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Summary

In recent years, a large number of papers have explored different attempts to endogenise technical change in climate models. The obvious reason is that technical change is widely considered the main route to achieving a significant reduction in global GHG emissions. This recent literature has emphasized that four factors – two inputs and two outputs – should play a major role when modelling technical change in climate models. The two inputs are R&D investments and Learning by Doing, the two outputs are energy-saving and fuel switching. Indeed, R&D investments and Learning by Doing are the main drivers of a climate-friendly technical change that eventually affect both energy intensity and fuel-mix. In this paper, we present and discuss an extension of the FEEM-RICE model in which these four factors are explicitly accounted for. In our new specification of endogenous technical change, an index of technical progress depends on both Learning by Researching and Learning by Doing. This index enters the equations defining energy intensity (i.e. the amount of carbon energy required to produce one unit of output) and carbon intensity (i.e. the level of carbonization of primarily used fuels). This new specification is embodied in the RICE 99 integrated assessment climate model and then used to generate a business as usual scenario and to analyze the relationship between climate policy and technical change. Sensitivity analysis is performed on different key parameters of the energy module in order to obtain crucial insights into the relative importance of the main channels through which technological changes affects the impact of human activities on climate. In addition, the effectiveness of different possible ways of combining Learning by Researching and Learning by Doing is also investigated.

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

JEL Classification: H0, H2, H3

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1. Introduction

Technological change (TC hereafter) 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. This evolution has been largely beneficial, even though asymmetrically distributed within and across societies. However, the economic growth fostered by technical changes has had and still has a large impact on natural resources and the global environment. Among these impacts, the release of large amounts of carbon into the atmosphere is certainly a potentially damaging one, at least in the long-run. The scientific consensus is that these emissions will contribute to changing the earth's climate, with the consequent expected effects on e.g. average temperature, sea level , precipitation patterns, and consequently on agriculture production, coastal zone urban settings, biodiversity, vector born diseases, etc.

Controlling the influence of human activities on climate is not an easy task. The international agreement that has so far come into force has only had a very small impact on greenhouse gas (GHG) atmospheric concentrations. Stabilizing these concentrations at, for example, twice the pre-industrial levels requires per capita global emissions to peak and then decline to (at least) half their 1990 value by the end of the twenty-first century. This seems to be feasible only through drastic technological change in the energy sector, i.e. technological innovation is increasingly seen as the main way of reconciling the current fundamental conflict between economic activity and environmental protection.

No one really believes or is ready to accept that the solution to the problem of climate change is to reduce the pace of economic growth. Instead, it is believed that changes in technology will bring about the long awaited de-coupling of economic growth from the generation of polluting emissions. There is a difference in attitude in this respect, though. Some maintain a faithful view that technological change, having a life of its own, will automatically solve the problem. Others express the conviction that the process of technological change by and large responds to impulses and incentives, and therefore has 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 (see the evidence in Galeotti, 2003).

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.

Indeed, these 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 technology changes endogenously and/or its change is induced by deliberate choices of agents and government intervention. Both bottom-up and top-down models, a long standing distinction in energy-economy-environment modelling, 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.

We do not intend to review here the recent literature on the role of TC in the economics of climate change and on the incorporation of induced TC in climate-economy models. This has been done elsewhere (Cf. Carraro and Galeotti, 2002, 2004; Löschel, 2002). Our intention here is rather to identify the main features that a model of technological change should possess (Cf. Clarke and Weyant, 2002 for a similar exercise) and then develop a new climate model in which most of these features are taken into account.

In the new model, dubbed FEEM-RICE, that will be presented and tested in this paper, changes in technology affect the economy and climate through modifications of both the energy intensity of production and the carbon emission intensity of energy consumed. The driver of these intensity ratios is a new, crucial variable, deemed Technical Progress (TP), which is a convex combination of two stocks, an abatement-based one and an R&D-based one. These stocks are designed to capture the two main modes of induced TC, Learning-by-Doing (LbD) and Learning-by-Researching (LbR). We hypothesize that these two sources of technical change cannot easily substitute one another.

As there is basically little guidance to the calibration of the crucial TC parameters, in particular in the context of a regional model of the world economy, we carry out a number of optimisation runs in which the key TC parameters are modified and their impact on energy and carbon intensity are quantified. This sensitivity analysis will enable us to test the robustness of the model and to identify which parameters from which our main results derive.

The remainder of the paper is as follows. Section 2 briefly surveys the recent literature on induced technical change and identifies the main features that an ideal model should possess. Section 3 presents the FEEM-RICE model and provides a technical discussion on how Technical Progress has been modelled. Section 4 presents the results of our policy analysis and tests the sensitivity of our formulation of technical change to changes in its main parameters. Some concluding comments and suggestions for further research close the paper.

2. Modelling Induced Technical Change: Key Features and the Ideal Case

Induced TC does not involve the mere passage of time, but it stems from deliberate research and the innovation decisions of economic agents. These decisions are influenced by a variety of economic factors that are not limited to the changes in relative prices. In other words, induced TC refers to both shifts *of* the production isoquant, and shifts *along* the production isoquant. Policy measures adopted at the local, national or international level play an important role in inducing these technological changes.

As noted by Clarke and Weyant (2002), theoretical work on endogenous TC comprises essentially of two strands: innovation theory and endogenous growth theory.[1] Innovation theory has a microeconomic focus, looks at individual firms and industries, and stresses the incentives and the inefficiencies that result from the failure to share the benefits of the innovation activity. Endogenous growth theory has a macroeconomic focus, and analyses how investment in innovation by private agents can be a source of aggregate economic growth.

Climate change models typically try to combine aspects of both theories. They both stress the importance of knowledge as being a public good and highlight the importance of spillovers, as the incomplete appropriability of the benefits from innovation by private firms creates positive externalities. Spillovers cause underinvestment in innovation, appropriability favours monopoly behaviour. Most theoretical work shows and empirical work confirms that markets do not invest efficiently in innovation and that underinvestment is significant enough to warrant attention by policy makers. This situation is known as “innovation market failures” and should represent an essential aspect of induced TC modelling. However, since these failures are also very complex, rigorous modelling is problematic.

It is nonetheless a useful exercise to consider the main ingredients of induced TC and the various aspects of those innovation market failures. Consideration of these elements will provide a sort of checklist that can be used against the numerical climate-economy models incorporating induced TC that have appeared in current literature. And, above all, it will be useful to identify the main features of the new model that will be described below.

Let us therefore summarize the main features that an ideal model of induced TC should possess (Cf. Clarke and Weyant, 2002):

- Because spillovers are a fundamental source of economic growth, they ought to be incorporated in any model aiming to model the long-term process of TC. A full accounting of spillovers in climate change models is probably asking too much, as they occur within industries, across industries

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[1] This is not to say that theorizing in the field of TC is limited to these two areas only. Innovation and endogenous growth are the two areas most directly relevant for modeling induced TC in climate-economy models.

within countries, and across countries. Clearly, however, to account for intersectoral spillovers a model must be disaggregated by sector, while to account for international spillovers the model must include regional disaggregation.

- The difference between private and social returns associated with innovation activity ought to be acknowledged. Private returns to R&D tend to be appreciably smaller than social returns, in proportions of 20-30% to around 50% according to the empirical study considered.
- Climate models with induced TC must specify the mechanism through which technological change takes place and the way it alters technology. The two mechanisms that have been considered to date are research and development spending and experience building. An advantage of the LbD approach is its simplicity and its reduced calibration requirements relative to the R&D approach. The latter, on the other hand, allows for more room for policy maneuvering (energy/environmental R&D can be subsidized or stimulated) and additional control variables to rely on. Clearly, neither approach is a complete picture of what goes on in reality, so models based on one or the other formulation inevitably miss something important. While no model can closely approximate the real world, the question is whether and at what modeling cost it is possible to account for both varieties of induced TC in a satisfactory manner.

- Besides the choice between the TC – R&D vs. experience drivers– it is also important to specify where and how those drivers actually bring about a change in technology. One distinction is between energy and non-energy sector. Our modeling strategy is to start with induced TC in the energy industry, leaving other TC as exogenous. While, as previously noted, it is true that intersectoral spillovers are important, it would probably be too complex to include the complex interrelations between energy technologies and other techonlogies. The resulting model would be too abstract or too cumbersome to be of any use.

- It may be worthwhile to consider two sources of energy-saving or carbon-saving improvements: decarbonization of energy services and reduction in the energy intensity of economic activities. The second source of TC is more complicated to account for since it involves R&D in sectors other than the energy industry. In the light of the previous remark, modelers may consider assumimg that the evolution of the energy intensity of non-energy technologies is exogenously generated.

- Induced TC is not an all-or-nothing proposition. There are complementary sources of technological advance. One is public sector R&D: publicly financed research will accompany subsidies to private R&D in the form of TC fostering policies. Another source is intersectoral spillovers, already mentioned above. The final source of TC is major innovations and breakthroughs. What do these complementary sources tell us about modeling TC? The implication is that ultimately some technological progress must remain exogenous.

- Technological heterogeneity is an important issue. One potential implication is discontinuous TC. Even if innovation is continuous and incremental in individual technologies, the aggregate production function's response to innovation investment may be non-linear and exhibit discontinuities. What do induced TC models miss when they aggregate technologies? Aggregate models are not able to account for the relevance of emerging technologies and the associated notion that the *allocation*, not only the *absolute level*, of innovation is important. In this respect, models can in principle account for heterogenous technologies. Bottom-up models are best suited for the purpose, whereas top-down models can probably at most distinguish between carbon-intensive and non-carbon-intensive technologies.

- TC is an uncertain process. Uncertainty affects both the rate and direction of TC. It also characterizes the potential for new technologies, that is the extent to which individual technologies will respond to R&D or experience, and the heterogeneity and discontinuities in technology development. Essentially these are "parameter" uncertainties, where the parameters refer to the response of technology to innovative effort or R&D. These are important for modeling and the issue can be addressed by basing that response on expected values of uncertain parameter distributions.

- Innovation takes time and is risky. To the extent that markets have different preferences for risk and time than society preferences, markets will invest in innovation differently than would be socially optimal. Risk aversion and discounting start to play a role when we consider technological heterogeneity, and emerging environmental technologies in particular. This aspect can be then best addressed by bottom-up models which are capable of distinguishing between more mature and newer technologies, and between more and less competitive technologies. The deviation of private risk aversion and time preference from socially preferred values can however also be captured, though in an ad hoc fashion, by bottom-up models that arbitrarily increase the price of R&D resources or adjust the spillover parameter(s)upward.

- Not all investment activity can be captured by models assuming rational behavior. Entrepreneurial spirit can also guide innovation choices. While climate models are likely to face serious difficulties in explicitly accounting for this aspect, they can nevertheless allow for an implication of quasi-rational, or routine-based behavior (as in evolutionary theories): the tendency to undertake research efforts on technologies already in use will bias private sector behavior toward dominant technologies. The effect is therefore similar to the one made in the previous point .

- The very essence of evolutionary economics and historical evidence suggest that technological change evolves with a lot of inertia. It is, in other words, characterized by path dependence. This implies that the rate, and especially the direction, of TC may respond sluggishly to economic stimuli relative to the no frictions standard neoclassical models. More problematically, it also implies that what we do today affects how the economy will respond in the future, i.e. today's actions redirect the future path of TC. Incorporating path dependence into climate models is probably prohibitively complicated, unless perhaps if we resort to adding time lags to the process of technology development.

- A final point refers to technology diffusion as opposed to technology innovation. One obvious way to account for this aspect is the introduction of time lags, as noted above. This strategy does not do justice to the importance and implications of technological diffusion vis-à-vis technology development, but it may represent a reasonable shortcut, an acceptable compromise to make especially in top-down models.

To date the literature on this includes only a few examples of numerical climate-economy models where induced TC is explicitly modelled. We do not intend to review these various models here. We simply mention these models and refer to Table 1 below for a picture showing which of the above ideal aspects each individual model does or does not address.

The models considered are, in the bottom-up energy systems class, versions of the multi-regional MESSAGE-MARKAL model (Messner, 1997; Barreto and Kypreos, 2002a; Criqui, Klaassen, and Schrattenholzer, 2000; Miketa and Schrattenholzer, 2002; Barreto and Kypreos, 2002b, 2004). These are 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, 2004). These models yield the optimal choice between several different technologies using given abatement costs and carbon emission targets. In addition, 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.

Among top-down models, we consider Manne and Richels (1992)'s MERGE model, a regional intertemporal growth model which combines a top-down perspective on the remainder of the economy together with a bottom-up representation of the energy supply sector. In a recent version of the model (Manne and Richels, 2002), one of the previous two electric backstop technologies, the low-cost one, is replaced by a LbD process. Another model which exploits the notion of LbD to endogenize technical change is DEMETER, a global 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; Gerlagh and van der Zwaan, 2004). A macroeconomic (top-down) model is specified and distinguishes 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.

Table 1: Induced TC Features of Some Climate Models

	R&D	Learning	Technology Spillovers	Private/social returns to R&D Opportunity cost of R&D	ITC in non-energy	Energy saving ITC	Carbon saving ITC	Public R&D complementary sources of TC	Technological heterogeneity	Technological uncertainty	Path dependence	Diffusion
R&DICE	yes	no	no	yes	no	no	yes	yes	yes	no[*]	no	no
ETC-RICE	yes	yes	yes	no	yes	no	yes	yes	no	no	no	no
Demeter 1	no	yes	no	no	no	yes	yes	yes	yes	yes	no	no
MERGE	no	yes	no	no	no	yes	yes	yes	yes	no[**]	yes	yes
ERIS/MARKAL/MESSAGE	no	yes	no	no	no	yes	yes	no	no	no	yes	yes
Barreto Kypreos	yes	yes	yes	no	no	yes	yes	no	no	no	yes	yes
Entice	yes	no	no	yes	no	no	yes	yes	no	no	no	no
Demeter 2	yes	yes	no	no	no	yes	yes	yes	yes	no	no	no
Entice-BR	yes	no	no	yes	no	no	yes	yes	yes	no	no	no
WIAGEM	yes	no	yes	yes	yes	yes	no	yes	yes	no	no	no
FEEM-RICE	yes	yes	no	no	no	yes	yes	yes	no	yes	no	no

[*] Uncertainty on technology is however discussed in Nordhaus, W. D. and Popp, D. (1997), “What is the value of Scientific Knowledge? An application to global warming using the PRICE Model”, The Energy Journal, 18-1, 1-44

[**] Uncertainty on technology is however discussed in Manne, A. S. and Richels, R.G. (2003), “Stabilizing Long-Term Temperature”, Working Paper, Stanford University

A recent evolution of DEMETER is the partial equilibrium model of energy supply and demand elaborated by Gerlagh and Lise (2003). DEMETER-2E, as it is called, entertains 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 labour in a technology which produces more and more energy input over time thanks to LbD.

An example of multi-region, multi-sector integrated assessment model with induced TC is Kemfert (2002)'s WIAGEM. In this recursive dynamic computable general equilibrium model, R&D spending affects the productivity of the energy input to the production process. More R&D therefore results in increased energy efficiency. It is to be noticed that R&D enters the model as a flow, whereas most of the other R&D-based models adopt the stock of knowledge, accumulated through R&D investments, as the driver of TC.

Finally, there are models of induced TC that extend the Nordhaus' RICE/DICE family of models. In particular, we include the optimal growth (regional) RICE models elaborated by Buonanno, Carraro, Castelnuovo, and Galeotti (2000) and Buonanno, Carraro and Galeotti (2002). These models, called ETC-RICE, extend Nordhaus and Yang (1996)'s RICE model to allow for a R&D-based formulation of induced TC. In the vein of Goulder and Mathai (2000), in subsequent work Castelnuovo, Galeotti, Gambarelli, and Vergalli (2003) specify a version of the ETC-RICE model that features instead an experience-based type of induced TC.

The new version of the RICE/DICE model (Nordhaus and Boyer, 2000) is used by Nordhaus (2002) to lay out a model of induced innovation brought about by R&D efforts. This study is often quoted by authors to support the conclusion that induced technical change is not very important. Input substitution away from "carbon energy", appears to be more relevant, relative to R&D-prompted innovation. The former reduces carbon intensity twice as much as the latter. Nordhaus compares two versions of DICE, the global counterpart of the RICE model. In one case, output-constrained movements along the production isoquant are considered; in the induced innovation version, capital is exogenous, i.e. there is no investment and no GDP growth, and there is a technology with fixed coefficients between carbon energy on the one hand and a capital-labor combination on the other. It remains to be seen how the results change when, more realistically, optimal economic growth is allowed.

This is precisely what Popp (2004a) does in his ENTICE model. 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. In addition, the author assumes that 50% of other R&D is crowded out by energy R&D, thus raising the opportunity cost of the latter.[2] In a very recent variation dubbed ENTICE-BR, Popp (2004b) extends the ENTICE model to also include an energy backstop technology. Finally, Popp (2004c) uses the ENTICE model to study the role of government subsidies

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[2] As stated, unlike Nordhaus' R&DICE model, Popp's ENTICE model does not impose zero substitution possibilities between energy on the one hand and capital and labor on the other when research is endogenously determined.

to climate-friendly R&D. These are found to significantly increase R&D, but to have little effect on the climate itself.

As can be seen from this brief overview – and above all from Table 1 in the Appendix – existing models fall short of addressing the ideal features of induced TC that were outlined at the beginning of this section. This is why, in the next section, we will present a new model of induced TC that we hope will prove more satisfactory than previous ones.

3. The FEEM-RICE Model

The FEEM-RICE model which we present hereafter is an extended version of the so-called RICE 99 model by Nordhaus and Boyer (2000). RICE 99 is a Ramsey-Koopmans single sector optimal growth model suitably extended to incorporate the interactions between economic activities and climate. There is one such model for each of the eight macro regions into which the world is divided: USA, Other High Income countries (OHI), OECD Europe (Europe), Russia and Eastern European countries (REE), Middle Income countries (MI), Lower Middle Income countries (LMI), China (CHN), and Low Income countries (LI).[3]

3.1 The Model General Structure

Within each region a central planner chooses the optimal paths of two control variables, fixed investment and carbon energy input, so as to maximize welfare, defined as the present value of per capita consumption. The value added created via production (net of climate change) according to a constant returns technology is used for investment and consumption, after subtraction of energy spending. The technology is Cobb-Douglas and combines the inputs from capital, labour and carbon energy together 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.

Compared to the previous RICE 96 model of Nordhaus and Yang (1996), this specification contains a more detailed regional disaggregation of the world. However, the main novelty of the new model is the introduction of an energy input. Because carbon dioxide is the only greenhouse gas considered, the input is directly measured in carbon units. The carbon energy can be thought of as the energy services derived from fossil-fuel consumption (e.g. derived from coal, petroleum, and natural gas). An implication of the introduction of this crucial input is that its market must be specified. While demand for carbon energy stems naturally from the first principles of the entrepreneur (or social planner)'s problem, a supply curve for this input is introduced somewhat ad hoc, and it allows for limited (albeit huge) long-run supplies at rising costs. Because of the optimal-growth framework, carbon-energy is efficiently allocated across time, which implies that low-cost carbon resources have

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[3] The countries belonging to each one of the macro-regions indicated above are listed in Nordhaus and Boyer's book. We refer to it as RICE 99 because it was made available by the authors through the web in 1999.

scarcity prices (Hotelling rents) and that carbon-energy prices rise over time.[4] The carbon-energy input is modelled as being the source of GHG emissions in the production process, and the cumulated emissions (i.e. concentrations) cause an increase in the worldwide temperature. To close the circle, global temperature (relative to pre-industrial levels) is responsible for the wedge between gross output and net of climate change effects.

Control variables are determined within a game-theory framework. Each country plays a non-cooperative Nash game in a dynamic setting which yields an Open Loop Nash equilibrium. In each region the planner maximizes its utility subject to the individual resource and capital constraints and the climate module for a given emission production of all the other players.[5] Kyoto-type international environmental agreements can be easily accommodated by adding a constraint stating that regional emissions cannot exceed a given upper limit. It is also possible to use the model in the presence of international emission trading. In this case the standard identity between sources and uses of resources specifies that output is used for consumption and investment, to which proceeds or sales from net imports of permits are be added.

Under the possibility of emission trading, the sequence whereby an equilibrium à la Nash is reached must be revised as follows. Each region maximizes its utility subject to the individual resource and capital constraints, the emission target constraint, and the climate module for a given optimal set of strategies of all the other players and a given price of permits (in the first round this is set at an arbitrary level). When all regions have made their optimal choices, the overall net demand for permits is computed at the given price. If the sum of net demands in each period is approximately zero, a Nash equilibrium is obtained; otherwise the price is revised in proportion to the market unbalance and each region's decision process starts again. The price of a unit of tradable emission permits is expressed in terms of the numéraire output price and there is an additional policy variable, i.e. the net demand for permits.

3.2 The Treatment of Technical Change in FEEM-RICE

The original RICE 99 model specifies the following production function (*n* indexes regions, *t* time periods):

$$(1) \qquad Q(n,t) = A(n,t)[K_F(n,t)^{1-\gamma-\alpha_n} CE(n,t)^{\alpha_n} L(n,t)^{\gamma}] - p_n^E CE(n,t)$$

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[4] Thus the new version of RICE incorporates a treatment of energy supply, which is seen as an exhaustible resource. Another addition is a revised and extended climate module which now includes a three-reservoir model calibrated to existing carbon-cycle models. The equations of the original model retained in FEEM-RICE are reported in the Appendix.

[5] As there is no international trade in the model, regions are interdependent through climate variables only. The absence of trade in goods among regions is an important limitation of all regional versions of RICE. We plan to address this issue in the near future.

where Q is output (gross of climate change effects), A the exogenously given level of technology and K_F, CE and L are the inputs from physical capital, carbon energy and labour, respectively, and p^E is fossil fuel price. Carbon emissions are proportional to carbon energy, that is:

$$(2) \qquad E(n,t) = \zeta(n,t)\, CE(n,t)$$

where E is industrial CO_2 emissions, while ς is an idiosyncratic carbon intensity ratio which also exogenously declines over time.[6] In this way, Nordhaus and Boyer (2000) make the assumption of a gradual, costless improvement of the green technology gained by the agents as time goes by. For the reasons discussed in the previous section, we consider this treatment of TC inadequate for a model designed to study issues related to climate change.

In previous work (see Carraro and Galeotti, 2002, 2004), we explored the consequences of two ways of endogenising the process of TC. First, in the "Learning-by-Researching" model, an endogenously generated stock of knowledge affected both factor productivity and the emission-output ratio (there was no energy input and emissions were linked directly to unabated output). Knowledge was the result of intertemporal optimal accumulation of R&D, where R&D is a choice variable describing a new investment opportunity in addition to consumption and physical investment. Secondly, in the "Learning-by-Doing" model, knowledge, conceived as a stock of experience, was approximated by installed capacity, in turn represented by physical capital accumulating through periodic investment. Again, this stock of experience affected both factor productivity and the emission-output ratio. This LbD approach entailed one less choice variable with respect to the R&D approach, but no further claim on resources created or on consumption and physical investment??, was made.

The main shortcomings of these formulations derive chiefly from the absence of an explicit energy module in the core model,. The absence of an energy production factor made it impossible to capture the effects of TC on the energy intensity of production. Moreover, the "Learning-by-Researching" and the "Learning-by-Doing" features of TC were modelled separately, whereas it would appear appropriate to include both sources of TC in the same model. Finally, approximating the stock of experience with physical capital was not very accurate, but the presence of the abatement rate as a model control variable made it difficult, if not impossible, to account for cumulated abatement efforts as the force driving the learning process.[7]

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[6] Throughout the paper we will indifferently refer to 'environmental' technology or 'green' technology when mentioning the time-varying coefficient ς.

[7] Recall that cumulated abatement was the variable used by Goulder and Mathai (2000) in the LbD version of their cost minimization model. The absence of the energy input, and therefore of an explicit price, made it also impossible to carry out any policy analysis on energy or carbon taxation.

In the newly developed model, the above shortcomings have been explicitly addressed and solved. In FEEM-RICE, we consider simultaneously both LbD and LbR as inputs of induced TC and we focus on the effects of TC on both the energy intensity of production and the carbon intensity of energy use. These features of the model allow us to address both energy-saving and energy-switching issues.

To clarify the importance of this two input-two output specification of TC, it is perhaps useful to refer to a time-honoured concept in environmental economics, namely Kaya's identity. In its generalized form, it can be represented as follows. Let $i = 1,.., I$ be the various GHG emissions, E, $j = 1,.., J$ be the various energy sources, S, $k = 1,.., K$ be the sectors in the economy, Y, and $n = 1,.., N$ be the countries in the world. Then, the world emissions of GHGs, E_t, can be decomposed as follows:

$$(3) \qquad E_t = \sum_n \sum_k \sum_j \sum_i \left(\frac{E_{ijkn}}{S_{jkn}} \right) \left(\frac{S_{jkn}}{Y_{kn}} \right) \left(\frac{Y_{kn}}{Y_n} \right) \left(\frac{Y_n}{L_n} \right) L$$

where L is total world population. Hence, world emissions are a product of two 'forces': techno-economic forces, given by carbon intensity (E/S) and energy intensity (S/Y), and socio-economic forces, given by output composition (Y_k/Y) and output levels (Y/L), as well as demographic dynamics L. Similarly to the RICE 99 model, FEEM-RICE has a single economic sector and a single energy source, namely carbon energy, CE, and endogenous emission are limited to industrial CO_2. Thus, the relationship stated in (3) can be rewritten for our specific case as:

$$(3') \qquad E_t = \sum_n \left(\frac{E_n}{CE_n} \right) \left(\frac{CE_n}{Y_n} \right) \left(\frac{Y_n}{L_n} \right) L$$

In addition to socio-economic forces – income and population – which are commonly modelled in endogenous growth models, our model allows us to endogenise both techno-economic forces, namely energy and carbon intensity[8].

The main novelty of our new formulation hinges on the relationship between TC and both Learning-by-Researching and Learning-by-Doing *at the same time*. We assume that innovation is brought about by R&D spending which contributes to the accumulation of the stock of existing knowledge.[9] In addition to this Learning-by-Researching effect, the model also accounts for the effect of Learning-by-Doing, now modelled in terms of cumulated abatement efforts. Thus, our index of technical change *TP* (Technical Progress) is defined as follows:

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[8] As in most models in current literature, population is exogenously determined. An important future development would be that of endogenising demographic changes, including migration flows across regions.

[9] It has to be pointed out that analysing R&D expenditure is complicated because (i) R&D is not always amenable to measurement and (ii) there is a great deal of uncertainty in the ability of R&D to generate technological change. These words of caution should be therefore borne in mind by the reader when going through the paper.

(4) $TP(n,t) = f[ABAT(n,t), K_R(n,t)]$

The variable *TP* is assumed 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). More specifically *TP* is formulated as a convex combination of the stocks of knowledge and abatement:

(5) $TP(n,t) = ABAT_s(n,t)^c K_R(n,t)^d$

where $K_R(n,t)$ is the stock of knowledge and $ABAT_S$ represents the stock of cumulated abatement, in turn defined as:

(6) $ABAT_S(n,t+1) = \delta_A ABAT(n,t) + (1-\delta_B) ABAT_s(n,t)$

$ABAT_F$ the abatement flow, δ_{A} the learning factor, i.e. the amount of abatement which translates into a learning experience, and δ_{B} being the depreciation rate of cumulated experience. The stock of knowledge $K_R(n,t)$ accumulates in the usual fashion:

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

where δ_{R} is the depreciation rate of knowledge.

How does Technical Progress affect the rest of the economy? As seen in equation (1), the factors of production are labour, physical capital and carbon energy. Let us first consider the effect of technical progress on factor productivity (the energy-intensity effect). In our model, the production function (1) is replaced by the following equation:

(1’) $Q(n,t) = A(n,t)[K_F(n,t)^{1-\alpha_n(TP)-\gamma} CE(n,t)^{\alpha_n(TP)} L(n,t)^{\gamma}] - p_e(n,t)\, CE(n,t)$

where:

(8) $$\alpha_n = \alpha_n[TP(n,t)] = \frac{\beta_{1n}}{2-\exp[-\beta_{0n} TP(n,t)]}$$

and β_{0n} and β_{1n} are region specific parameters. Thus, an increase in the endogenously determined Technical Progress variable reduces – *ceteris paribus* – the output elasticity of the energy input. It is worth noting that the output technology in (1’) also accounts for a fraction of TC which evolves exogenously, thus following an explicit suggestion by Clarke and Weyant (2000) and the discussion in the previous section.

Let us now turn to the effect of Technical Progress on the carbon intensity of energy consumption. As shown in (2), effective energy results from both fossil fuel use and (exogenous) TC in the energy sector. In our model, we assume that *TP* serves the purpose of reducing, *ceteris paribus,* the level of carbon emissions. More precisely, equation (2) is replaced by:

$$\text{(2')} \qquad E(n,t) = h[CE(n,t), TP(n,t)] = \varsigma(n,t)\left\{\frac{1}{2-\exp[-\psi_n TP(n,t)]}\right\} CE(n,t)\,,$$

Here an increase in *TP* progressively reduces the amount of emissions generated by a unit of fossil fuel consumed. Finally, we recognize that R&D spending absorbs some resources, that is:

$$\text{(9)} \qquad Y(n,t) = C(n,t) + I(n,t) + R\,\&\,D(n,t) + p(t)NIP(n,t)$$

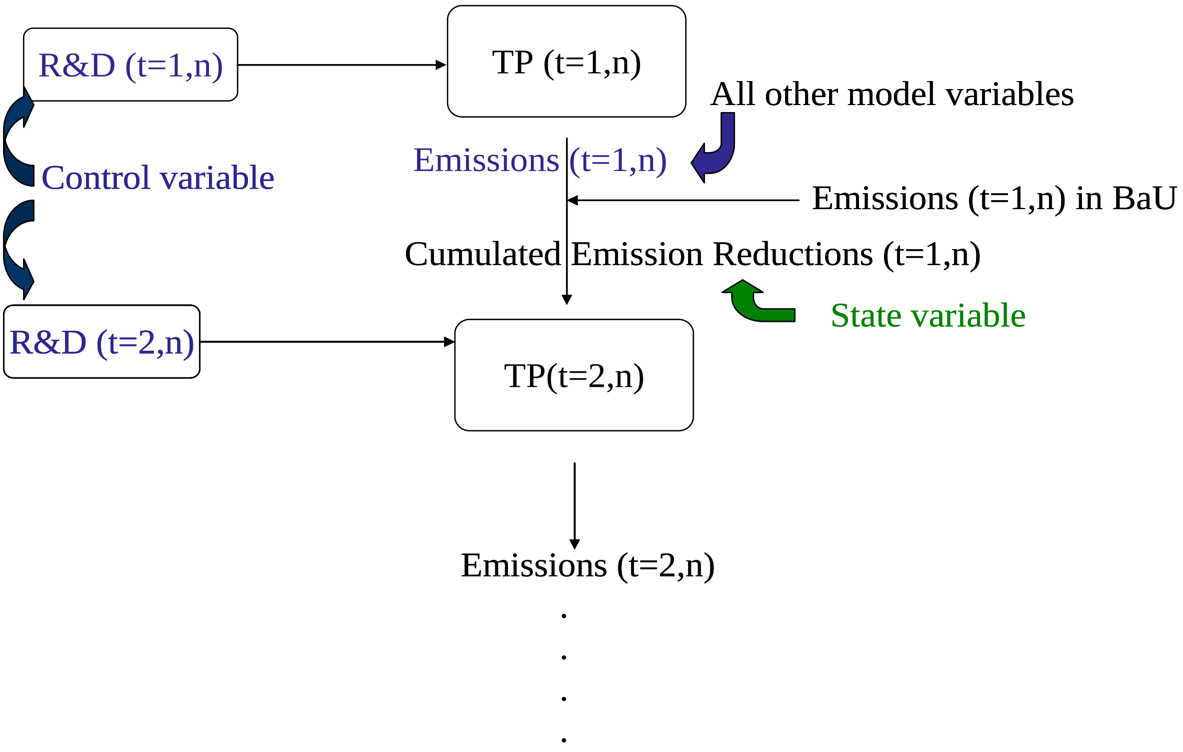
where Y is output net of climate change effects, C is consumption, I gross fixed capital formation, *R&D* research and development expenditures, p^P is the equilibrium price on the emissions rights, and *NIP* is the net demand for permits.

It may be noted that there is only one type of R&D effort that helps both to save energy and switch the energy needs away from fossil fuels. Although in principle it could be argued that the innovation activity resulting in technologies using less energy is different from the innovation activity resulting in the development of clean energy technologies, in practice accounting for this fact in highly aggregate models like FEEM-RICE is probably too complicated to be worth considering . Finally, “red” TC – i.e. purely productivity-enhancing TC (captured by the *A* index in the production function) – has been kept exogenous, albeit time varying, though we believe that “red” R&D can also be endogenised (this is something we plan to do in future work).

To further clarify our formulation of induced TC, let us highlight the dynamic interrelationships between the different variables and their role in the model. First of all, let us notice that R&D is a control variable, whereas stock of knowledge and cumulated abatement are state variables. Therefore, R&D can be used strategically by regulators in each region of the model, whereas LbD is an output of the regulator’s strategic behaviour (which also includes the optimal path of other control variables, e.g. investment and demand for permits). This is quite clear at the beginning of the game (see Figure 1). At stage one, only LbR through R&D investments occurs. This modifies TP (which evolves both endogenously and exogenously) and yields some amount of abatement, i.e. some abatement experience which becomes LbD. Both LbR and LbD then affects TP in the subsequent stages.

In short, the fundamental driver of technical progress is basic research and R&D investments. This induces knowledge accumulation and experience in emission abatement in various regions of the world. In turn, these variables move technology towards a more environment-friendly dynamic path.

Figure 1. Effects of LbR and LbD on Technical Progress.



Our quite general solution to account for induced TC comes obviously at a cost. Basically, little information to calibrate the model parameters is available.[10] The best strategy we can follow is to guess-estimate the critical TC parameters and then compare the output of the models with data on observed variables. At the same time, we perform an extensive sensitivity analysis on the parameters of our formulation of induced TC . This is what will be shown in the next section.

4. Results and Sensitivity Analysis

In this section, we present the outputs of the model in its basic calibration and the results of our sensitivity analysis. The basic calibration is obtained by using the parameters of the original RICE 99 models and by assuming that *c* and *d* are both equal to 0.5. Sensitivity analysis is then performed by assuming $d = 1-c$ and varying *c*. Through these two parameters we control for the role of researching vs. learning in the process of TC, whereas through the parameters β_o and ψ we control for the impact of technical progress on energy intensity and carbon intensity respectively (see Figure 2).

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[10] For this reason we attribute some parameters the same numerical value for all regions.

Figure 2. The Crucial Parameters of the Induced TC Model.

The initial values of the main parameters are shown in Table 2 below:

Table 2. Initial parameter values

Parameter	β_o	δ_P	δ_A	δ_B	ψ	c	d
Value	0.8	0.05	0.1	0.05	0.8	0.5	1-c

Extensive sensitivity analysis has been performed on the parameters β_0, ψ and *c*. Results are shown in Figures A.1-A.12 (see the Appendix) for three scenarios:

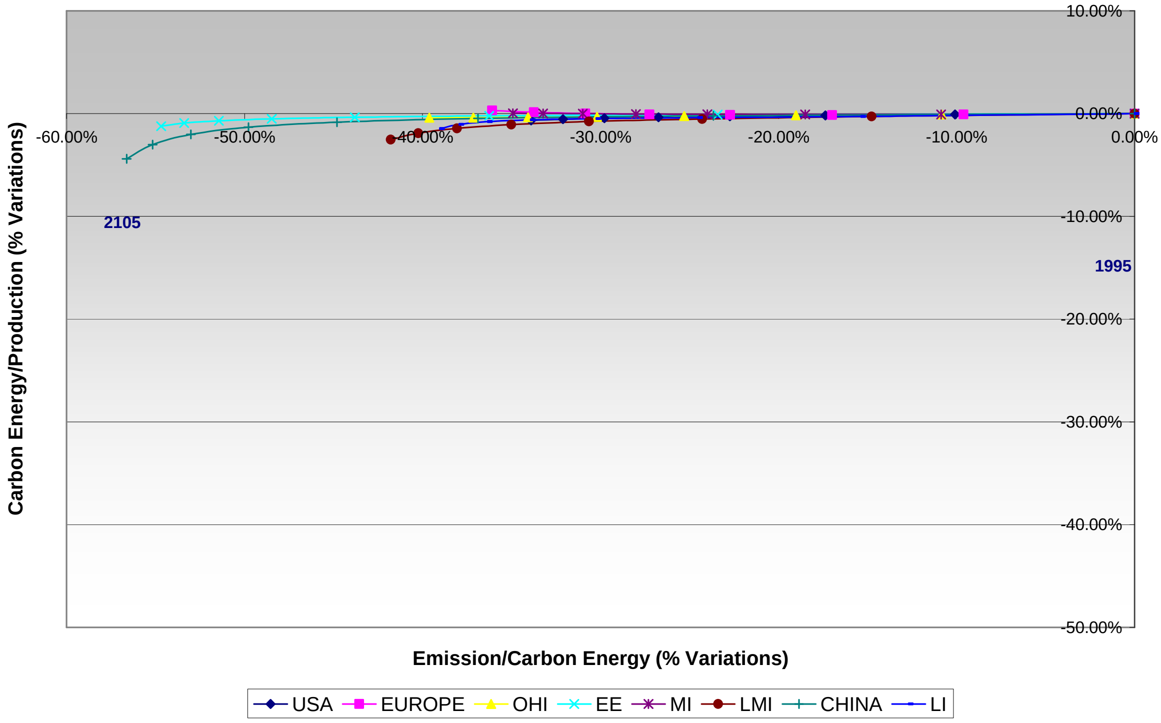
- the business as usual (BaU) scenario in which no climate policy intervention is envisaged;
- the 550 ppmv stabilisation scenario in which CO_2 concentrations are stabilised by adopting domestic measures only (including R&D investments); and
- the 550 ppmv stabilisation scenario in which all countries/regions achieve the stabilisation target by also participating in a global emission trading market.

There is no special reason to choose these three scenarios rather than other ones. In addition to the standard business as usual scenario – that proves very helpful in calibrating the model – we analyse two 550 ppmv stabilisation scenarios in order to test how the model reacts to different policies designed to achieve a fairly ambitious climate objective. In the first stabilisation scenario, the goal is to analyse the role of technical change in the absence of emission trading (a flexibility mechanism that was already shown to be a substitute for technical change in achieving climate stabilisation targets. See Buonanno *et al.*, 2000, 2002). In the second stabilisation scenario, the goal is to check the different incentives to innovation provided by the presence of global emission trading, i.e. of low cost abatement opportunities for developed countries.

Before discussing the outcomes of the sensitivity analysis, let us present the main features of the model in the business as usual scenario. To do that in a very concise way, the dynamics of energy intensity and carbon intensity is shown in the same diagram. Figure 3 shows the dynamics of these two variables in the case of exogenous technical change.[11] Figure 4 shows the case in which technical change in endogenised according to the two input–two output formulation presented above. The time horizon is 1995-2105.

The difference between the two cases is clear and relevant. When technical change is exogenous, almost all emission reductions take place through a reduction of carbon intensity (fuel switching). By contrast, when technical change is endogenous, both carbon intensity and energy intensity are reduced over time, thanks to the accumulation of knowledge and to the learning by doing effect. Therefore, the version of the model with endogenous technical change better captures the dynamic path towards technologies which consume less energy and above all less polluting energy.

Figure 3. Carbon Intensity vs. Energy Intensity.
Exogenous technical change in the BaU scenario



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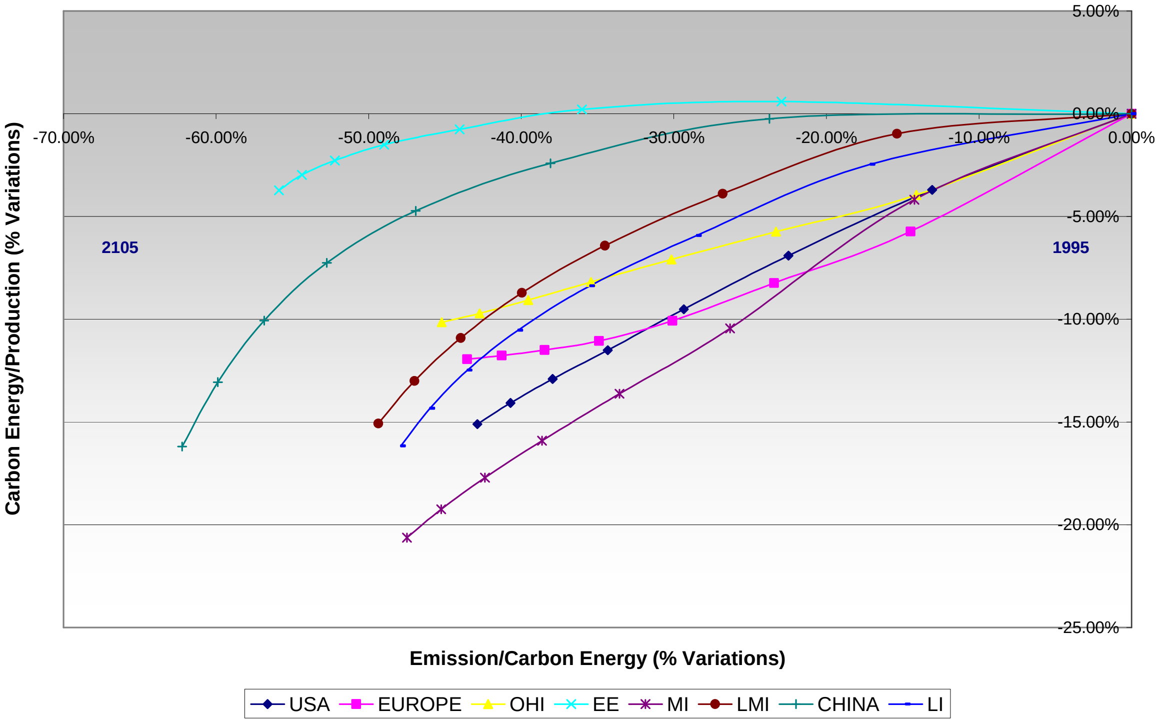
[11] The exogenous component of technical change is the one calibrated by Boyer and Nordhaus for the RICE 99 model, but modified so as to play a weaker role when coupled with our endogenous component of TC.

Figure 4. Carbon Intensity vs. Energy Intensity.
Endogenous technical change in the BaU scenario



As for regional differences, let us focus on the model with endogenous technical change, which is the one that produces more satisfactory results. Notice that in Eastern Europe and China the main contribution to GHG emission reduction comes from fuel-switching rather than from energy-saving. The opposite holds for Middle Income countries, and for the US above all. In Europe and Japan (the main country in Other High Income countries category) emission reductions are more difficult. Smaller emission reductions can be achieved – relative to the other countries – and the curves first suggest that fuel-switching investments can actually reduce emissions, but then energy-saving becomes the dominant strategy.

As a further contribution to the understanding of the features of our model of induced TC, let us analyse the contribution of the different components of technical change to the reduction of aggregate carbon intensity (see Table 3).

Table 3. Contributions of Different TC Components to Lowering Carbon Intensity

		1995	2105
Carbon Intensity Index	Exogenous Tech. Change	1	0.56
	Endogenous LbR based Tech. Change	1	0.42
	Endogenous LbR and LbD based Tech. Change	1	0.34

If only exogenous technical change is assumed, carbon intensity is going to be reduced by 44% in the next century. By adding the R&D based component of endogenous technical change, the total reduction achieves -58% with respect to the 1995 level. Finally, the contribution of both LbR and LbD leads, in our formulation, to a total reduction of carbon intensity of –66%.

It is also interesting to notice that the model strongly reacts to the imposition of climate targets (see Figure 5 and 6). If a 550 ppmv stabilisation target has to be achieved through domestic abatement and technical change, initially fuel-switching possibilities are exploited in all countries, but then the only way to achieve the target is to increase energy-efficiency.

This is however less true in the case of endogenous technical change than in the case of exogenous technical change. With this latter formulation the model shows some extreme dynamic paths. In the BaU scenario without climate targets, if TC is exogenous, almost all emission reductions are achieved through fuel-switching. With an ambitious climate target and exogenous TC, an opposite path is revealed, i.e. most emission reductions must be achieved through an increase in energy-efficiency, in particular in the long-run.[12]

The model with endogenous technical change shows a more balanced dynamics of energy intensity and carbon intensity. Both fuel-switching and energy-saving are occurring in all countries, and fuel-switching plays a more important role than in the case of exogenous technical change. In addition, China and Eastern countries must provide a much more relevant contribution to emission reduction (let us stress that the stabilisation scenario is a normative one and is used to analyse our new formulation of TC and not to derive policy recommendations).

Figure 5 and 6 confirm the difficulty experienced by Europe and Japan in reducing emissions. Indeed, the first best solution computed by the model allocates emission reduction across the world regions in an optimal way, i.e. efficiency is achieved through marginal abatement cost equalisation. Therefore, the smaller abatement in Europe and Japan indicates that abatement costs are higher in these two regions than in the other world regions. This is another indicator that confirms the good quality of our formulation of induced TC and of its calibration.

To further check the quality of the model we analyse the results of the sensitivity analysis that has been performed on the main parameters of the model. These results are shown in Figures A.1-A.12 in the Appendix. Let us summarise the main conclusions.

An increasing effect of technical change on energy saving (an increase of the parameter β_0) has the expected consequences. In particular, temperature and carbon concentration decrease with β_0 in the three scenarios (see Figure A.1 and A.2).

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[12] Recall that the exogenous component is based on the one calibrated by Boyer and Nordhaus for RICE 99, but modified as mentioned in the previous footnote.

Figure 5. Carbon Intensity vs. Energy Intensity.
Exogenous technical change in a 550 ppmv optimal stabilization run.

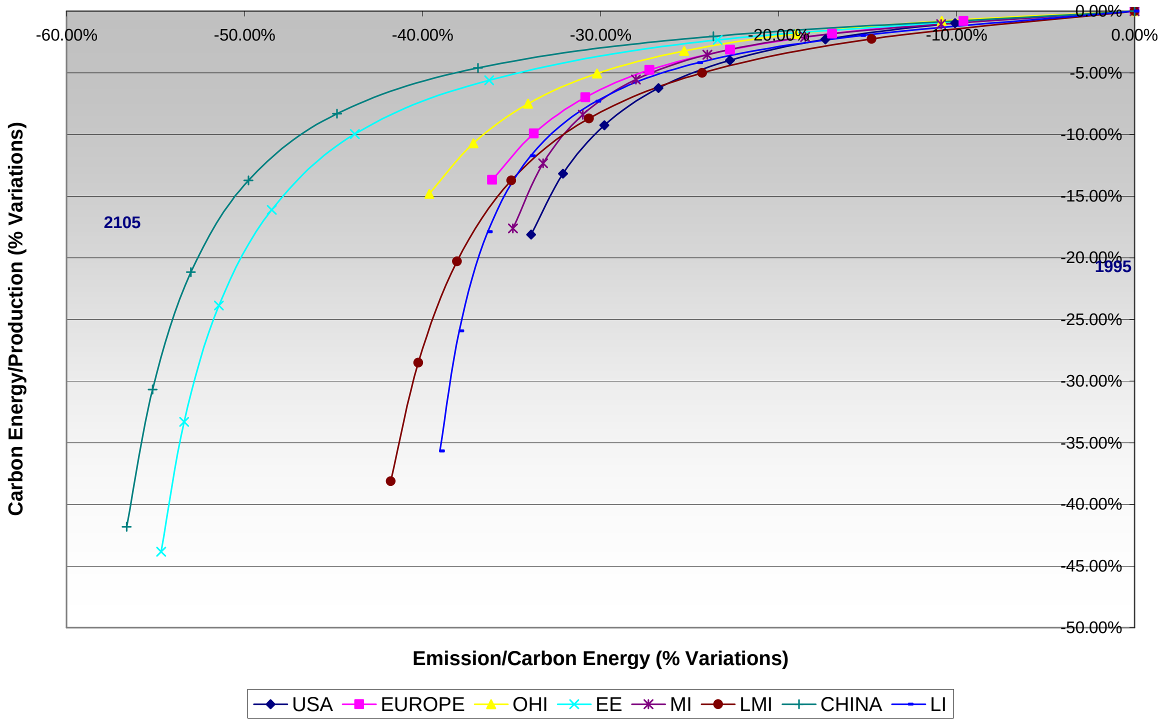
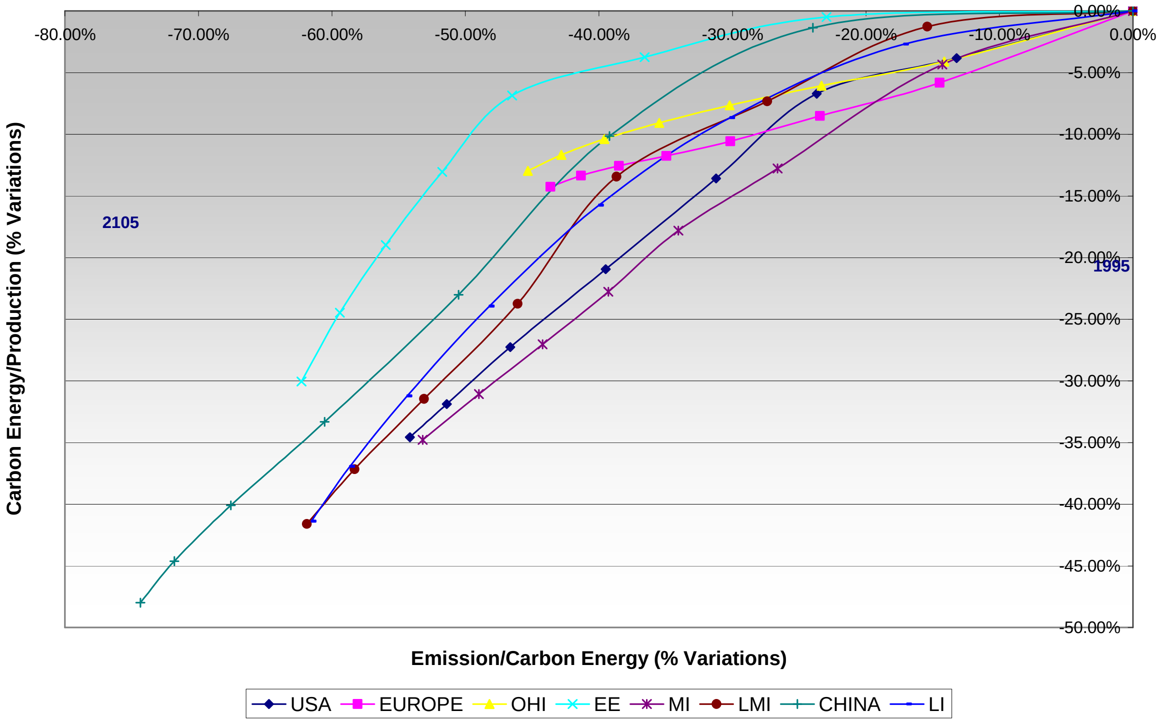


Figure 6. Carbon Intensity vs. Energy Intensity.
Endogenous technical change in a 550 ppmv optimal stabilization run



A small difference across scenarios emerges as far R&D investments and TC are concerned. In the BaU, an increase of β_0, i.e. a more effective R&D, leads to an increase in R&D investments. The opposite occurs for high values of β_0 when a stabilisation target is imposed (see Figure A.3). The explanation goes as follows. In the model R&D plays a twofold role. It fosters economic growth and reduces the impact of economic growth on the environment. When induced TC is exogenous, only the first effect is strategically chosen by the regulator. Therefore, an increase of β_0 gives the regulator more freedom to use R&D for growth purposes. When the effect of TC on emissions is endogenous, and there is a stabilisation target, the regulator wants to minimise the adverse effects that R&D investments may have on emissions through economic growth. Therefore, the optimal strategy is to reduce R&D when its effectiveness on energy-saving becomes large (i.e. for high values of β_0).

In the third scenario, where global emission trading is allowed for, the price of permits tends to become lower as β_0 increases (see Figure A.4). The reason is that an increase of β_0 increases the effectiveness of TC in increasing energy efficiency, thus reducing energy consumption and GHG emissions. As a consequence, the world demand for permits becomes smaller and the equilibrium permit price is lower.

The regularity and consistency of the responses of the model to relevant changes in the parameter β_0 suggest that its structure and calibration are robust and coherent.

The same conclusion can be achieved by looking at the effects of changes in the parameter ψ, which controls for the impacts of induced TC on carbon intensity (see Figure A.5-A.8). Again temperature and carbon concentration become lower as ψ increases, i.e. as TC becomes more effective in inducing fuel-switching and therefore in lowering carbon intensity. However, notice how the effects are much smaller than in the case of changes in β_0, i.e. in the effects on energy intensity. This shows again that the model structure is such that energy saving is more effective than fuel switching in reducing emissions, at least in the long run (results are shown for the year 2105).

The tiny impacts of changes in the parameter ψ explain why the dynamics of R&D investments are different in the case of changes in ψ than in the case of changes in β_0 (see Figure A.7). In the BaU case there are almost no changes in R&D expenditure, whereas in the two stabilisation scenarios there is a very small increase in R&D expenditure. The reason is that a positive change of ψ induces a very modest improvement of the carbon intensity ratio. Therefore, despite the emission increase through growth effects, the regulator finds it optimal (i.e. necessary) to slightly increase R&D investments to stabilise GHG emissions.

Finally, the permit price is slowly declining with positive changes of the parameter ψ, at least in the long run (see Figure A.8). The reason is a small reduction of the demand for permits induced by the slightly enhanced performance of technical change in reducing GHG emissions.

The last part of our sensitivity analysis concerns the parameters c and d that control for the relative importance of LbR vs. LbD in fostering technical change. When c increases, i.e. when the LbR component becomes relatively more important in shaping the dynamics of technical change, both and temperature and carbon concentration decrease in the BAU scenario (see Figure A.9 and A.10). This is partly the case in the two stabilisation scenarios, where carbon concentrations and temperature first slightly increase and then decrease. However, in all cases the minimum concentration and temperature level is achieved for large values of *c*, which confirms that LbR is the fundamental driver of technical change in the model, whereas LbD is a very relevant side effect.

For this same reason, R&D investments increase with *c*, i.e. the more LbR is effective, the more the regulator finds it optimal to invest in R&D (see Figure A.11). However, for very large values of *c*, the regulator can reduce its R&D investments given their large effectiveness in fostering technical progress.

Finally, the dynamics of the permit price reflect the impact of R&D and technical progress on the demand for permits (see Figure A.12). When *c* becomes large, R&D investments become more effective in reducing both energy and carbon intensity, i.e. GHG emissions. As a consequence, regulators in various countries reduce their net demand for permits, thus negatively affecting the permit price.

5. Concluding Remarks

The model presented in this paper is an extension of the FEEM-RICE model in which both Learning by Researching and Learning by Doing are explicitly accounted for through an index of Technical Progress. Moreover, our index of Technical Progress affects both the relationship between the variables of the macro-dynamic model and energy intensity and the one with carbon intensity. More precisely, R&D investments induce the developments of environment-friendly technologies through which GHG emission abatement can be undertaken. At the same time, these abatement activities increase experience and produce learning, which enhance the effectiveness of environment-friendly technologies in reducing GHG emissions. The emission reduction takes place through both energy-saving and fuel-switching effects. In the model, the different components of technical change have a differentiated impact on both effects.

The FEEM-RICE model with the two input-two factor specification of technical change described in previous sections has been used to analyse the optimal dynamic paths of investments, R&D expenditure, carbon concentrations and temperature in three different scenarios: the BaU scenario and two stabilisation scenarios. In the second stabilisation scenario, permit trading was allowed for and the optimal demand for permits in various regions of the world has been computed. The goal was not normative, i.e. it was not to discuss optimal abatement trajectories, or what climate policy should do, but rather positive, i.e. to understand how the model reacts when either different targets are imposed, or different policy instruments are used.

In addition, an extensive sensitivity analysis with respect to the main parameters of our 2x2 formulation of technical change has been carried out. This sensitivity analysis has shown the robustness of the model when parameters are changed around the calibrated values and the consistency of the results when large changes in the parameters are imposed.

The next steps in our research agenda can be described as follows. First, we would like to look more closely at the opportunity cost of R&D. Second, it would be useful to extend the model in order to include a non-energy sector, thus making it possible to have a better representation of fuel switching dynamics. Third, the possibility of a growing effectiveness of carbon sequestration technologies could be accounted for in the model. Finally, and most importantly, stochastic components of the process of technical change – and therefore uncertainty – must be modelled to develop a more realistic analysis of climate policy.

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Appendix

1. Other Model Equations

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 99 model.

In each region, *n*, there is a social planner who maximizes the following utility function (*n* indexes the world's regions, *t* are 10-year time spans):

(A1) $$W_n = \sum_t U\left[C_n(t), L_n(t)\right]R(t) = \sum_t L_n(t)\left\{\log\left[c_n(t)\right]\right\}R(t)$$

where the pure time preference discount factor is given by:

(A2) $$R(t) = \prod_{v=0}^{t}\left[1+\rho(v)\right]^{-10}$$

and the pure rate of time preference $\rho(v)$ is assumed to decline over time.

The maximization problem is subject to:

(A3) $$Q_n(t) = \Omega_n(t)\left\{A_n(t)K_{nF}(t)^{1-\gamma-\alpha}L_n(t)^{\gamma}CE_n(t)^{\alpha} - p_n^E(t)CE_n(t)\right\}$$

(A4) $$c_n(t) = \frac{C_n(t)}{L_n(t)}$$

(A5) $$K_{nF}(t+1) = (1-\delta_K)K_{nF}(t) + I_n(t+1)$$

(A6) $$Q_n(t) = C_n(t) + I_n(t)$$

(A7) $$E_n(t) = \varsigma_n(t)CE_n(t)$$

(A8) $$p_n^E(t) = q(t) + markup_n^E$$

(A9) $$M_{AT}(t+1) = \sum_n\left[E_n(t) + LU_j(t)\right] + \phi_{11}M_{AT}(t) + \phi_{21}M_{UP}(t)$$

(A10) $$M_{UP}(t+1) = \phi_{22}M_{UP}(t) + \phi_{12}M_{AT}(t) + \phi_{32}M_{LO}(t)$$

(A11) $$M_{LO}(t+1) = \phi_{33}M_{LO}(t) + \phi_{23}M_{UP}(t)$$

(A12) $$F(t) = \eta\left\{\log\left[M_{AT}(t)/M_{AT}^{PI}\right] - \log(2)\right\} + O(t)$$

(A13) $$T(t+1) = T(t) + \sigma_1\left\{F(t+1) - \lambda T(t) - \sigma_2\left[T(t) - T_{LO}(t)\right]\right\}$$

(A14) $$\Omega_n(t) = \frac{1}{1+\theta_{1,n}T(t)+\theta_{2,n}T(t)^2}$$

List of variables:

W = welfare

U = instantaneous utility

C = consumption

L = population

R = discount factor

Q = production

Ω = damage

A = productivity or technology index

K_F = capital stock

CE = carbon energy

p^E = cost of carbon energy

I = fixed investment

E = carbon emissions

M_{AT} = atmospheric CO_2 concentrations

LU = land-use carbon emissions

M_{UP} = upper oceans/biosphere CO_2 concentrations

M_{LO} = lower oceans CO_2 concentrations

F = radiative forcing

T = temperature level

q = costs of extraction of industrial emissions

List of parameters:

α, γ = parameters of production function

δ_K = rate of depreciation of capital stock

ζ = exogenous technical change effect of energy on CO_2 emissions (carbon intensity)

$\phi_{11}, \phi_{12}, \phi_{21}, \phi_{22}, \phi_{23}, \phi_{32}, \phi_{33}$ = parameters of the carbon transition matrix

η = increase in radiative forcing due to doubling of CO_2 concentrations from pre-industrial levels

σ_1, σ_2 = temperature dynamics parameters

λ = climate sensitivity parameter

$markup^E$ = regional energy services markup

θ_1, θ_2 = parameters of the damage function

M_{AT}^{PI} = pre-industrial atmospheric CO_2 concentrations

O = increase in radiative forcing over pre-industrial levels due to exogenous anthropogenic causes

ρ = discount rate

T_{LO} = lower ocean temperature

2. Sensitivity Analysis

Figure A.1. Temperature in degree C above pre-industrial levels in 2105 for a Growing Energy-Saving Effect

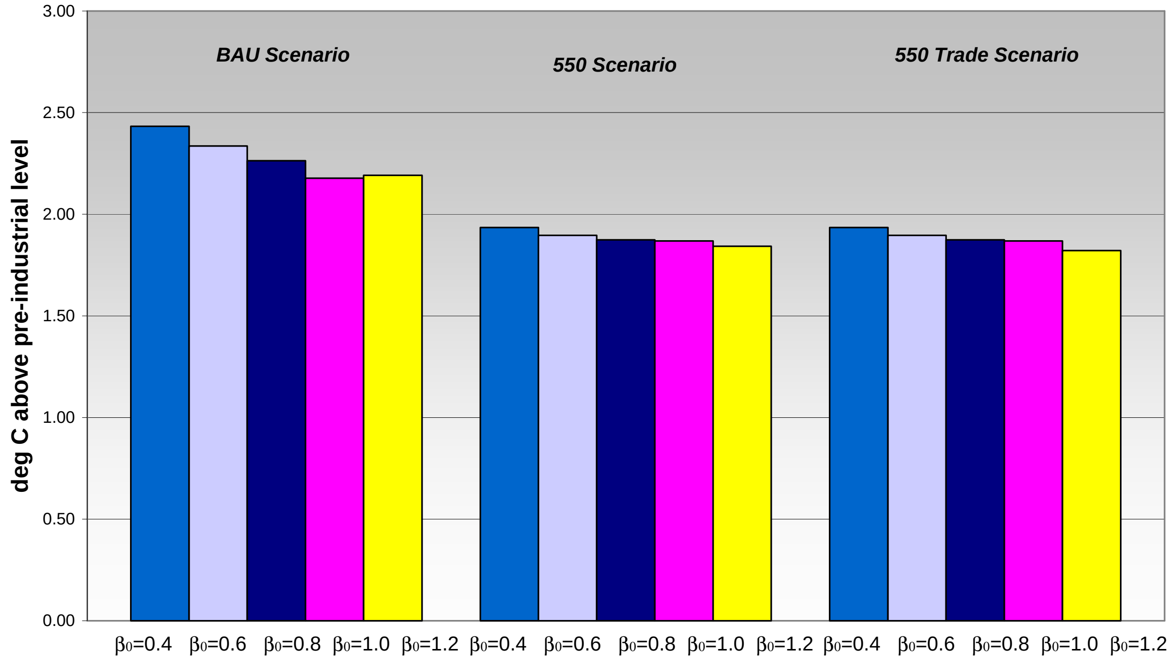


Figure A.2. Carbon Concentration Levels in 2105 for a Growing Energy-Saving Effect

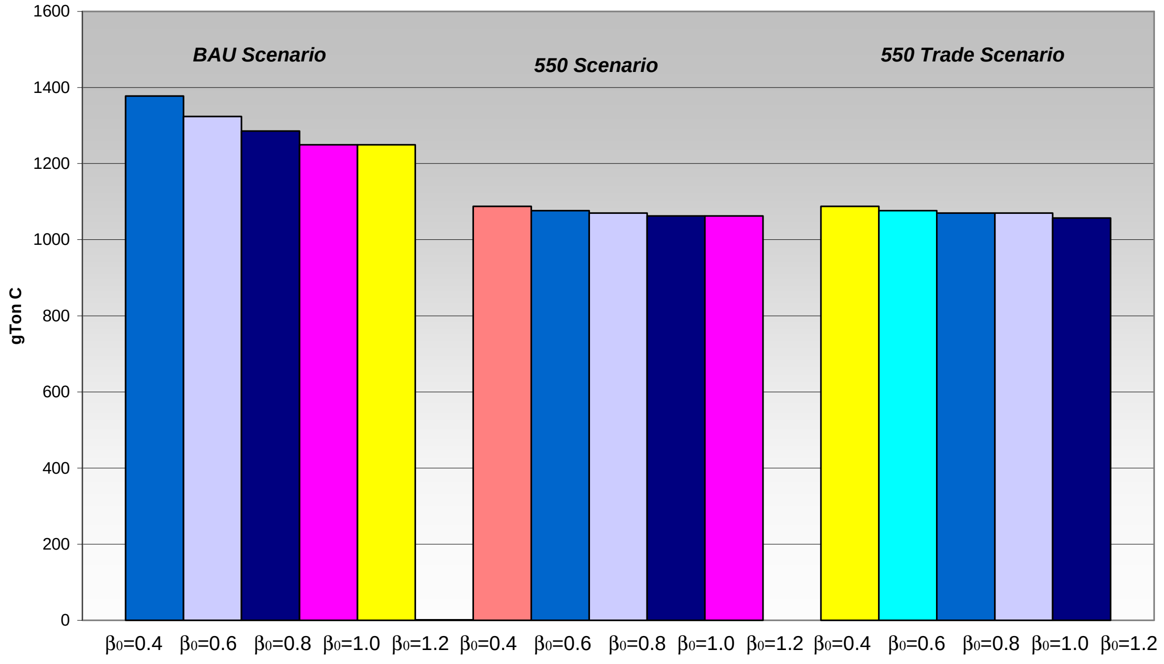


Figure A.3. Average R&D Expenditure over GPD for a Growing Energy-Saving Effect

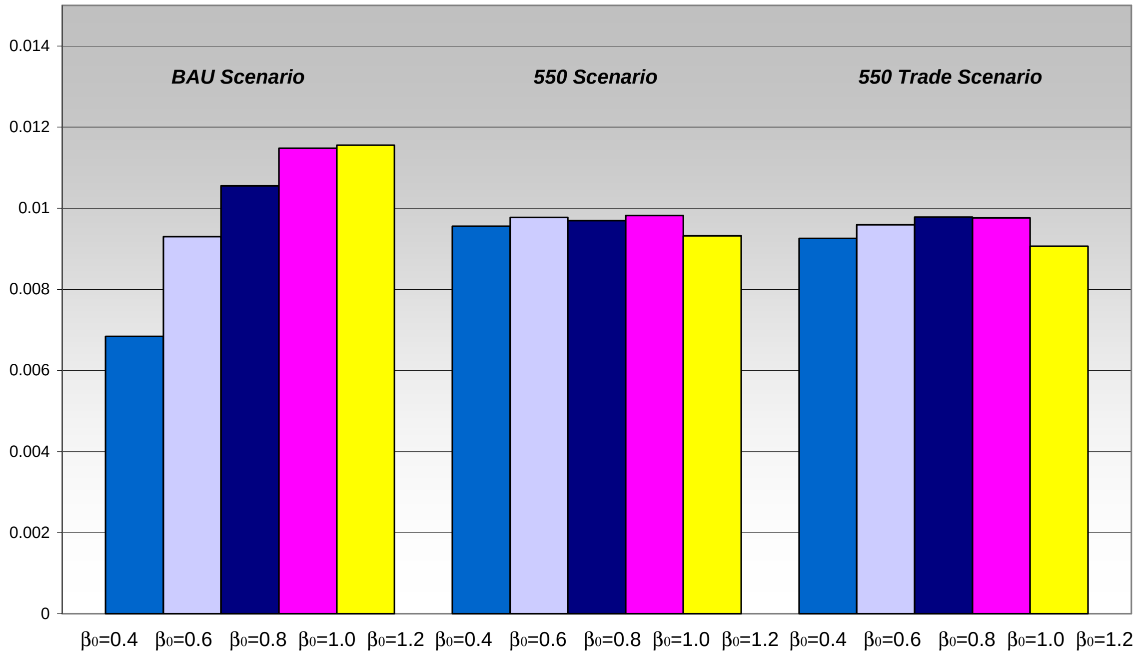


Figure A.4. Price of permits for a Growing Energy-Saving Effect

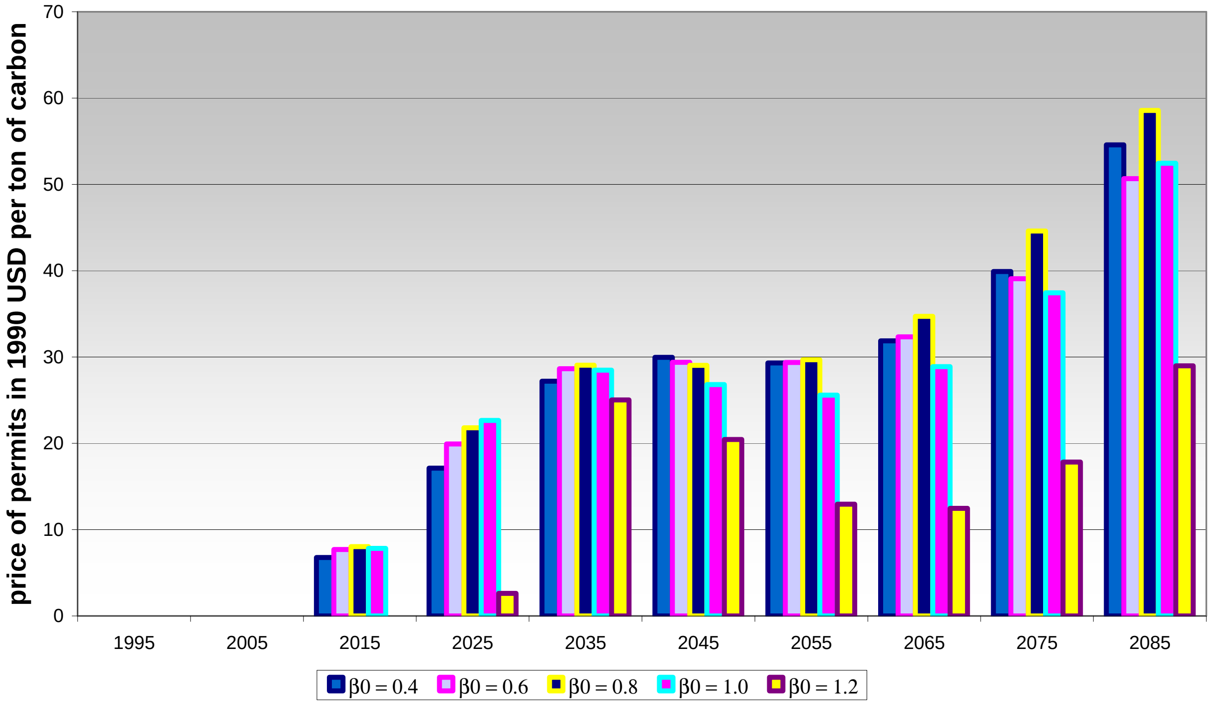


Figure A.5. Temperature in degree C above pre-industrial levels in 2105 for a Growing Fuel-Switching Effect

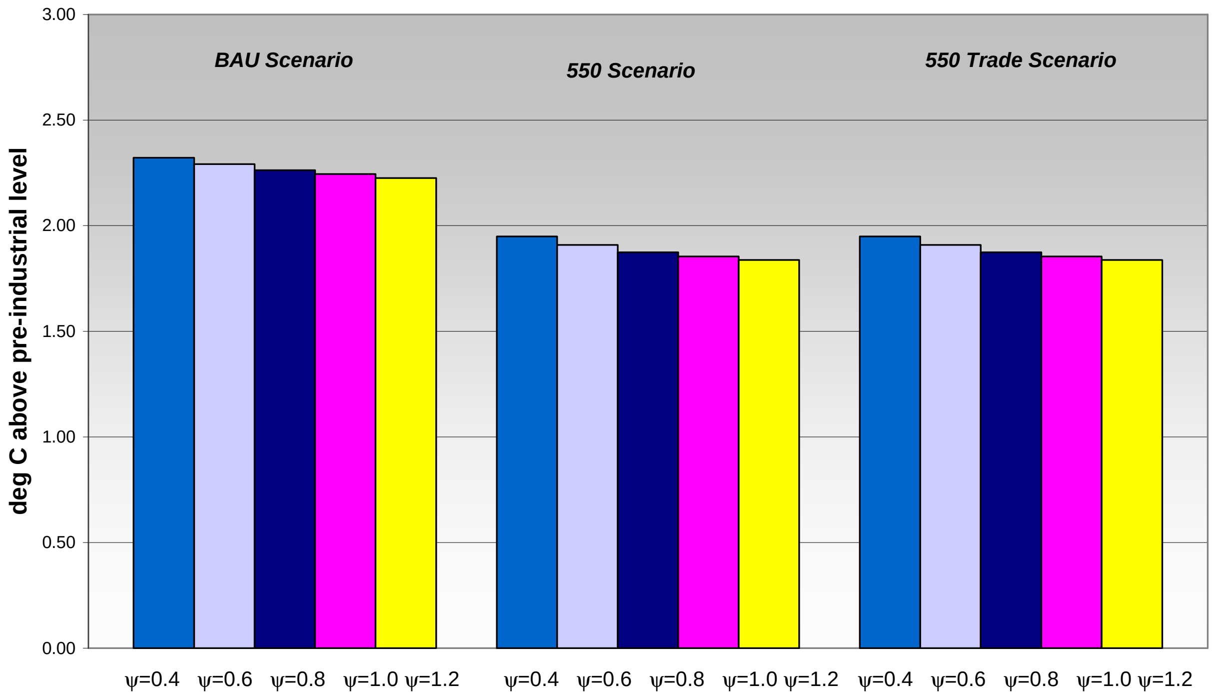


Figure A.6. Carbon Concentration levels in 2105 for a Growing Fuel-Switching Effect

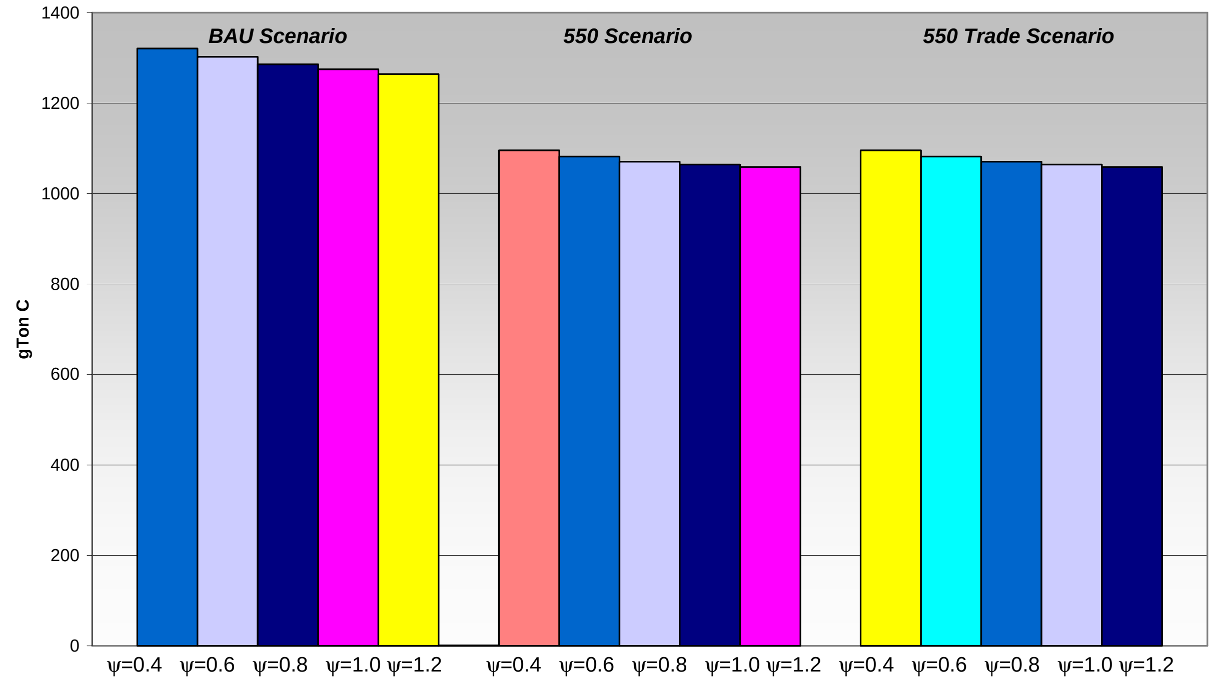


Figure A.7. Average R&D Expenditure over GPD for a Growing Fuel-Switching Effect

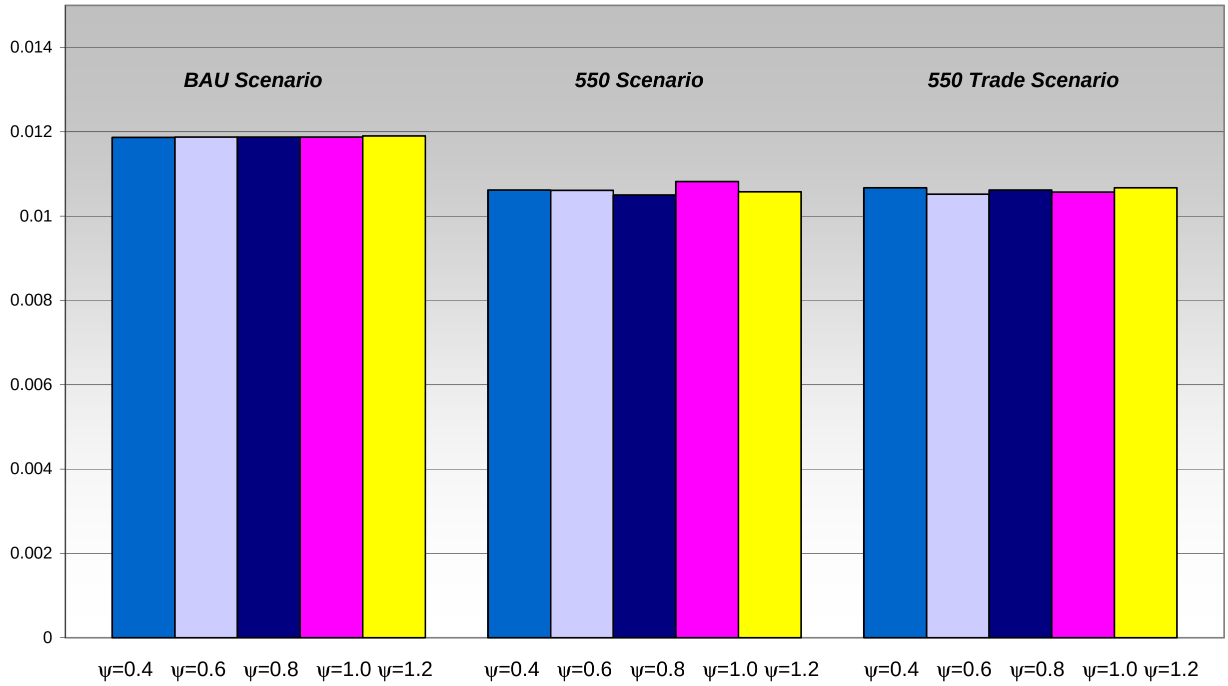


Figure A.8. Price of permits for a Growing Fuel-Switching Effect

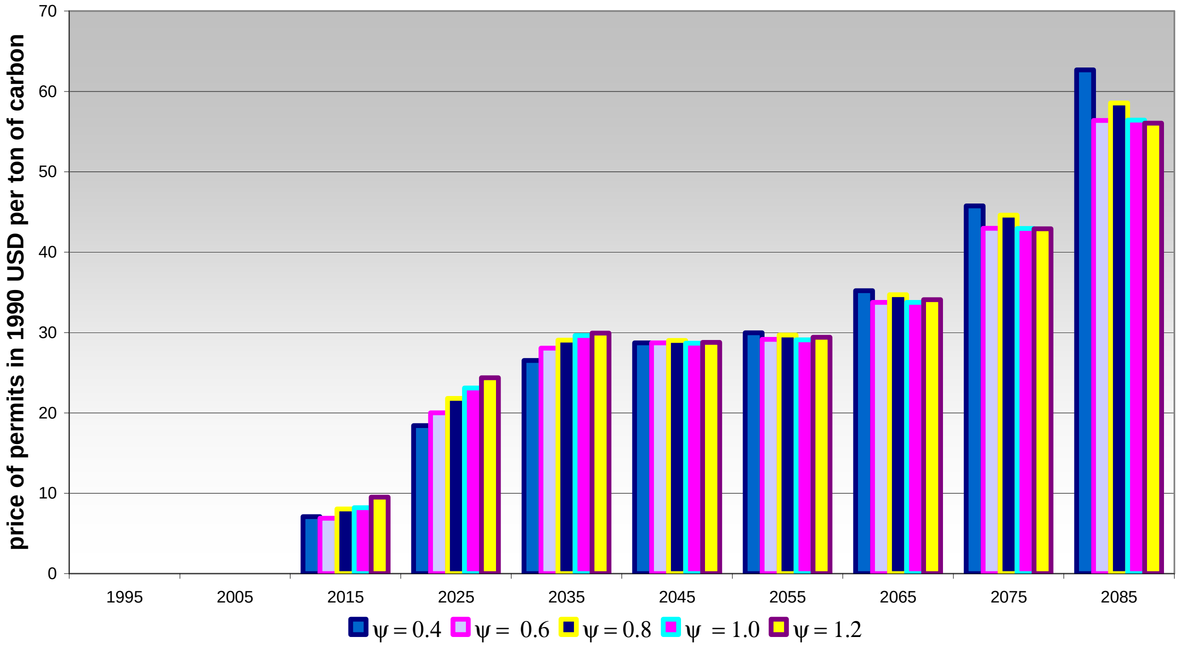


Figure A.9. Temperature in 2105 for Different TP formulations

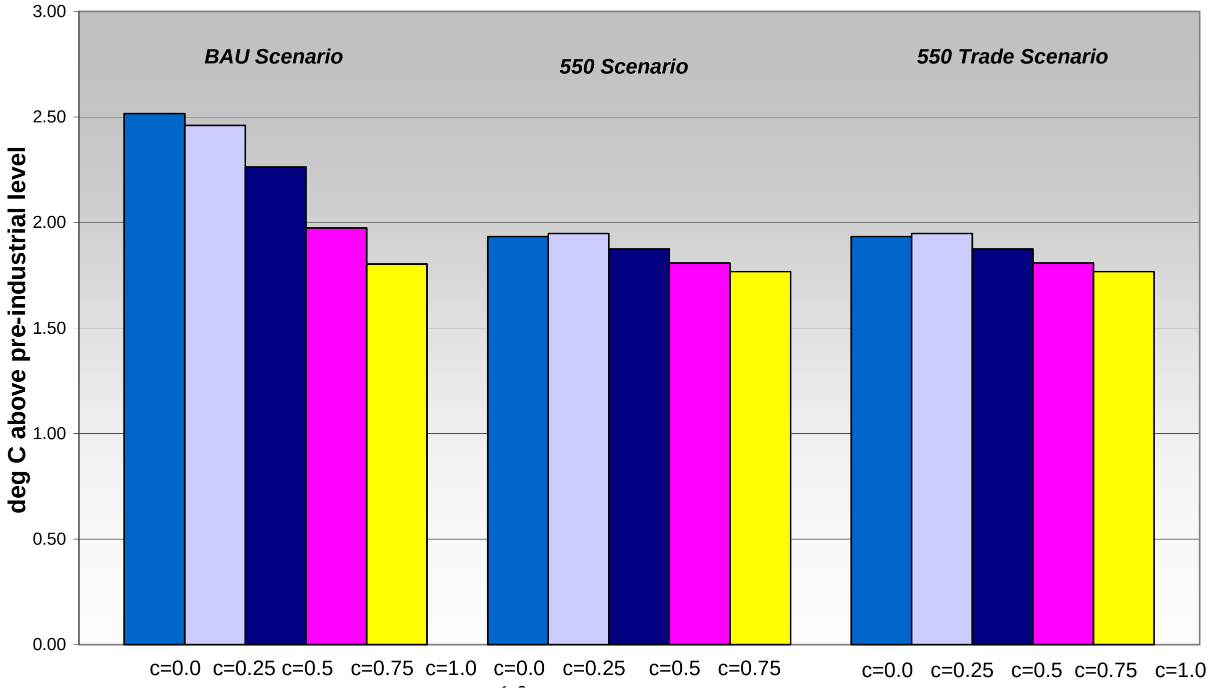


Figure A.10. Carbon Concentration in 2105 for Different TP formulations

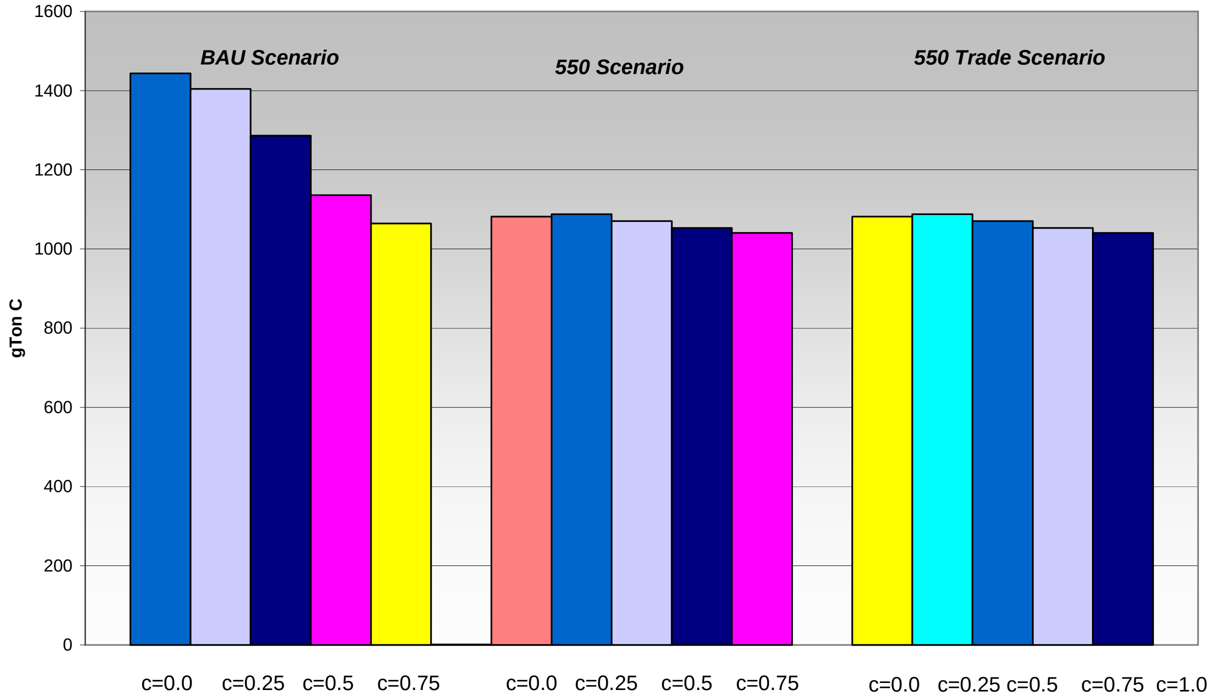


Figure A.11. Average R&D Expenditure over GPD for Different TP formulations

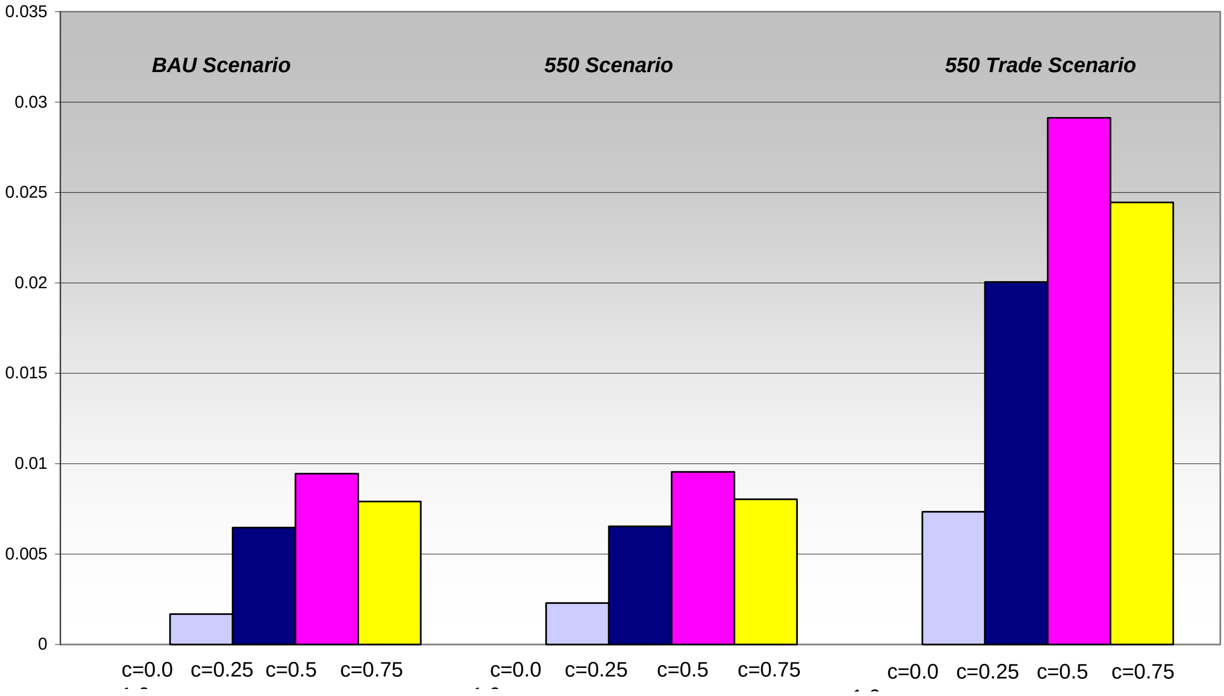
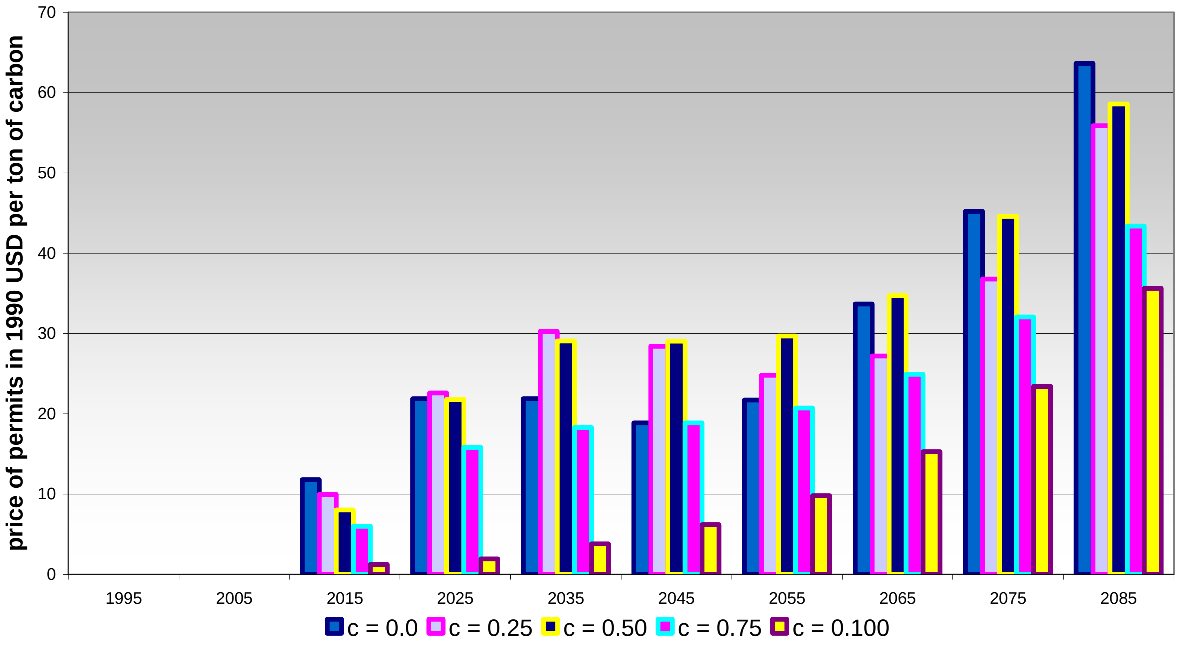


Figure A.12. Price of permits for different TP formulations



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(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

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