.09553	0.0093	0.0166	0.025	0.05	0.0727
ROW	0.07292	0.02241	0.00251	0.02224	0.0084	0.0093	0.025	0.05	0.3934

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

Table 2: Welfare under Alternative Specifications of Technical Change

Specification of Technical Change	*Year*	*World*	*USA*	*JPN*	*EEC*	*FSU*	*CHN*	*ROW*
Exogenous R&D	1990	53,85	17,52	17,61	14,95	2,34	0,26	1,17
	2040	237,96	70,41	89,02	61,10	9,98	1,67	5,78
	2100	330,92	95,47	124,76	82,76	14,73	3,64	9,56
Endogenous R&D	1990	53,84	17,52	17,61	14,95	2,33	0,26	1,17
	2040	237,92	70,42	89,03	61,09	9,93	1,67	5,78
	2100	331,37	95,47	124,91	82,85	14,93	3,64	9,56
Exogenous R&D with Spillovers	1990	54,93	17,59	18,54	15,03	2,34	0,26	1,17
	1990	238,06	70,87	88,56	61,15	10,00	1,67	5,80
	2100	331,19	96,66	123,18	83,13	14,84	3,69	9,69
Endogenous R&D with Spillovers	1990	54,81	17,52	18,52	15,00	2,34	0,26	1,17
	2040	237,67	70,83	88,37	61,06	9,94	1,67	5,80
	2100	329,57	96,31	122,47	82,70	14,83	3,64	9,61
Exogenous LbD	1990	59,73	18,81	20,72	16,26	2,46	0,26	1,22
	2040	258,46	75,23	97,45	66,67	10,83	1,79	6,49
	2100	357,65	101,38	135,07	90,10	16,08	4,01	11,02
Endogenous LbD	1990	59,71	18,81	20,72	16,25	2,45	0,26	1,22
	2040	258,34	75,24	97,42	66,63	10,77	1,79	6,49
	2100	357,69	101,38	135,09	90,12	16,06	4,01	11,02

Note: Welfare is expressed as cumulated per capita discounted consumption (in thousands of 1990 US dollars).

Table 3: Level of Emissions under Alternative Specifications of Technical Change

Specification of Technical Change	*World*	*USA*	*Japan*	*Europe*	*FSU*	*China*	*ROW*
Exogenous R&D	21,82	2,08	0,37	0,98	0,83	4,08	13,47
Endogenous R&D	19,88	2,00	0,40	1,04	0,68	3,93	11,83
Exogenous R&D with Spillovers	19,14	2,00	0,35	0,96	0,85	3,59	11,40
Endogenous R&D with Spillovers	20,66	2,03	0,37	0,98	0,81	4,24	12,23
Exogenous LbD	21,82	2,08	0,37	0,98	0,83	4,08	13,47
Endogenous LbD	22,77	2,08	0,36	0,96	0,80	4,60	13,96

Note: Average level of emission over the simulation period, emissions are measured in billions of tons carbon per year.

Table 4: Price of Permits under Alternative Specifications of Technical Change and Alternative Strategies for Constraining Permit Offers

Specification of Technical Change	*90% Market Power*		*90% Non-optimal Banking*	
	2010	2020	2010	2020
Exogenous R&D	*18%*	*13%*	*17,70%*	*0,04%*
Endogenous R&D	*24%*	*17%*	*24%*	*0,01%*
Exogenous LbD	*15%*	*11%*	*13%*	*0,04%*
Endogenous LbD	*15%*	*10%*	*15%*	*0,02%*

Note: the price of permits is measured in 19090 USD per ton. Percentage differences are relative to the case of unconstrained permits offer.

Figure 1: Alternative Formulations of Technical Change: World GNP

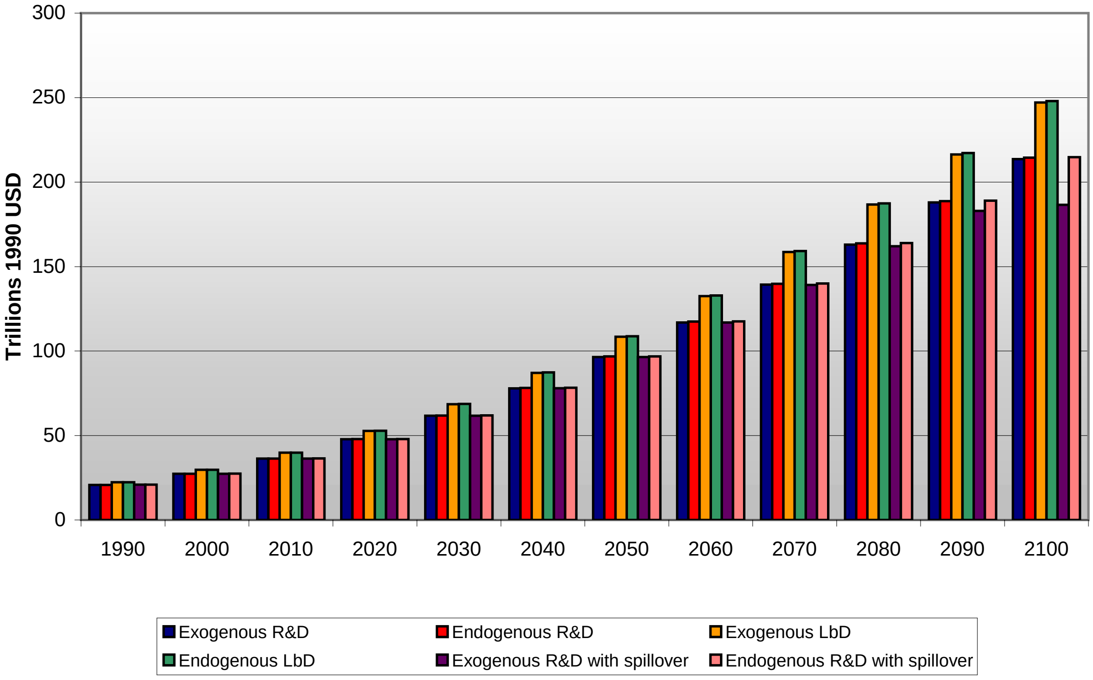


Figure 2: Alternative Formulations of Technical Change: CO_2 Concentrations

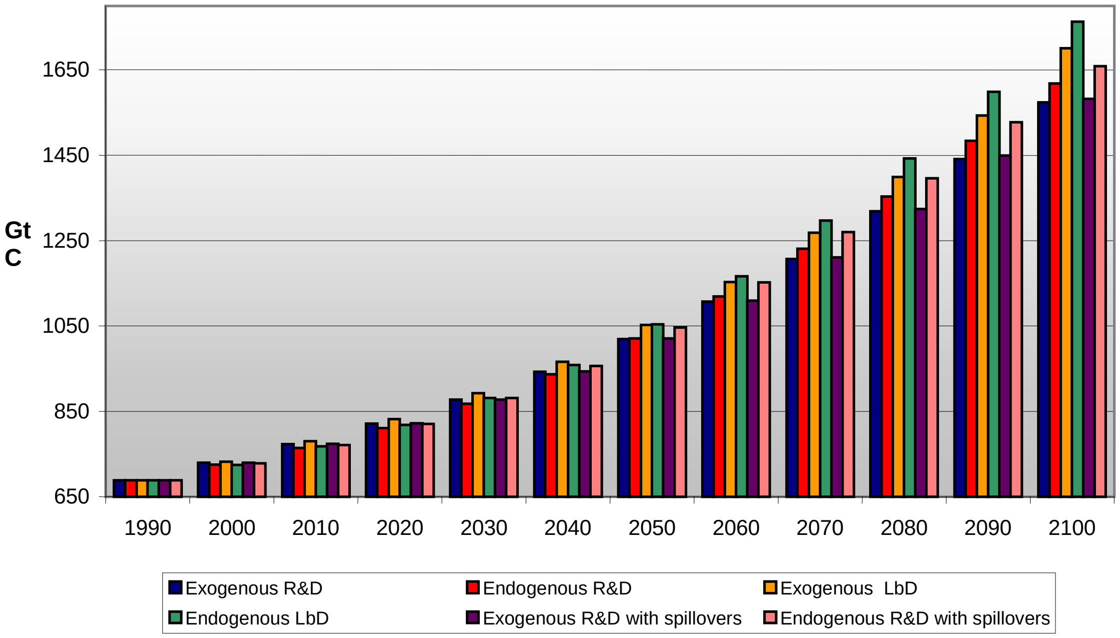


Figure 3: Alternative Formulations of Technical Change: Temperature

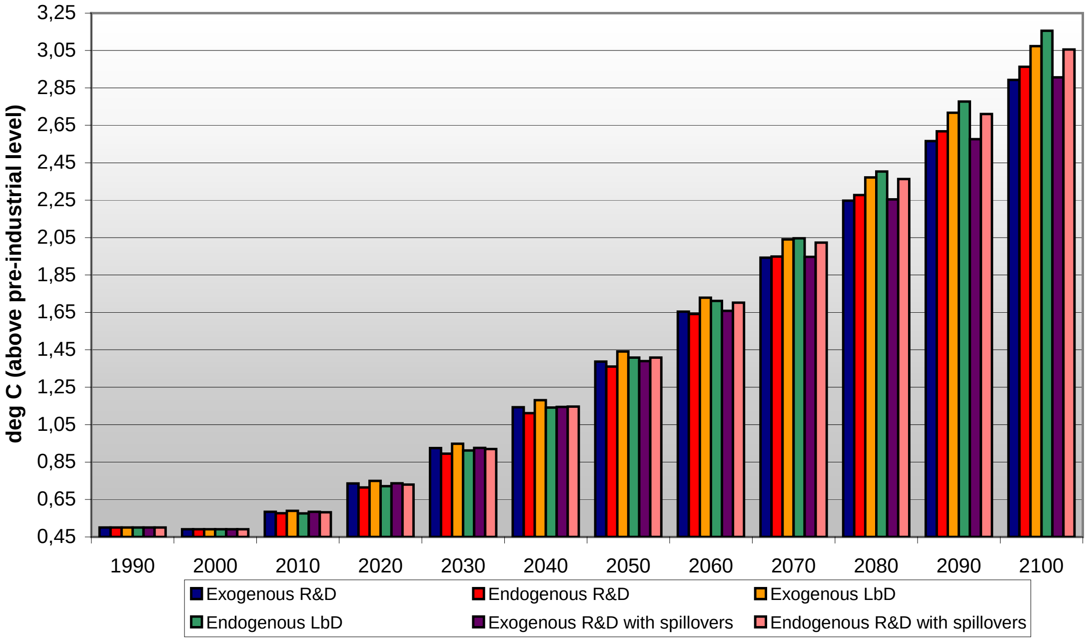


Figure 4: Alternative Formulations of Technical Change: R&D Expenditures

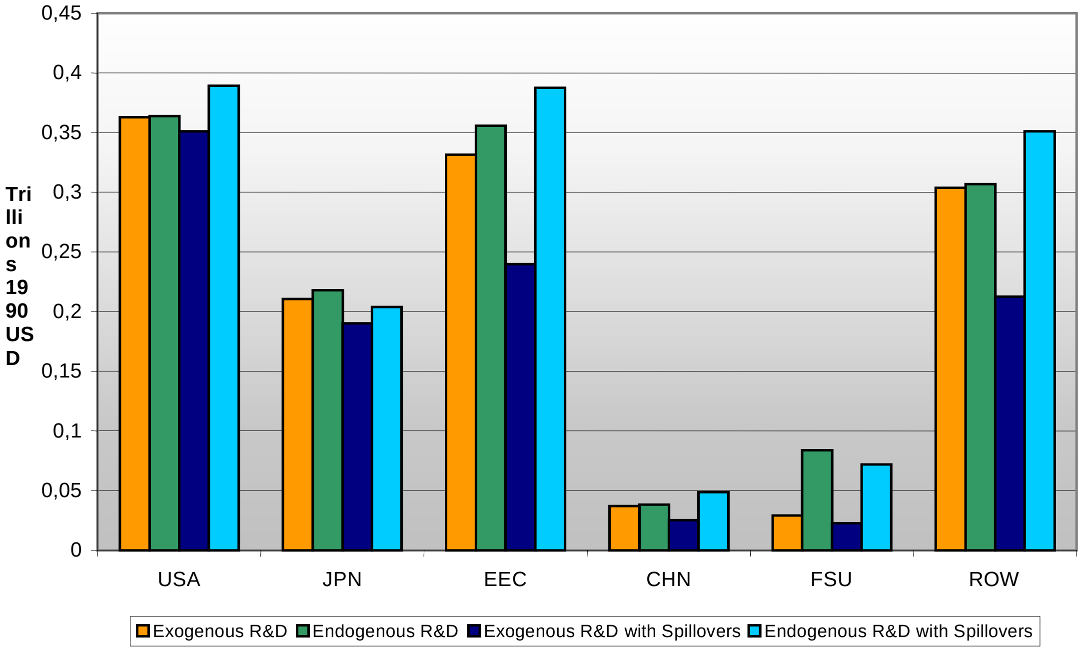


Figure 5: Alternative Formulations of Technical Change: Emission Control Rate

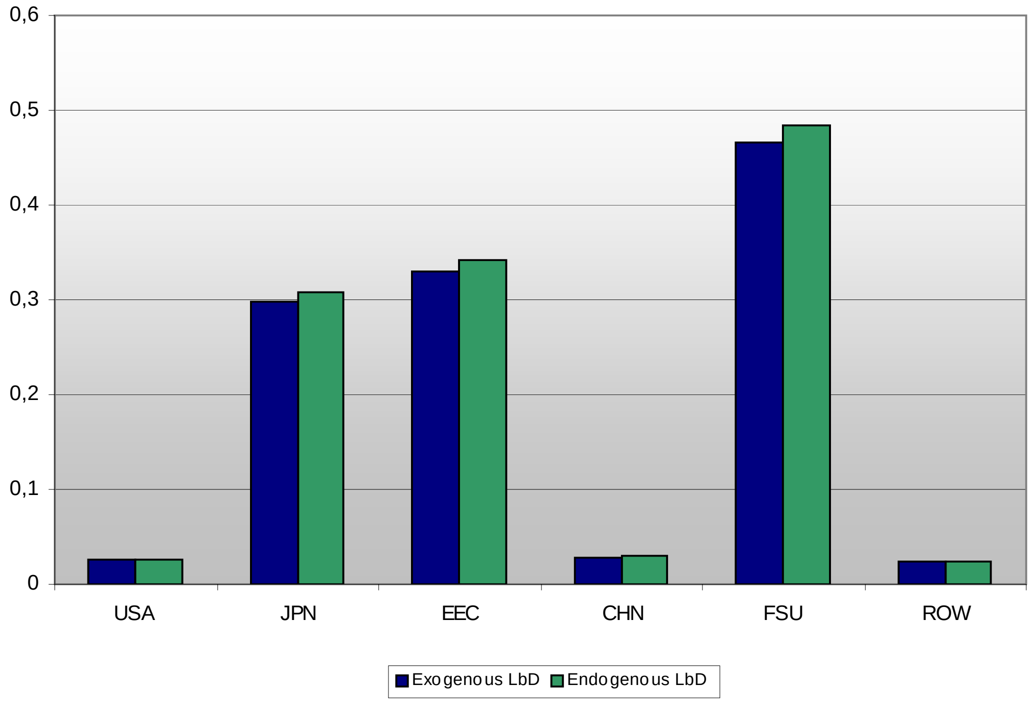
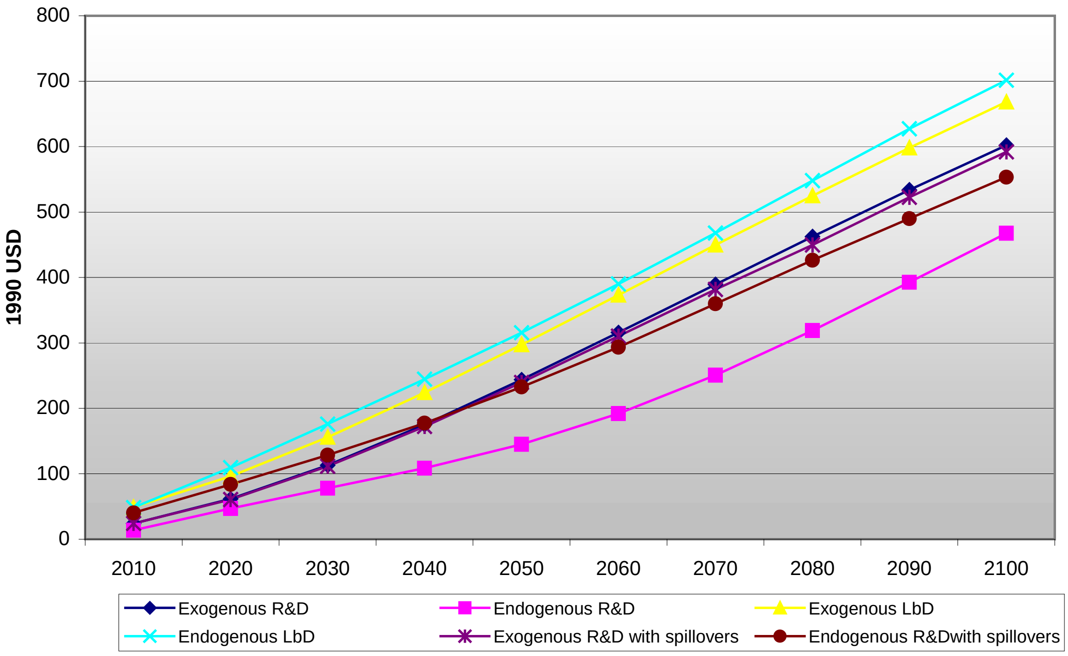


Figure 6: Alternative Formulations of Technical Change: Price of Permits



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(lix) This paper was presented at the ENGIME Workshop on "Mapping Diversity", Leuven, May 16-17, 2002

(lx) This paper was presented at the EuroConference on "Auctions and Market Design: Theory, Evidence and Applications", organised by the Fondazione Eni Enrico Mattei, Milan, September 26-28, 2002

(lxi) This paper was presented at the Eighth Meeting of the Coalition Theory Network organised by the GREQAM, Aix-en-Provence, France, January 24-25, 2003

(lxii) This paper was presented at the ENGIME Workshop on "Communication across Cultures in Multicultural Cities", The Hague, November 7-8, 2002

(lxiii) This paper was presented at the ENGIME Workshop on "Social dynamics and conflicts in multicultural cities", Milan, March 20-21, 2003

(lxiv) This paper was presented at the International Conference on "Theoretical Topics in Ecological Economics", organised by the Abdus Salam International Centre for Theoretical Physics - ICTP, the Beijer International Institute of Ecological Economics, and Fondazione Eni Enrico Mattei – FEEM Trieste, February 10-21, 2003

(lxv) This paper was presented at the EuroConference on "Auctions and Market Design: Theory, Evidence and Applications" organised by Fondazione Eni Enrico Mattei and sponsored by the EU, Milan, September 25-27, 2003

(lxvi) This paper has been presented at the 4th BioEcon Workshop on "Economic Analysis of Policies for Biodiversity Conservation" organised on behalf of the BIOECON Network by Fondazione Eni Enrico Mattei, Venice International University (VIU) and University College London (UCL) , Venice, August 28-29, 2003

(lxvii) This paper has been presented at the international conference on "Tourism and Sustainable Economic Development – Macro and Micro Economic Issues" jointly organised by CRENoS (Università di Cagliari e Sassari, Italy) and Fondazione Eni Enrico Mattei, and supported by the World Bank, Sardinia, September 19-20, 2003

(lxviii) This paper was presented at the ENGIME Workshop on "Governance and Policies in Multicultural Cities", Rome, June 5-6, 2003

(lxix) This paper was presented at the Fourth EEP Plenary Workshop and EEP Conference "The Future of Climate Policy", Cagliari, Italy, 27-28 March 2003

(lxx) This paper was presented at the 9th Coalition Theory Workshop on "Collective Decisions and Institutional Design" organised by the Universitat Autònoma de Barcelona and held in Barcelona, Spain, January 30-31, 2004

(lxxi) This paper was presented at the EuroConference on "Auctions and Market Design: Theory, Evidence and Applications", organised by Fondazione Eni Enrico Mattei and Consip and sponsored by the EU, Rome, September 23-25, 2004

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