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Summary

Many predictions and conclusions in the climate change literature have been made and drawn on the basis of theoretical analyses and quantitative models that assume exogenous technological change. One is naturally led to wonder whether those conclusions and policy prescriptions hold in the more realistic case of endogenously evolving technologies. In previous work we took a popular integrated assessment model and modified it so as to allow for an explicit role of the stock of knowledge which accumulates through R&D investment. In our formulation knowledge affects both the output production technology and the emission-output ratio. In this paper we make further progress in our efforts aimed to model the process of technological change. In keeping with recent theories of endogenous growth, we specify two ways in which knowledge accumulates: via a deliberate, optimally selected R&D decision or via experience, giving rise to Learning by Doing. As an illustration, we simulate the model under the two versions of endogenous technical change and look at the dynamics of a selected number of relevant variables, including growth rates of GDP and physical capital, as well as total emissions and rate of domestic abatement.

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

JEL: H0, H2, H3

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LEARNING BY DOING *vs* LEARNING BY RESEARCHING IN A MODEL OF CLIMATE CHANGE POLICY ANALYSIS

1. Introduction

That current rates of greenhouse gas emissions cannot be sustained in the long run is by now an undisputed fact. Current production modes, with their associated levels of fossil fuel consumption, cannot proceed at present rates.

No one really believes or is ready to accept, however, that the solution of the climate change problem consists of reducing the pace of economic growth. Instead, it is believed that changes in technology will bring about the longed decoupling of economic growth from 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 it has therefore to be fostered by appropriate policy actions.

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, models have been proposed where the 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 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. No model designed for climate change policy analysis has however yet been proposed that incorporates both approaches in a single conceptual framework. This is what the model presented here does.

In previous work we presented a model in which both endogenous and induced technical change were taken into account (Buonanno, Carraro, Castelnuovo, and

Galeotti, 2000, 2001; Buonanno, Carraro, and Galeotti, 2001).[1] In particular, it was 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). Extending Nordhaus and Yang (1996)'s RICE model we 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).[2] 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 policy variable envisaged by the model.

Using that model, which we labeled "ETC-RICE", the policy game played by the six regions in which the world is divided was solved. Each region chooses the optimal level of four instruments: fixed investments, R&D expenditures, rate of emission control, and the amount of permits which each country wants to buy or sell. In addition, the model was modified in order to allow for emission trading, which was then studied both amongst Annex B countries only and amongst all countries under the Kyoto Protocol. We considered two versions of the model: 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.[3]

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

[2] 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. Technical change still evolves exogenously. We started our research on endogenous and induced technical change before this new version of the RICE model was available. This is the reason why LbD is incorporated in the old version of RICE. We are in the process of making the transition to the new version, for which some preliminary and provisional results are available (Castelnuovo and Galeotti, 2002).

[3] International spillovers of knowledge were also introduced in a version of the ETC-RICE model, with the stock of world knowledge affecting both production and emission technologies.

In this paper we take the same model but extend it so as to allow for an alternative source of technical change, Learning by Doing. In particular, we use arguments originally made by Arrow (1962) in supposing that the accumulation of knowledge occurs not as a result of deliberate (R&D) efforts, but as a side effect of conventional economic activity. LbD has been introduced in climate models first in the bottom-up approach by Anderson and Bird (1992) and Messner (1995, 1997). Central in these dynamic energy simulation models is the notion of "learning curve", which 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 our further extension of the RICE model, we 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 we 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 these model specifications make 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.

The paper begins in Section 2 with a brief review of the literature on endogenous environmental technical change in order to set the scene for our specific modeling proposal. In Section 3, the model is presented, starting from the basic version and leading up to our two alternative formulations. In the section we also describe how the model accounts for international emission trading and our parameter calibration choices. In order to quantify the effects of introducing induced technical change either via R&D or via LBD, Section 4 presents results of some illustrative simulation runs under alternative environmental policy scenarios, coherent with the implementation of the

Kyoto Protocol.[4] First, the impact of imposing an emission target without allowing for trade is studied. Then, emission trading is considered, with exchange taking place amongst Annex B countries. A few final remarks together with directions for further research close the paper.

2. On Environmental Endogenous Technical Change Modeling

While there is little debate over the importance of energy efficiency in limiting greenhouse gas (GHG) emissions, there is 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 this basis, debate has centred 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 (1999) note that this debate opposes "technologists" and economists, who hold very different views about the issue.

"Technologists" believe that there are plentiful opportunities for low-cost improvements in energy efficiency, and that realizing 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 the appropriate technology and market creation policies, significant GHG reduction can be achieved at very low cost. In essence, the approach is restricted to constraining energy-efficiency decisions with the goal of overcoming the existing "market barriers" to the penetration of various technologies that enhance 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 reduction is more costly than the technologists argue, and it puts relatively more emphasis on market-based GHG control policies like carbon taxes or tradable carbon permit systems to encourage the least costly means of carbon efficiency (not necessarily

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[4] These simulation exercises are not meant to be realistic, given the recent developments in international climate negotiation. We use the Kyoto Protocol for our simulations because the content of that agreement is well understood.

energy efficiency) enhancement available to individual energy users. One possibility is to substitute polluting inputs with less polluting ones within the existing technology. An alternative is for firms to make deliberate choices purporting to develop new less polluting production methods, i.e. undertake innovation activities. In this 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 two motivating forces, profitable investment and strategic advantage, against which to consider costs of carrying out R&D, including appropriability considerations. 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 distinctive of LbD and of the technologist approach.

In terms of environmental modeling, the bottom-up approach has mostly appealed to 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.

A number of bottom-up models have integrated endogenous technological change that assumes LbD. Examples are MESSAGE (Messner, 1995, 1997) and MARKAL (Barreto and Kypreos, 1999), dynamic linear programming models of the energy sector that are generally used in tandem with the MACRO 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). They optimize a choice between different technologies using given abatement costs and carbon emission targets. These models 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, an optimal trajectory with lower emissions in the near term is found with endogenous technical change. 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 of the eight technologies considered cumulative R&D expenditures increased rather than decreasing investment costs (Criqui, Klaassen, and Schrattenholzer, 2000) (see also Miketa and Schrattenholzer, 2002).

In terms of top-down modelling, the focus has been more on R&D induced technical change than on LbD. The RICE model (Nordhaus and Yang, 1996) 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).

Buonanno, Carraro, Castelnuovo, and Galeotti (2000, 2001) and Buonanno, Carraro, and Galeotti (2001) extend the RICE model by endogenizing both environmental and non-environmental technical change and by allowing for trading of emission permits. In the model, called ETC-RICE, each country plays a non-cooperative Nash game in a dynamic setting, which yields an Open Loop Nash equilibrium. It is assumed that innovation is brought about by R&D spending which contributes to the accumulation of knowledge. The stock of existing knowledge is a factor of production, which therefore enhances the rate of productivity. This is a form of endogenous technical change. Besides this channel, however, knowledge also serves the purpose of reducing, ceteris paribus, the level of carbon emissions. This is referred to in the literature as induced technical change. The authors compare the costs of complying with the CO_2 targets agreed upon in Kyoto with and without induced technical change. The authors analyse this issue under several policy options, that is when emission trade is not allowed, is restricted to (all) Annex B countries only and, finally, is extended to all world countries. Finally, Buchner, Carraro, and Cersosimo (2001) employ the ETC-RICE model to assess the consequences of the "new" Bonn/Marrakech agreements on permit prices and quantities exchanged, domestic abatement, R&D activity and emissions.

A very recent model, called DEMETER, which incorporates endogenous technical change, is proposed by van der Zwaan, Gerlagh, Klaassen, and Schrattenholzer (2002) (see also Gerlagh and van der Zwaan, 2000). A macroeconomic (top-down) model is specified that 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 systems (bottom-up) models. The model is a global one, not therefore designed to 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.

Besides Nordhaus' RICE, the other probably most popular climate model is Manne and Richels (1992)' MERGE model. Like RICE, MERGE is an intertemporal general equilibrium 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, 2002), 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 do not find a big impact of LbD relative to previous analyses without that possibility.

Finally, it is to be mentioned the model of knowledge accumulation of Goulder and Mathai (2000), in which a central planner chooses time paths of abatement and R&D efforts in order to minimise the present value of the costs of abating emissions and of R&D expenditures subject to an emission target. The abatement cost function depends both on abatement and on the stock of knowledge 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 problem 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.

This model is one of the few examples, if not the only one so far, that accommodates both forms of endogenous technical change. Its economic structure is however quite simplified as it is a constrained cost minimization problem with no concern for economic growth and welfare and for policies other than abatement and R&D. The model proposed here entertains instead both R&D-based and LbD modes of technical change in a single sector optimal economic growth setup. It is to this model that we now turn.

3. Model Description

In our extension of the RICE model, technical change is no longer exogenous. In particular, we assume that there exists an endogenously generated stock of knowledge which affects both factor productivity and the emission-output ratio. The main feature of this paper concerns the way 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 new choice variable. In the LbD, we quite 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, in addition to consumption and physical investment. Our purpose is to compare the outcomes of some simulations, in order to verify the robustness of the results to the implementation of the above defined two different approaches.

3.1 The Model with No Induced Technical Change

As a starting point we consider the specification of the model which only allows for endogenous technical change, i.e. the case in which knowledge affects only factor productivity. In the case innovation is brought about by R&D spending, it is assumed that the stock of knowledge is a factor of production, which enters a country production technology along with physical capital and labor.[5] Knowledge therefore enhances the rate of productivity (see Griliches, 1979 and 1984). Hence, the RICE production function is modified as follows:

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

where Q is output (gross of climate change effects), A the exogenously given level of technology and K_R, L and K_F are respectively the inputs from knowledge capital, labor and physical capital (n and t index time and country respectively). The stock of knowledge accumulates as follows:

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

where $R\&D$ are expenditures in Research and Development and δ_R is the rate of knowledge depreciation. Finally, $R\&D$ spending is included in the fundamental identity of sources and uses:

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

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[5] We do not dispute the fact that this technological specification is quite restrictive, mainly for the lack of energy inputs, and therefore not very suited for climate change policy analysis. Our purpose has not clearly been that of modifying the basic structure of the RICE model.

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

$$Y(n,t) = \Omega(n,t)Q(n,t) \tag{4}$$

with Ω being an output scaling factor capturing emissions controls and to damages from climate change.

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

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

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

With LbD equation (2) is missing in this version of the model and equation (3a) reverts back to its original formulation in the RICE model:

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

This implies that, under the LBD approach, knowledge creation does not place any claim on resources, *ceteris paribus.*

3.2 Accounting for Induced Technical Change

As said above, besides affecting factor productivity, knowledge influences also 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 as follows:

$$E(n,t) = [1-\mu(n,t)]\sigma(n,t)Q(n,t), \qquad 0 \le \mu(n,t) \le 1 \tag{5}$$

where μ is the domestic abatement rate and σ is the exogenously given emissions-output ratio.[6] Accounting for induced technical change, (5) is modified as follows:

$$E(n,t) = [\sigma_n + \chi_n^R \exp(-\alpha_n^R K_R(n,t))][1-\mu(n,t)]Q(n,t) \tag{5a}$$

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.[7]

With a LbD-based knowledge accumulation, equation (5a) is simply replaced by the following:

$$E(n,t) = [\sigma_n + \chi_n^L \exp(-\alpha_n^L K_F(n,t))][1-\mu(n,t)]Q(n,t) \tag{5b}$$

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, and therefore the overall level of pollution emissions, on the other hand.[8]

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[6] Notice that along the paper we will use the expression 'emissions-output ratio' as to indicate the time-varying, idiosyncratic coefficient σ(n,t). In fact, as equation (5) 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 so consider as synonymous the terms 'emissions-output ratio' and 'sigma'.

[7] 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.

[8] 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,

3.3 Accounting for Emission Trading

As stated in the Introduction, the goal of this paper is to assess the implications of the two alternative specifications concerning knowledge accumulation proposed above. Therefore, the two versions of the ETC-RICE model are used to quantify some resource allocation effects under different assumptions on the use of the so-called "flexibility mechanisms". Despite the last indications about the fate of the Kyoto Protocol, we chose to explore some scenarios which nowadays may appear counterfactual. In particular, we would like to compare the Business As Usual (BAU) scenario with a case in which emission trading is not allowed ('Kyoto' scenario) and one in which trading takes place amongst all the Annex B countries, including the US ('ET-A1' case). This reason for this choice is twofold. First, the purpose of this paper is not that of assessing the immediate economic effects of complying with Kyoto. It is instead that of analyzing the consequences of different feasible environmental policies, in order to compare the outcomes stemming from two theoretically different approaches. Second, the time horizon considered is rather long (2000-2050), implying that recent political decisions, like the US withdrawal from the Kyoto agreement, are not likely to remain unchanged for such a long period.

Going back to the model specification, 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 sources and uses identity. Hence, equations (3a) and (3b) have to be respectively replaced by the following:

$$Y(n,t) = C(n,t) + I(n,t) + R\,\&\,D(n,t) + p(t)NIP(n,t) \tag{6a}$$

$$Y(n,t) = C(n,t) + I(n,t) + p(t)NIP(n,t) \tag{6b}$$

In addition, equation (7) states that the Kyoto limits can be relaxed in the case of emission trading:

$$E(n,t) \le Kyoto(n) + NIP(n,t) \tag{7}$$

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we draw a symmetry between the R&D-driven Knowledge case and the LbD-driven one in order to perform sensible comparisons between these two frameworks.

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 (6a) and (6b), resources produced by the economy must be devoted, in addition to consumption, investment and, in (6a), research and development, to net purchases of emission permits. Equation (7) states that a region's emissions may exceed the limit set in Kyoto if permits are bought, and vice versa in the case of sales of permits. Note that *p(t)* is the price of a unit of tradable emission permits expressed in terms of the *numeraire* output price. Moreover, there is an additional policy variable to be considered in this case, which is net demand for permits *NI*P.

Under the possibility of emission trading, the sequence whereby a Nash equilibrium is reached can be described as follows. Each region maximises its utility subject to the individual resource and capital constraints, now including the Kyoto constraint, and the climate module for a given emission (i.e. abatement) strategy of all the other players and a given price of permits *p(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.

3.4 Parameter Calibration

As for parameter calibration and data requirements for the newly introduced variables, we proceed as follows. Firstly, coefficients already present in the original RICE 96 model are left unchanged. Next, when the R&D driven stock of knowledge is considered as an input of the production function (see equation (1a)), for each region we calibrate the coefficient β_n^R so as to obtain in the year 2000 a value of the R&D-output ratio equal to the 1990 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.[9] For the remaining three macro-regions 1990 values of the knowledge stock are constructed by taking the average ratio between knowledge and

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

physical capital of the three industrialised 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 (5a) are OLS estimated using time series of the emissions-output ratio and of the stock of knowledge (the sample runs from years 1990 to 2120, i.e. it consists of ten years of data). The data for the former variable are those used by Nordhaus and Yang (1996), while those for the latter variable are recovered from a BAU simulation conducted using the original emissions-output ratio $\sigma(n,t)$ of the RICE 96 model.[10] 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 RICE 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. Actually, in this case we arbitrarily set the value of this elasticity to be equal to 1/10 of the capital-output elasticity as in Nordhaus and Yang (1996)' s RICE model. Technically speaking, we do so because of the impossibility of replicating the original Business As Usual scenario without setting that elasticity equal to zero. Hence, in this way we are basically augmenting the physical capital productivity in order to mimic the LbD effect. Given the high level of arbitrariness involved in this operation, we perform a sensitivity test, by admitting in a second stage of our analysis a larger LbD coefficient, which is now set to be equal to 3/10 of the original capital-output elasticity. We will see how the results change when this second coefficient value is taken into account. Once imposed the value β to the elasticity parameter, we simulate a BAU scenario with 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 (5b) using the same time series of the emissions-output ratio as in the former OLS regressions, while replacing the stock of knowledge with the stock of physical capital (the sample still runs from years 1990 to 2120). Table 1 collects all the new coefficients and initial values introduced in the RICE96 model.

---

[10] 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.

Table 1: Coefficients of the ETC-RICE Model

	α_n^R	χ_n^R	α_n^L	χ_n^L	σ_n	β_n^R	β_{low}^L	β_{high}^L	$\delta_{R,K}$	$K_R(n,1990)$
USA	0.195440	0.019369	0.042667	0.023259	0.00971	0.04355	0.025	0.075	0.05	1.24200
Japan	0.522430	0.005270	0.122960	0.008230	0.00600	0.04550	0.025	0.075	0.05	0.27773
Europe	0.296490	0.007659	0.045242	0.009928	0.00699	0.03180	0.025	0.075	0.05	0.75526
China	0.618650	0.112771	0.024206	0.110836	0.00904	0.01080	0.025	0.075	0.05	0.03145
FSU	1.197400	0.095579	0.080718	0.095531	0.00935	0.01660	0.025	0.075	0.05	0.07269
ROW	0.072926	0.022409	0.002510	0.022241	0.00845	0.00927	0.025	0.075	0.05	0.39343

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

4. Endogenous Induced Technical Change: Optimal Reaction to Different Environmental Policies

In order to quantify the effects of introducing induced technical change first via R&D and then via LbD, some resource allocation choices in different environmental policy scenarios, coherent with the implementation of the Kyoto Protocol, are considered. As stated above, the impact of imposing an emission target without allowing for trade is studied. Then, emission trading is considered, with exchange taking place amongst Annex B countries (Et-A1). For each optimization run, time paths of the following control variables (abatement, fixed investment, R&D expenditures, net demand for permits) are obtained and their impacts on the endogenous variables (emissions, GNP, consumption, and so on) over the period 2000-2050 (the well-known “Kyoto forever” scenario) computed. In what follows, we will focus mainly on the following control variables: consumption, fixed investment, domestic abatement and R&D expenditures. In our analysis we refer to ‘average differences’, the differences being computed by considering the optimal values assumed by the variables of interest in the ‘Kyoto’ and ‘Et-A1’ scenarios, and by subtracting to those values the figures recorded under the Business-As-Usual hypothesis. In particular, in our analysis we care about control variables such as consumption of the *numeraire* good, physical capital, domestic abatement rate, and (where present) R&D expenditures. For ease of presentation we only display average figures over the simulation period 2010-2050. Moreover, we restrict our investigations to Annex B countries, assembled as in the original RICE Model, leaving out countries that do not have any commitment in the Kyoto Protocol.

4.1 R&D-based Technological Change

As stated above, in our extension of the model technical change is no longer exogenous: knowledge is endogenously generated and affects factor productivity (ETC – Endogenous Technical Change) or both factor productivity and the emission-output ratio (ITC – Induced Technical Change). As to better appreciate the different stimuli on the control variables that the two specifications generate, in our graphs exogenous and endogenous sigma cases (i.e. ETC and ITC) are always jointly presented.

Consider first the case in which the environmental technology evolves exogenously. Starting from the BAU scenario, the imposition of an emission ceiling turns out being a ceiling on production, via equations (1a), (4), and (5). This leads all Annex B countries to experience a welfare loss, since the average level of consumption unambiguously decreases, as shown in Figure 1. This is due to the reduction of physical capital stock by about 2-3% relative to the BAU scenario, as Figure 2 suggests. Domestic abatement rates are inevitably enhanced when constraints on emissions are imposed, as evident in Figure 3. Notice that, in this framework, R&D expenditures exerts a positive effect uniquely on the inputs' productivity. Hence, it is not surprising to observe a lower average level of R&D expenditures after the imposition of the emissions' caps (Figure 4, top panel).

Indeed, there seem to be some important deviations when allowing for the endogenous environmental technical change to be part of our analysis. In fact, in this latter case agents find profitable to *raise* their R&D expenditures when upper bounds on emissions are activated (Figure 4, bottom panel); they do so in order to improve their environmental technology, so being allowed to grow more (i.e. to reduce capital accumulation *less* than in the exogenous environmental technological change case after the imposition of the Kyoto constraints) and finally to consume more (Figures 1 and 2). Not surprisingly, given the positive influence of the stock of R&D-driven Knowledge on the environmental technology, agents' R&D expenditures turn out being *complementary* to the domestic abatement action, while when the environmental technology is exogenous they are s*ubstitutes* (due to the fact that R&D expenditures raise production and, as a by product, pollution). To summarize, when agents can shape their emissions-output ratio, they are able to exploit this additional possibility to increase their welfare.

When emission trading between Annex B countries is permitted, all the regions are better off. This is hardly surprising, given that we each region is endowed with an extra degree of freedom, i.e. the possibility to trading rights to pollute. Figure 1 confirms this fact.

It is interesting to understand where these welfare-gains derive from. In fact, not all the consumption's variation stems from an augmented production (caused by an increased average stock of capital). Indeed, the effects on the average variation of capital cannot be predicted *a priori*. Investment choices depend crucially on the role each country will have in the market: depending on the equilibrium price of emission permits, endogenously generated by the model, and on the basis of other information such as the domestic abatement cost, each country decides whether to act as a permits seller or buyer. In particular, in a very simplified view, a region will choose to be a seller when the marginal earnings from the emission permits market are higher than the marginal expenses needed in order to lower the emissions to the optimal point under the Kyoto ceiling. These expenses can be both direct (abatement costs) and indirect (less production, via lower average growth rate of capital, or more R&D). The opposite holds for buyers, i.e. costs for permits are lower than expenses to reduce emissions under Kyoto targets.

The considerations just made can explain why the Former Soviet Union (seller) *reduces* the optimal stock of capital more under trading, while USA, EU, and Japan (buyers) reduce it less (Figure 2). This is possible given the 'relaxation' of the constraints on emissions they enjoy when they purchase a positive amount of permits. This brings buyers to lower the emission control rate, since they may acquire on the market what they were previously obliged to obtain through domestic action. On the contrary, FSU (the unique seller) uses abatement and R&D expenditures as strategic variables; i.e., this country strongly raises them, in order to create a high number of emission permits to be conveniently sold on the market.

When the emission-output ratio is endogenous, the differences existing in the regions' optimal behaviours when moving from Kyoto to Et-A1 are qualitatively in line with what already observed. Quantitatively, the possibility of influencing the emissions-output ratio is welfare enhancing (this is true for all the regions, and in particular for

FSU). All the changes noted in the previous paragraph and regarding physical capital, domestic abatement rate, and R&D expenditures appear to be of smaller magnitudes.

4.2 LbD-based Technological Change

Compared to the 'Learning by Researching' approach, the LbD version of the model presents one less choice variable, i.e. the control variables are now limited to consumption, domestic abatement, fixed investment and net demand for permits, since fixed capital replaces R&D expenditures in the role of accumulating knowledge. Hence, physical capital now plays the same role that knowledge capital had in the R&D approach. Notice that this fact has some implications. On the one hand, the physical capital's marginal returns are higher, so for a given amount of capital the overall production is now higher.[11] This induces optimising agents to invest quite a lot of resources in physical capital, in order to fully exploit its increased marginal productivity. In this set up there is *not* any distinction between the input per se (physical capital) and the element which enhances its productivity (Knowledge). So, it is not possible to substitute welfare today (i.e. less consumption) with higher productivity of the input tomorrow (i.e. more Knowledge *given the same amount of capital*). Instead, this is possible in the R&D-driven Knowledge case. In our opinion, this distinction is important. In fact, it is true that R&D is a costly avenue to improve the stock of Knowledge. However, it is also a different aggregate with respect to capital, so – at least in our analysis - it allows a more free management of the available resources with respect to the LbD case. If the case of environmental technical change is endogenous, agents have to modify their amount of physical capital in order to improve the emissions-output ratio. This does not happen in the R&D case. Roughly put, in our set up LbD causes Knowledge growth for free, but agents are a bit more constrained in their choices with respect to the R&D-driven Knowledge case. These considerations will be of help in interpreting the results we obtained.

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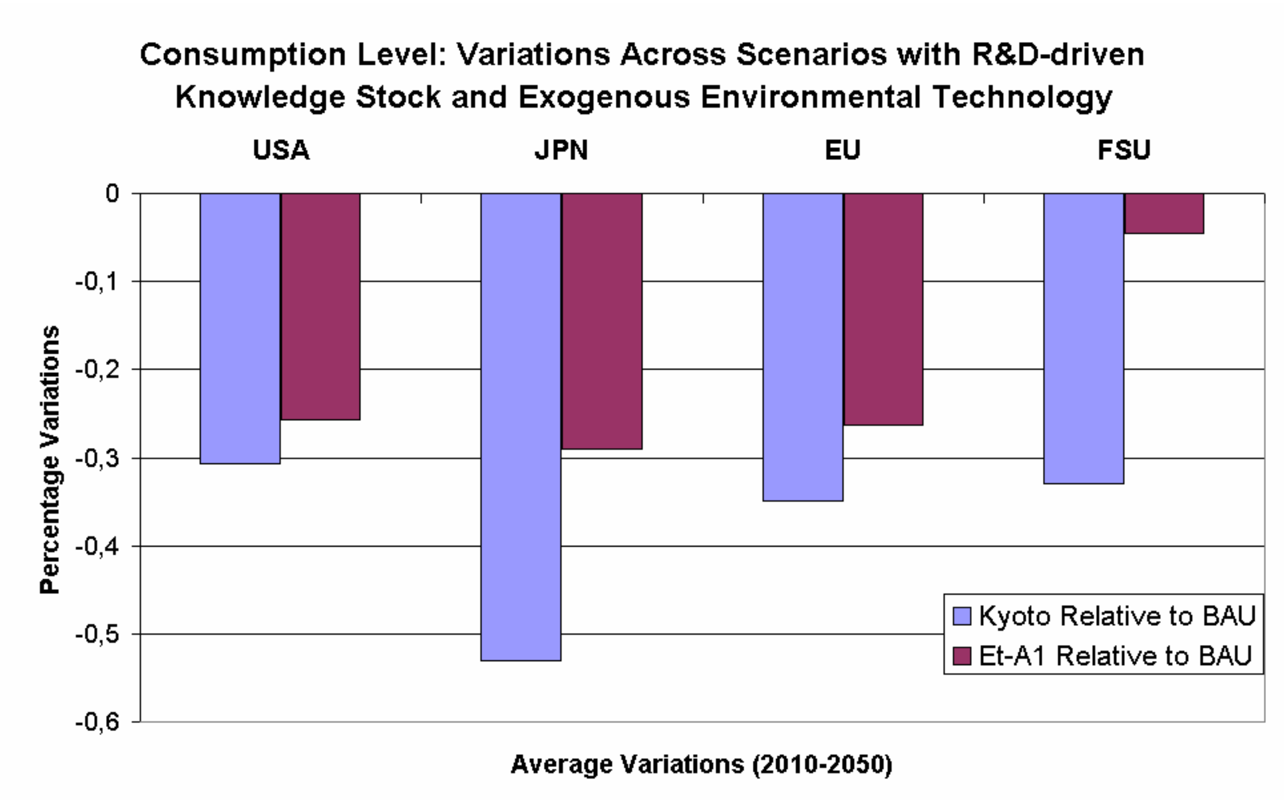
[11] There is an important assumption behind our way of accounting for LbD. When determining the optimal amount of resources to be invested in physical capital, agents are perfectly aware of the 'learning effect' triggered by capital accumulation. Hence, they fully understand that the marginal productivity of capital is enhanced by the learning effect, and take it into account when determining their optimal decisions.

Figure 1


Consumption Level: Variations Across Scenarios with R&D-driven Knowledge Stock and Exogenous Environmental Technology
USA
JPN
EU
FSU
0
-0,1
-0,2
-0,3
-0,4
-0,5
-0,6
Percentage Variations
Kyoto Relative to BAU
Et-A1 Relative to BAU
Average Variations (2010-2050)

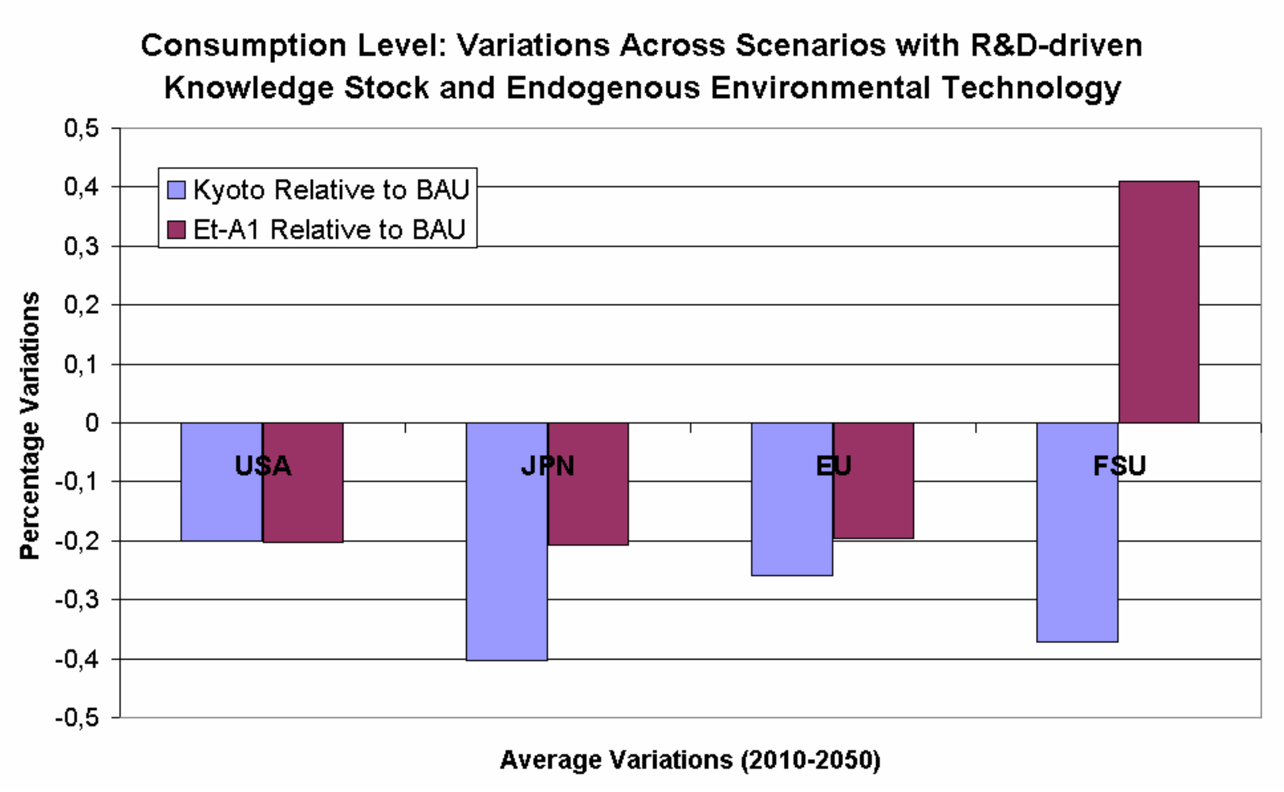
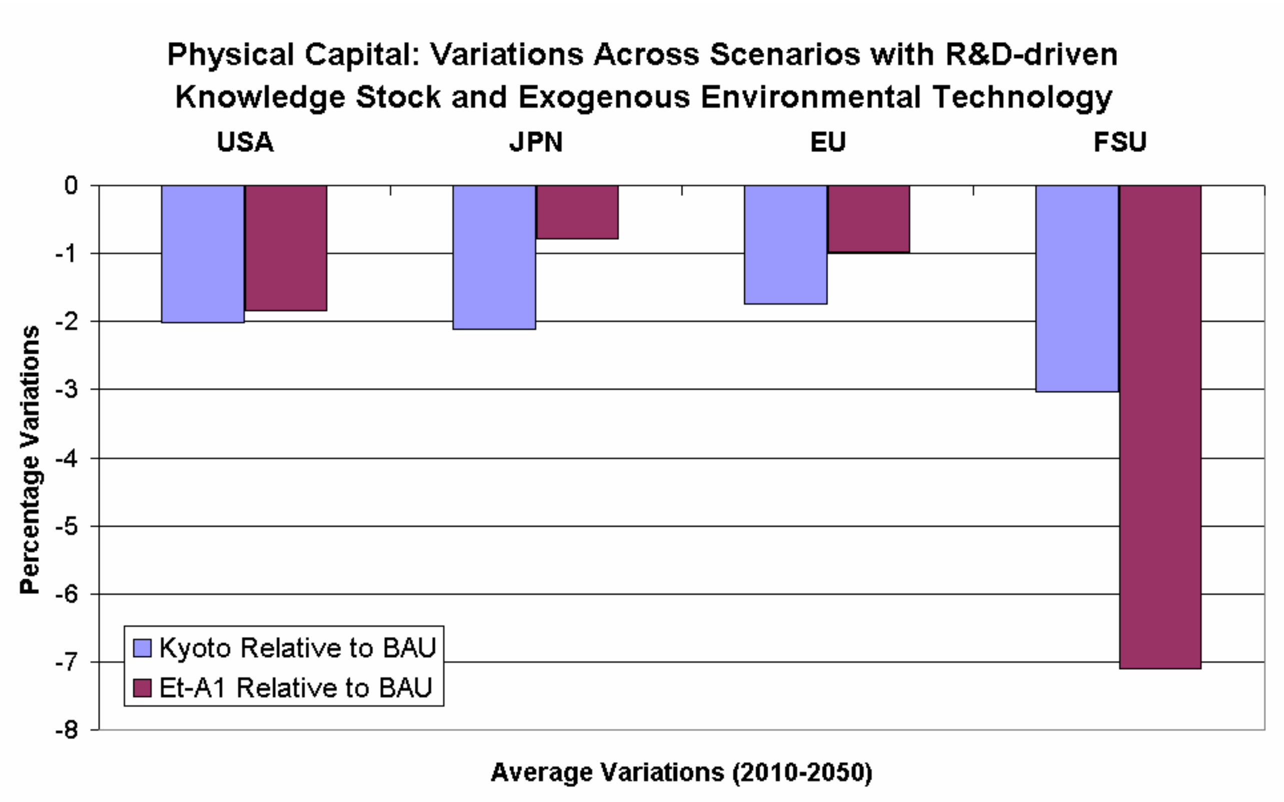

Consumption Level: Variations Across Scenarios with R&D-driven Knowledge Stock and Endogenous Environmental Technology
0,5
0,4
0,3
0,2
0,1
0
-0,1
-0,2
-0,3
-0,4
-0,5
Percentage Variations
Kyoto Relative to BAU
Et-A1 Relative to BAU
USA
JPN
EU
FSU
Average Variations (2010-2050)

Figure 2


Physical Capital: Variations Across Scenarios with R&D-driven Knowledge Stock and Exogenous Environmental Technology
USA
JPN
EU
FSU
0
-1
-2
-3
-4
-5
-6
-7
-8
Percentage Variations
Kyoto Relative to BAU
Et-A1 Relative to BAU
Average Variations (2010-2050)

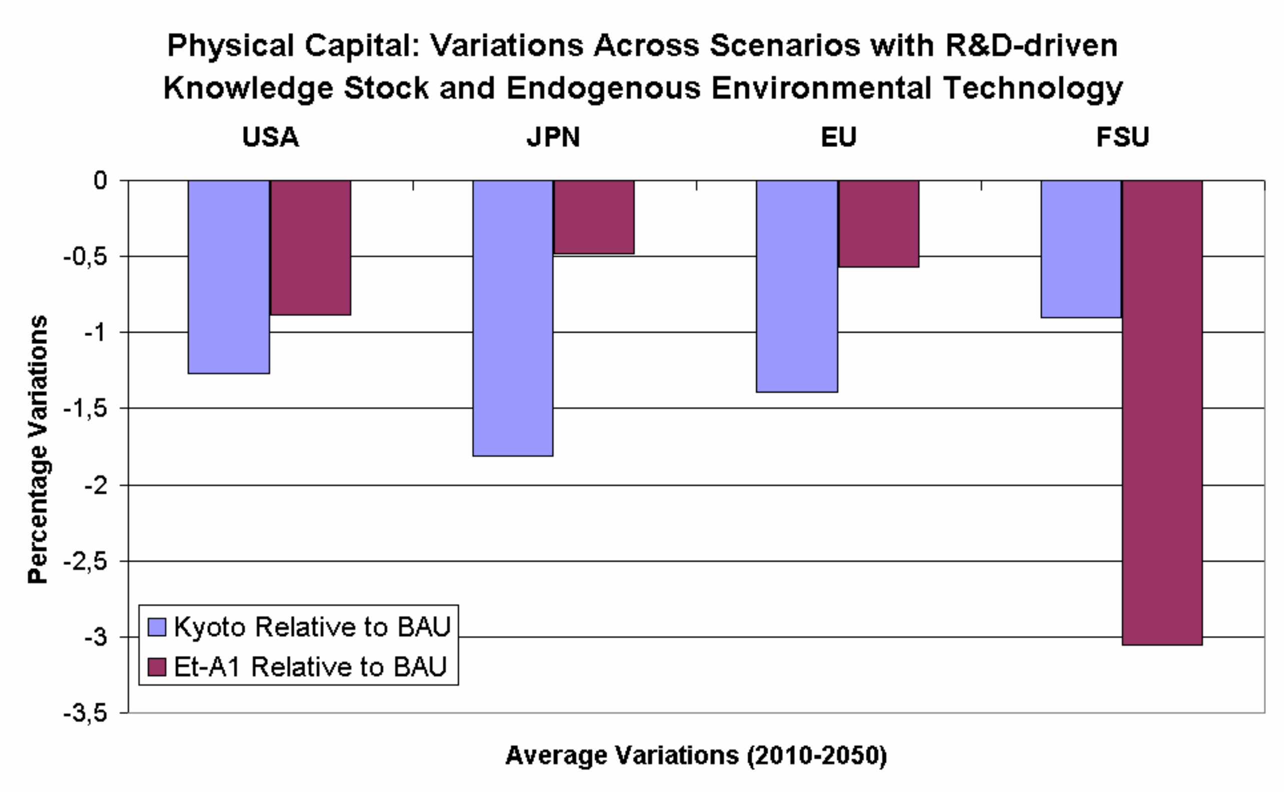
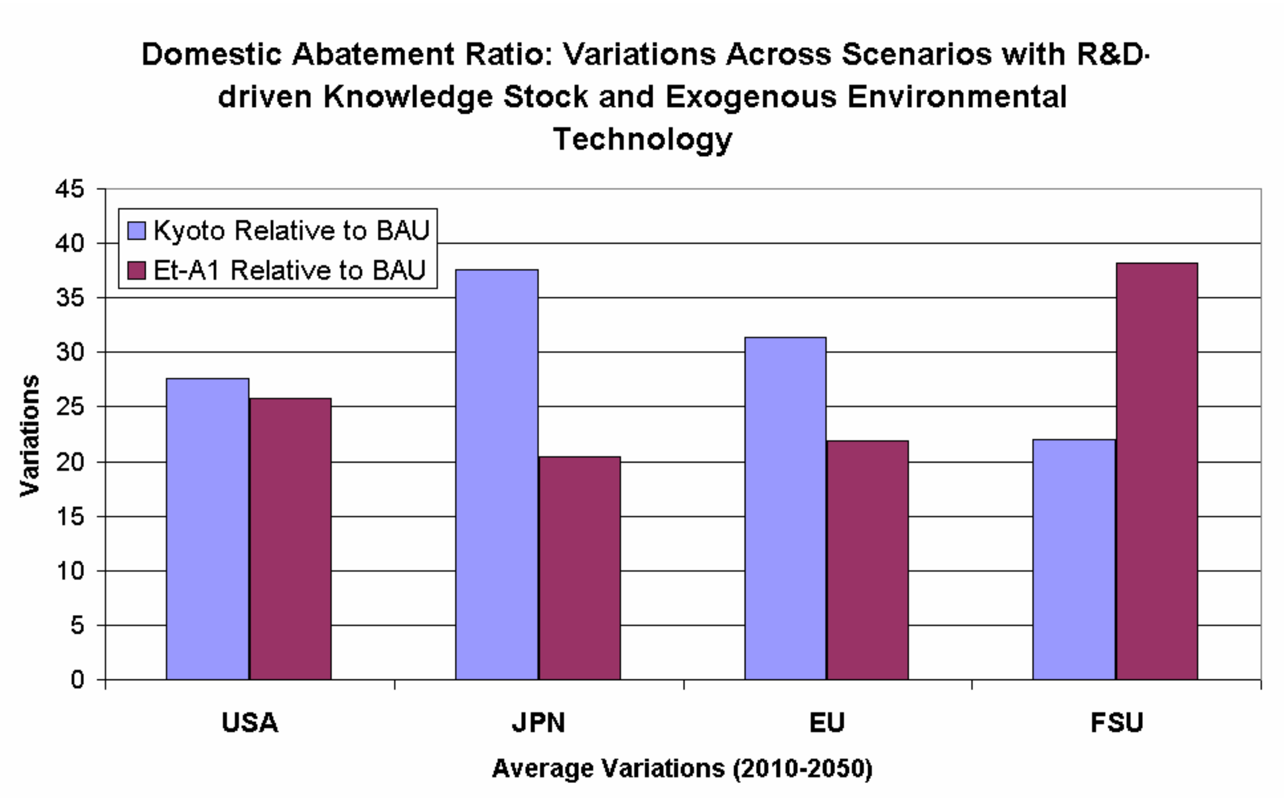

Physical Capital: Variations Across Scenarios with R&D-driven Knowledge Stock and Endogenous Environmental Technology
USA
JPN
EU
FSU
0
-0,5
-1
-1,5
-2
-2,5
-3
-3,5
Percentage Variations
Kyoto Relative to BAU
Et-A1 Relative to BAU
Average Variations (2010-2050)

Figure 3


Domestic Abatement Ratio: Variations Across Scenarios with R&D-driven Knowledge Stock and Exogenous Environmental Technology
Kyoto Relative to BAU
Et-A1 Relative to BAU
Variations
45
40
35
30
25
20
15
10
5
0
USA
JPN
EU
FSU
Average Variations (2010-2050)

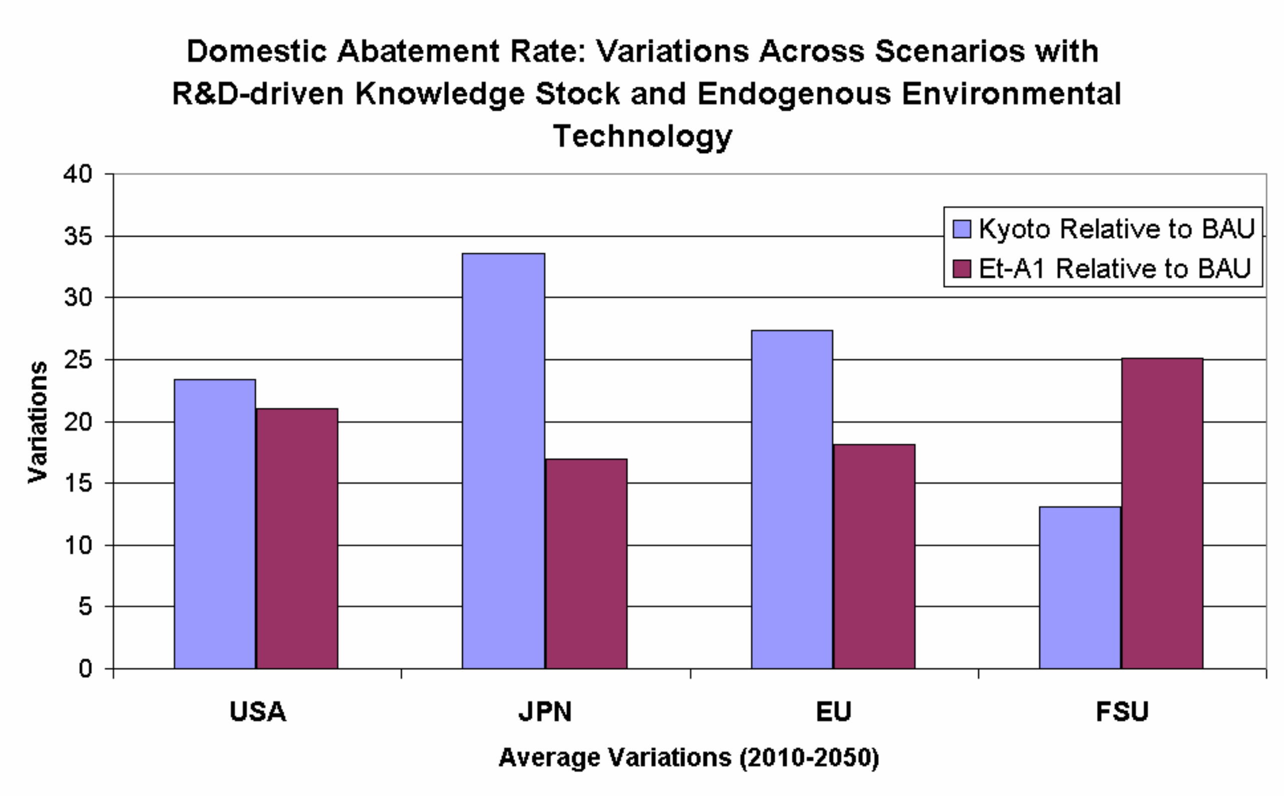
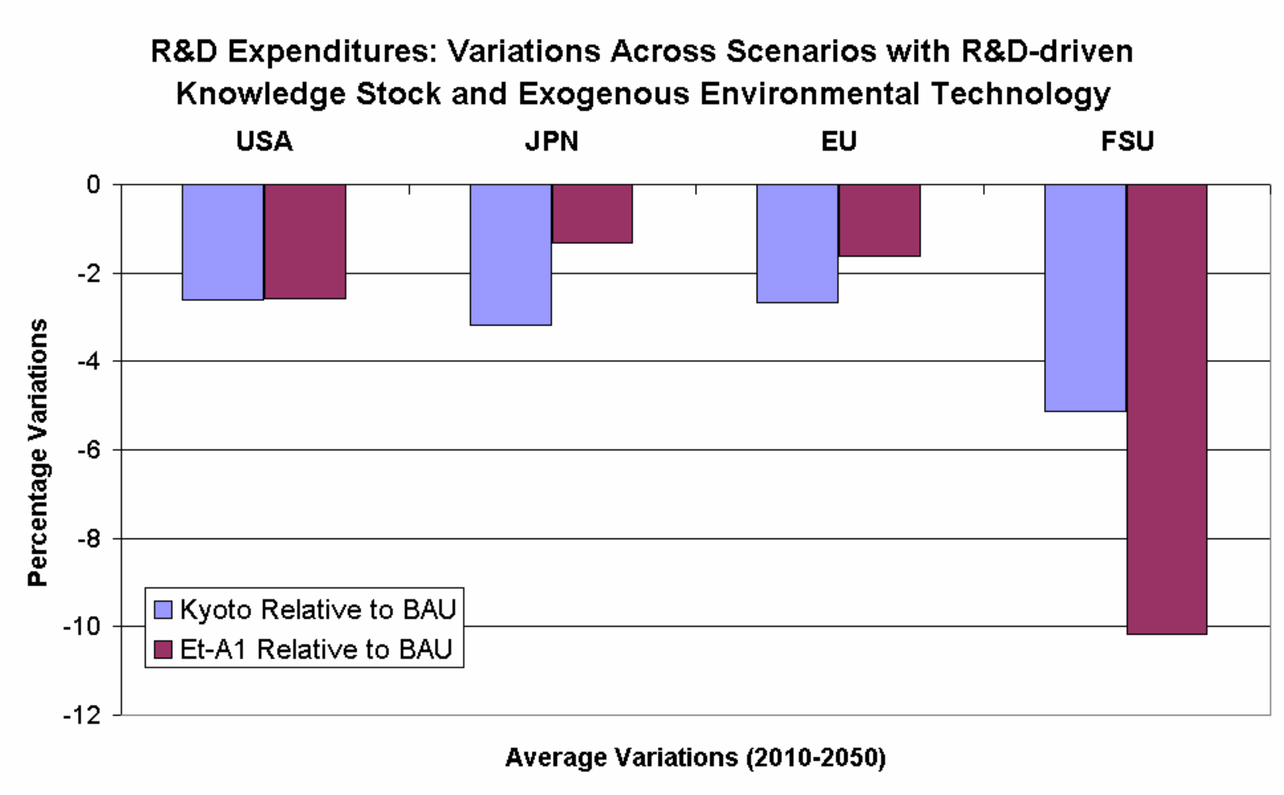
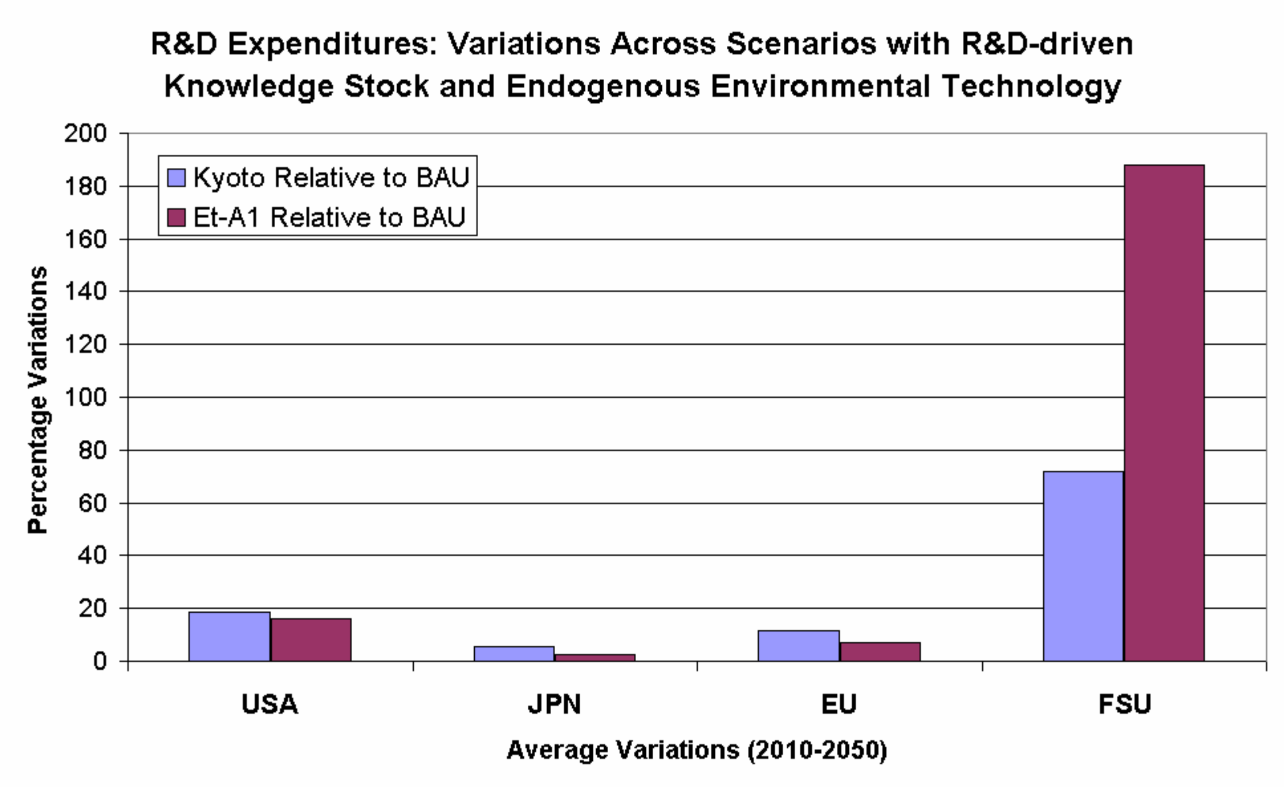

Domestic Abatement Rate: Variations Across Scenarios with R&D-driven Knowledge Stock and Endogenous Environmental Technology
Kyoto Relative to BAU
Et-A1 Relative to BAU
Variations
40
35
30
25
20
15
10
5
0
USA
JPN
EU
FSU
Average Variations (2010-2050)

Figure 4


R&D Expenditures: Variations Across Scenarios with R&D-driven Knowledge Stock and Exogenous Environmental Technology
USA
JPN
EU
FSU
0
-2
-4
-6
-8
-10
-12
Percentage Variations
Kyoto Relative to BAU
Et-A1 Relative to BAU
Average Variations (2010-2050)


R&D Expenditures: Variations Across Scenarios with R&D-driven Knowledge Stock and Endogenous Environmental Technology
200
180
160
140
120
100
80
60
40
20
0
Percentage Variations
Kyoto Relative to BAU
Et-A1 Relative to BAU
USA
JPN
EU
FSU
Average Variations (2010-2050)

Recall that, under our formulation of the LbD technological evolution, the elasticity of physical capital is augmented in a manner that induces increasing returns to scale of the inputs in the production function. Since the value of what we called 'learning-by-doing coefficient' (β^L) is arbitrarily chosen, we run the model using two different values, β^L=0.025 and β^L=0.075. In this way we assess the sensitivity of results. Relative to the previous approach the results present some significant differences.

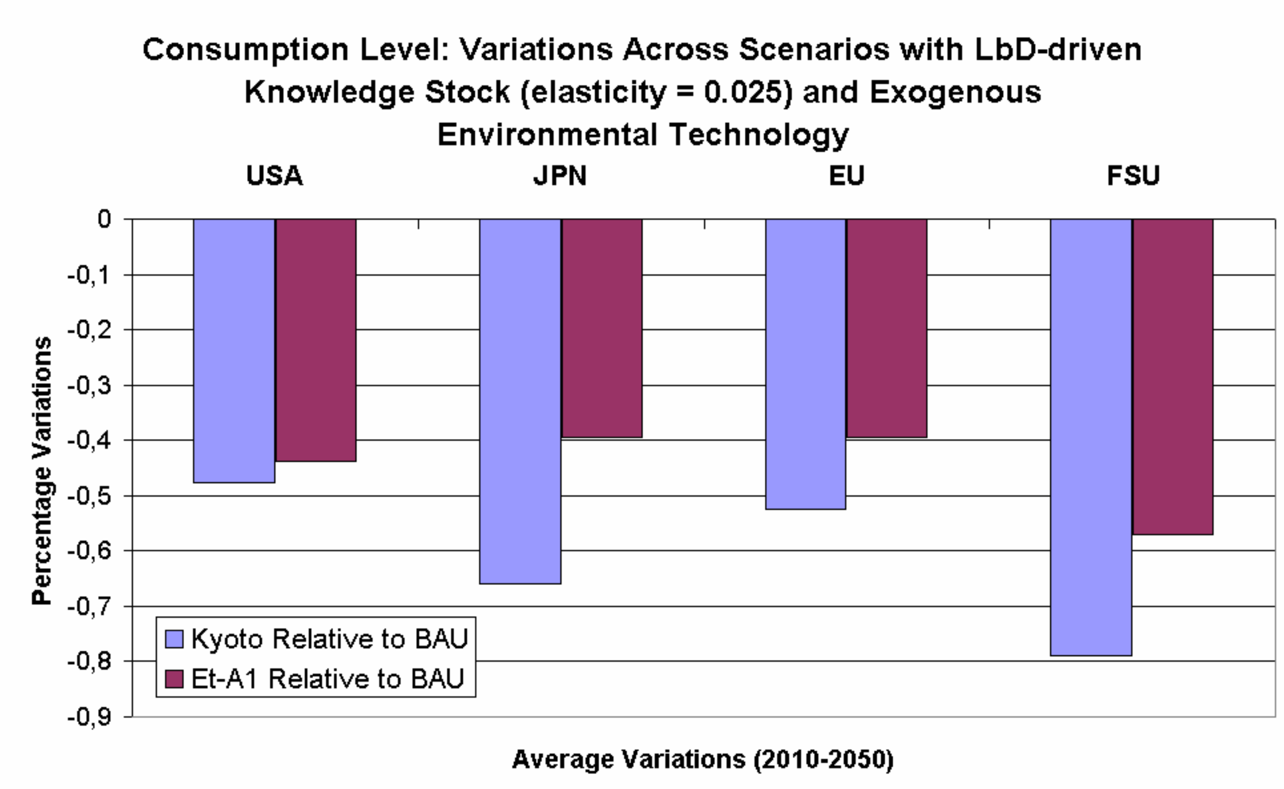
Let us consider the case of exogenous sigma. We start our analysis with the case in which the LbD effect is lower (i.e. $\beta^L = 0.025$). The imposition of an emission ceiling, without the possibility of trading emission permits, turns out being a ceiling on production, so a ceiling on fixed capital, which leads to a decrease in consumption, as depicted in Figure 5. Indeed, the reduction in physical capital seems to be slightly bigger than in the R&D-driven case (compare Figures 2 and 6). This is justified by the fact that, in the BAU scenario, agents are not emissions-constrained, so decide to accumulate quite a lot of capital. When the Kyoto limits become part of the framework, the reduction of the physical capital has to be such that, even considering the high productivity of capital, the pollution stemming from the production activity does not exceed the environmental constraints; hence, the reduction is quantitatively important. Not surprisingly, agents abate domestically in order to comply with Kyoto; the increase in the domestic efforts is larger with the LbD hypothesis (compare Figures 3 and 7).

How do things change when the environmental technical change is allowed for? Indeed, the welfare reduction is milder in this latter case. Indeed, with a low value of β^L the fact that the environmental technology is driven by the stock of physical capital does not seem to be too problematic. Notice the striking difference that exists between the physical capital variations registered under exogenous vs. endogenous environmental technology. In the latter case, agents in general *augment* the amount of resources allocated to physical capital, because in this way they are both much more productive and environmentally efficient (i.e. a given amount of output causes the emissions of a small flow of emissions). De facto, this is the situation in which the agents are able to exploit all the large returns that can come from the LbD-driven Knowledge, so there is a strong incentive to keep investing in physical capital. As far as the domestic abatement rate is concerned, we do not notice remarkable differences with respect to the case with exogenous sigma.

When allowing for the emissions trading, what we observe is that the regions acting as purchasers on the permits market (i.e. USA, Japan, and Europe) slightly augment their capital accumulation, whilst the seller (namely, FSU) experiences a further reduction as far as this variable is concerned, since it finds it profitable to reduce emissions in order to enjoy the gains from trade stemming from the emissions market. Consistently, the purchasers reduce their domestic abatement efforts, whilst the sellers increase them optimally.

When considering a much higher Knowledge-output elasticity (i.e. $\beta^L = 0.075$), results turn out being qualitatively in line with those already presented (compare Figures 5-7 with Figures 8-10). The only exception is represented by the variation of physical capital in presence of environmental constraints. In case of endogenous emission-output ratio, what it turns out is that USA and FSU behave as we have commented above (i.e. with positive variations), while JPN and EU *reduce* their stocks. Why so? This apparently surprising result may be explained by focusing on both the large productivity of the physical capital and the environmental efficiency featuring these two regions. In fact, given that they are two high-tech countries from an environmental viewpoint, when having to tackle the Kyoto limits they should increase their Knowledge quite a lot in order to reduce their emissions-output ratio. Given the framework at hand, for them this would imply the need of augmenting quite a lot the stock of capital, whose returns are very high, i.e. the production level coming from the newly accumulated stock of capital would be very large. But this would bring to a high level of pollution, incompatible with the Kyoto constraints. That is why, given our structure of the economy, it is optimal for environmentally advanced countries to *reduce* their amount of capital, in order to maximize the overall returns coming from capital. Instead, USA and FSU, whose environmental technology is low, face low marginal cost of abatement, and it is much easier for them to grow via capital accumulation so creating emissions which are compatible with their environmental constraints.

Figure 5


Consumption Level: Variations Across Scenarios with LbD-driven Knowledge Stock (elasticity = 0.025) and Exogenous Environmental Technology
USA
JPN
EU
FSU
0
-0,1
-0,2
-0,3
-0,4
-0,5
-0,6
-0,7
-0,8
-0,9
Percentage Variations
Kyoto Relative to BAU
Et-A1 Relative to BAU
Average Variations (2010-2050)

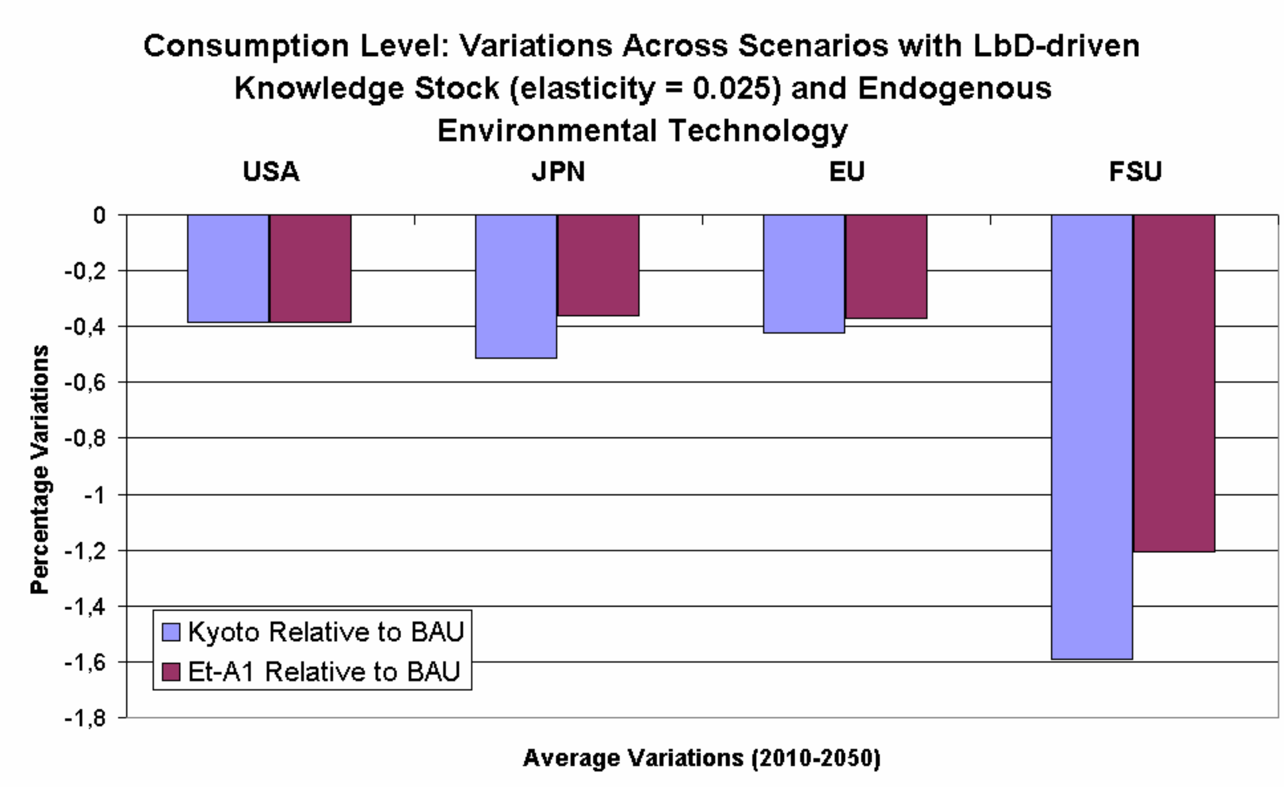

Consumption Level: Variations Across Scenarios with LbD-driven Knowledge Stock (elasticity = 0.025) and Endogenous Environmental Technology
USA
JPN
EU
FSU
0
-0,2
-0,4
-0,6
-0,8
-1
-1,2
-1,4
-1,6
-1,8
Percentage Variations
Kyoto Relative to BAU
Et-A1 Relative to BAU
Average Variations (2010-2050)

Figure 6

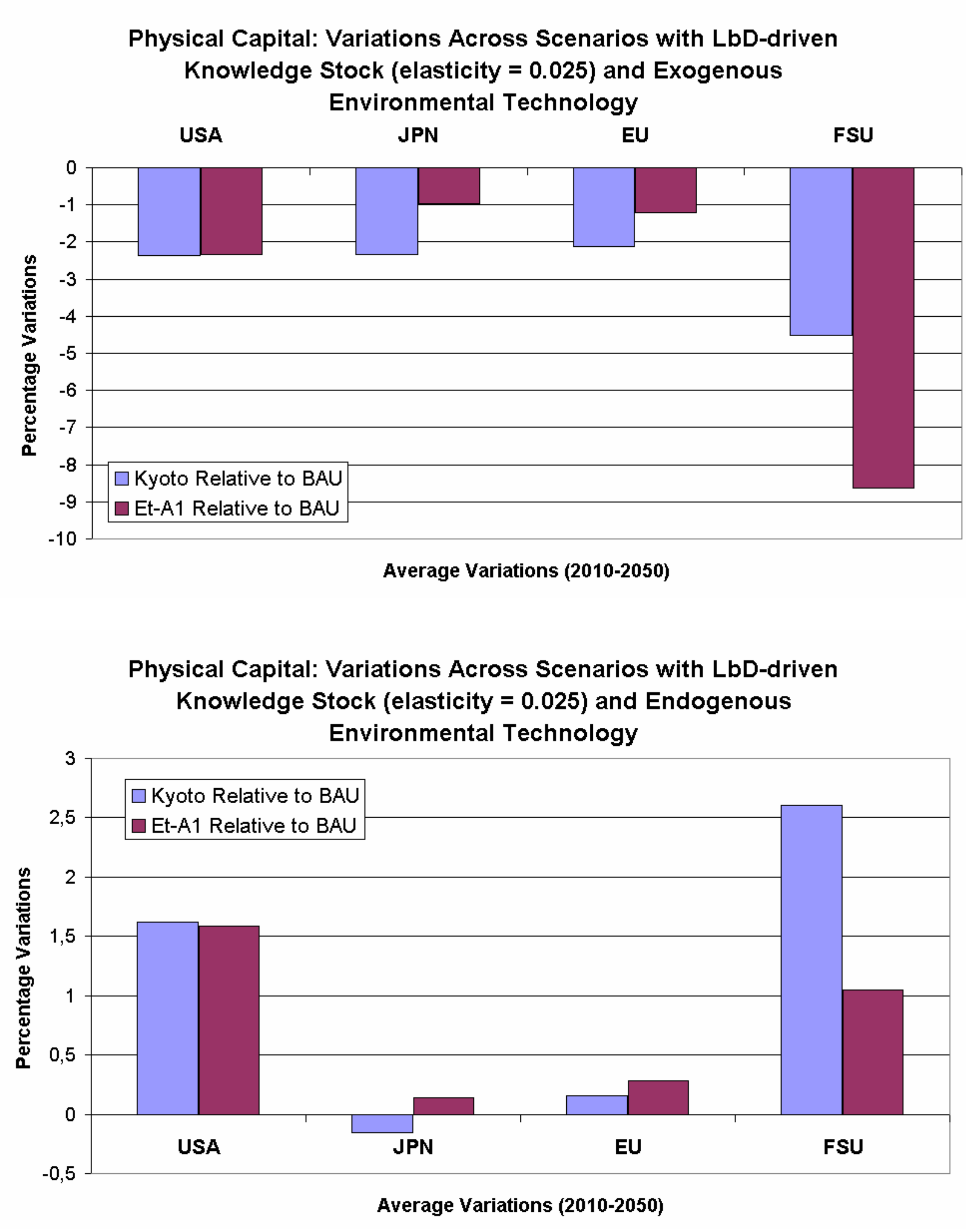
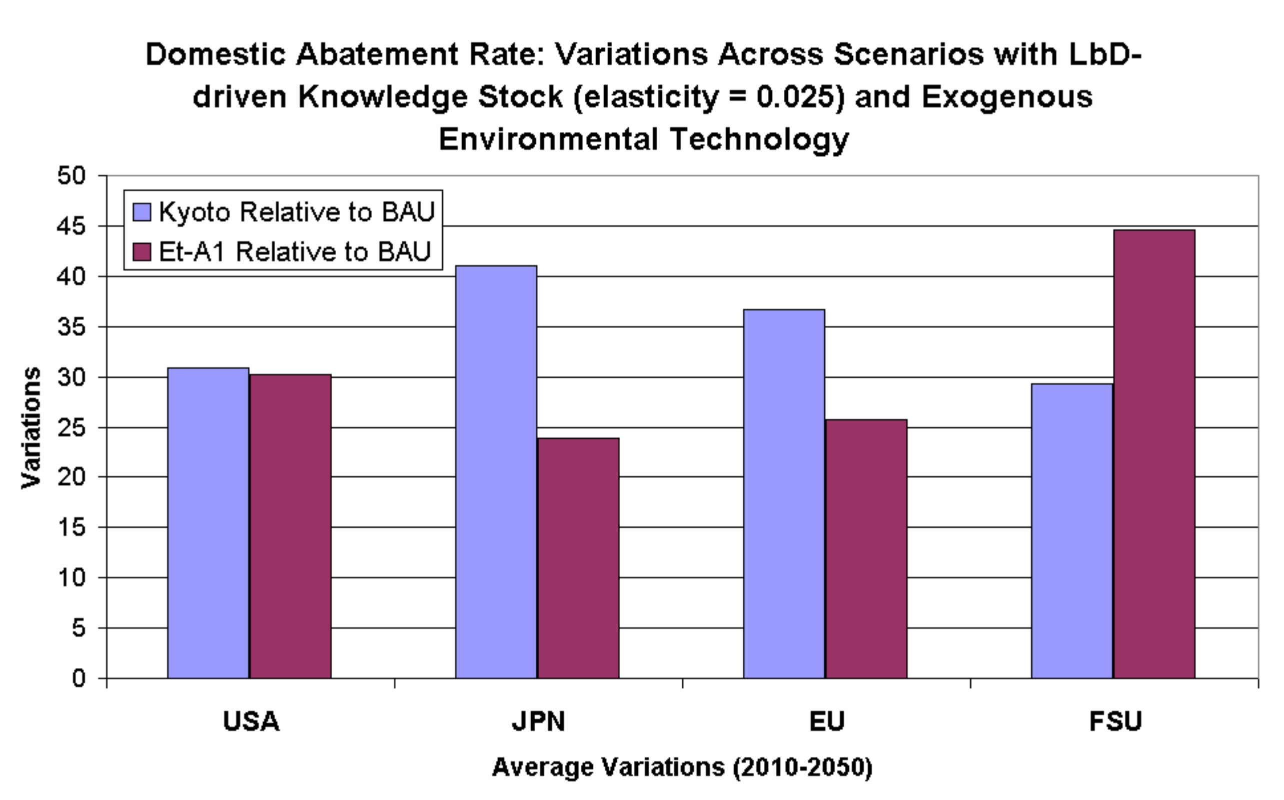

Physical Capital: Variations Across Scenarios with LbD-driven Knowledge Stock (elasticity = 0.025) and Exogenous Environmental Technology
USA
JPN
EU
FSU
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
Percentage Variations
Kyoto Relative to BAU
Et-A1 Relative to BAU
Average Variations (2010-2050)
Physical Capital: Variations Across Scenarios with LbD-driven Knowledge Stock (elasticity = 0.025) and Endogenous Environmental Technology
3
2,5
2
1,5
1
0,5
0
-0,5
Percentage Variations
Kyoto Relative to BAU
Et-A1 Relative to BAU
USA
JPN
EU
FSU
Average Variations (2010-2050)

Figure 7


Domestic Abatement Rate: Variations Across Scenarios with LbD-driven Knowledge Stock (elasticity = 0.025) and Exogenous Environmental Technology
Kyoto Relative to BAU
Et-A1 Relative to BAU
Variations
50
45
40
35
30
25
20
15
10
5
0
USA
JPN
EU
FSU
Average Variations (2010-2050)

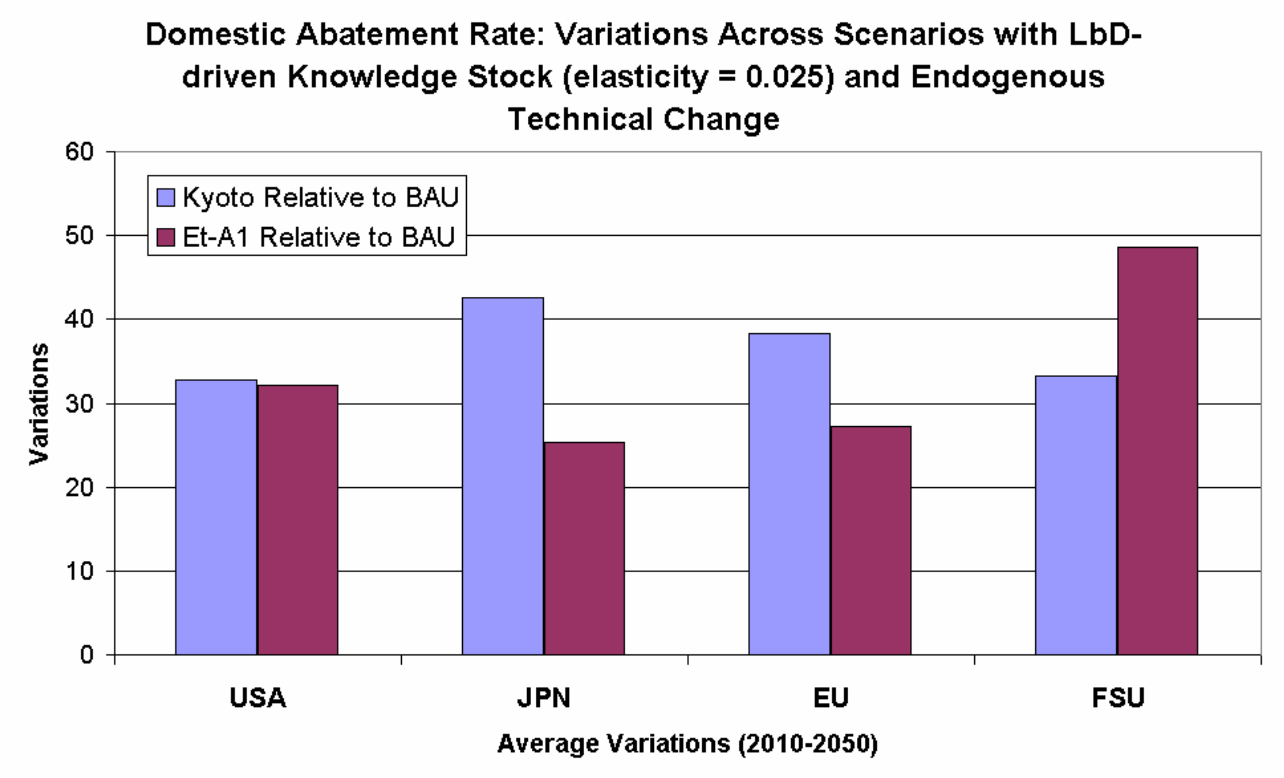
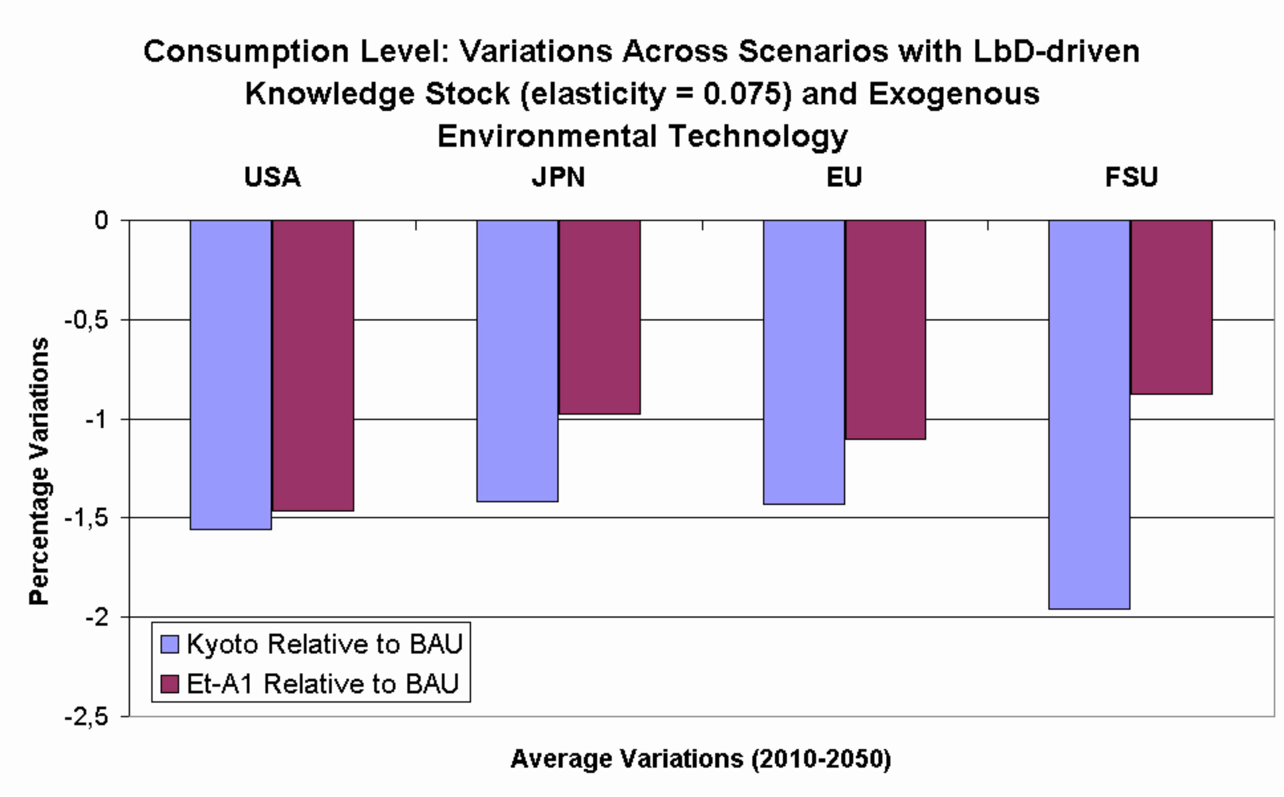
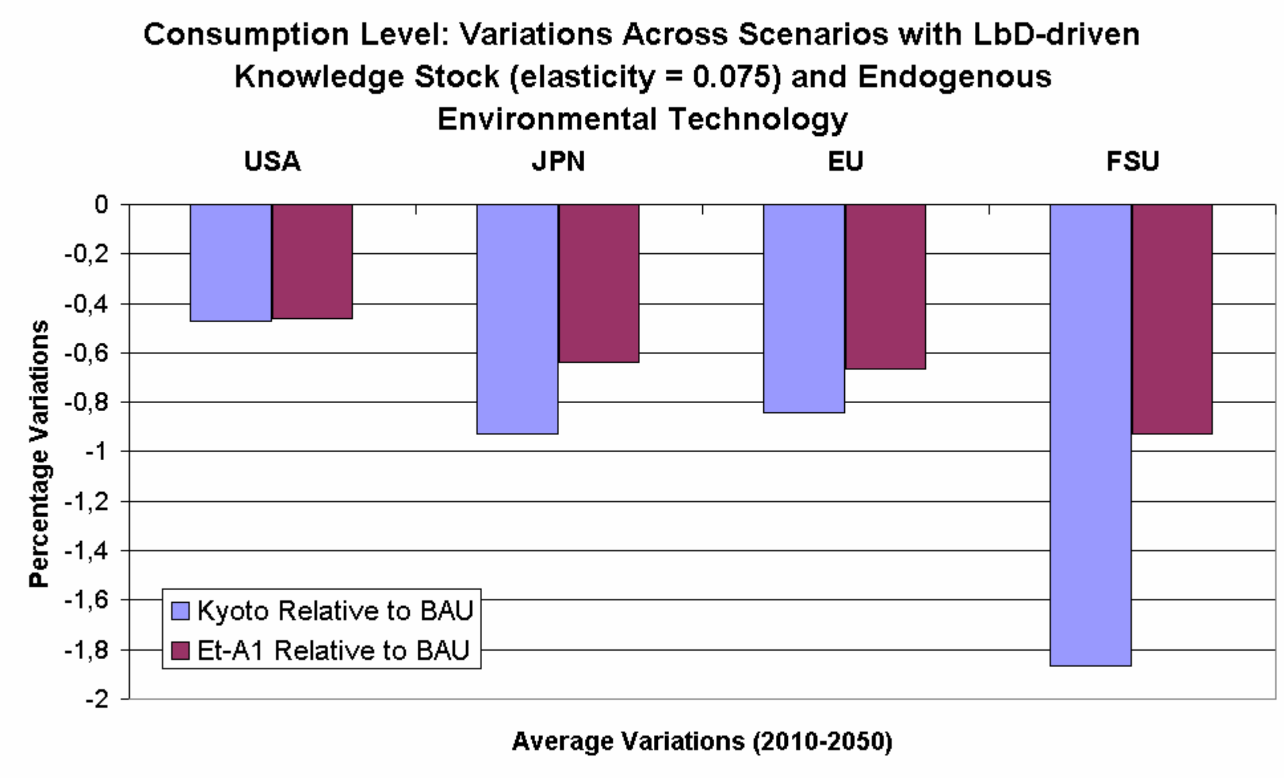

Domestic Abatement Rate: Variations Across Scenarios with LbD-driven Knowledge Stock (elasticity = 0.025) and Endogenous Technical Change
Kyoto Relative to BAU
Et-A1 Relative to BAU
Variations
60
50
40
30
20
10
0
USA
JPN
EU
FSU
Average Variations (2010-2050)

Figure 8

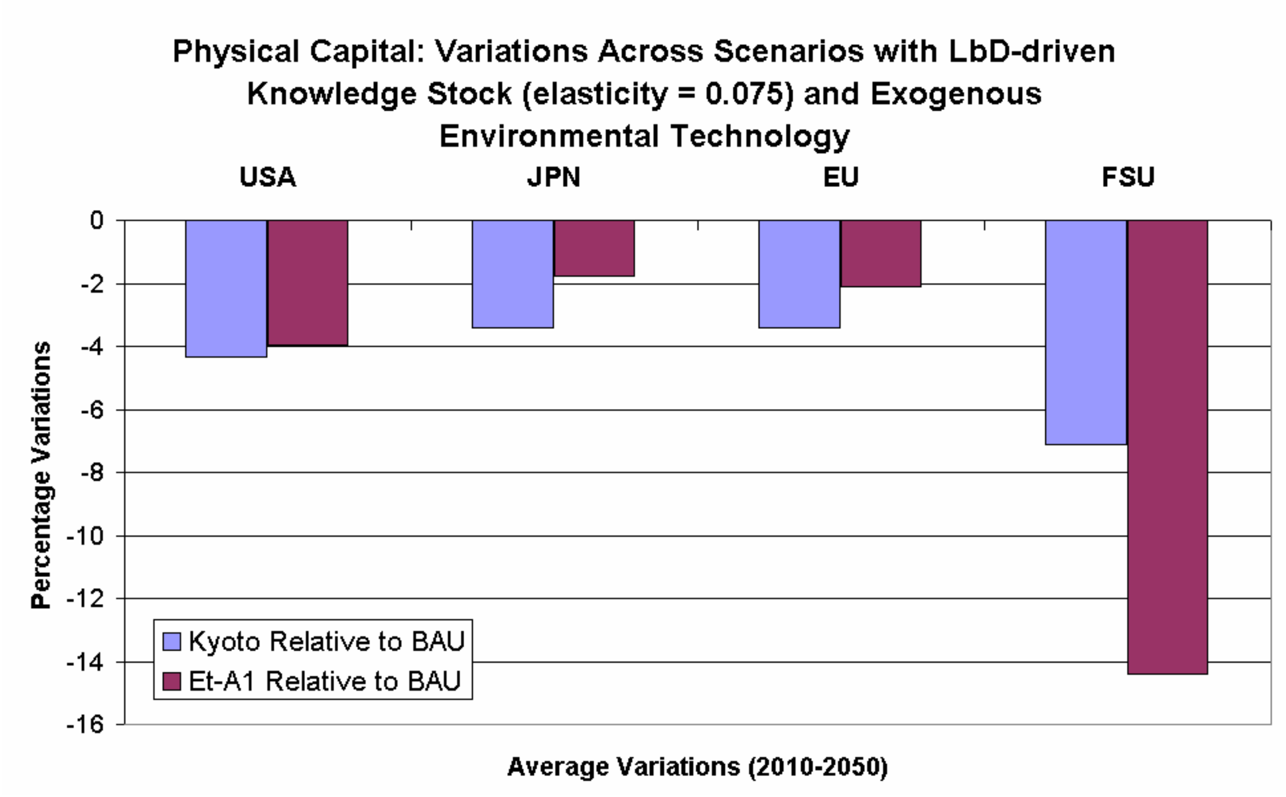


Consumption Level: Variations Across Scenarios with LbD-driven Knowledge Stock (elasticity = 0.075) and Exogenous Environmental Technology
USA
JPN
EU
FSU
0
-0,5
-1
-1,5
-2
-2,5
Percentage Variations
Kyoto Relative to BAU
Et-A1 Relative to BAU
Average Variations (2010-2050)

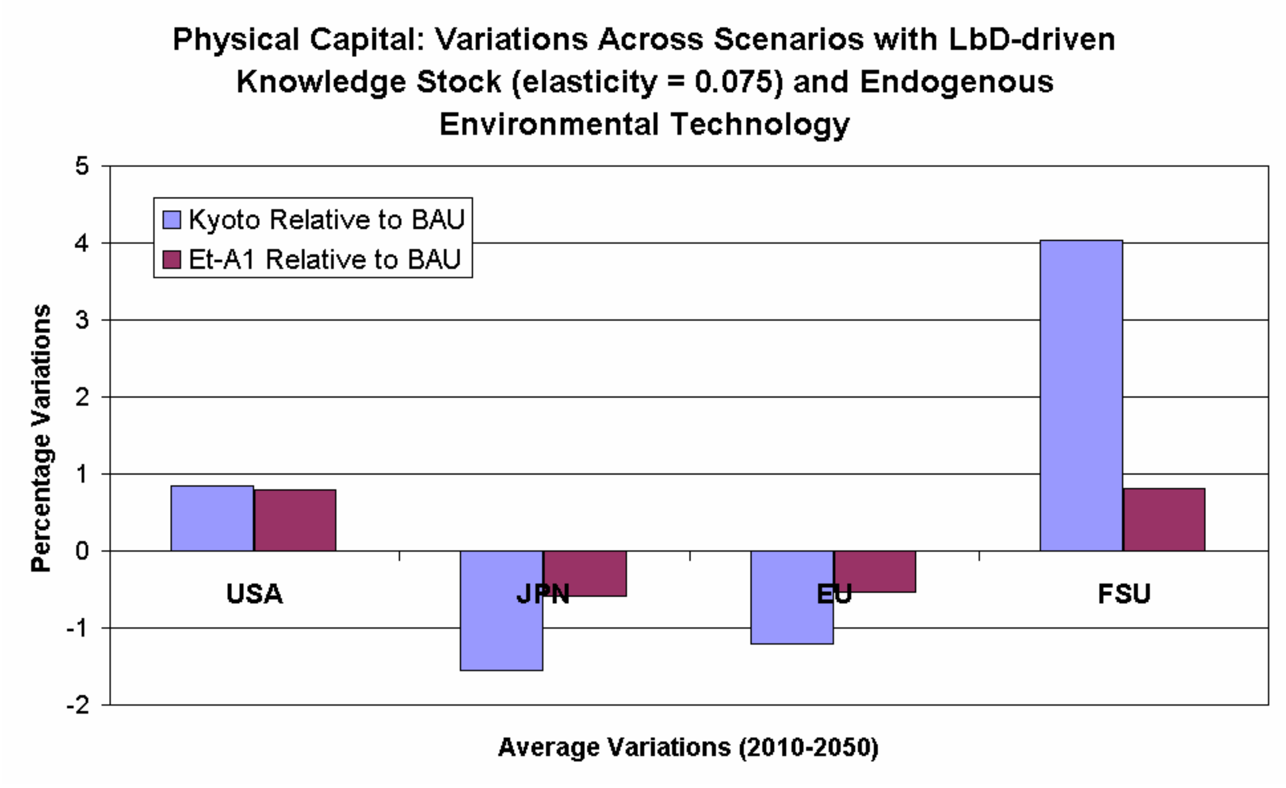


Consumption Level: Variations Across Scenarios with LbD-driven Knowledge Stock (elasticity = 0.075) and Endogenous Environmental Technology
USA
JPN
EU
FSU
0
-0,2
-0,4
-0,6
-0,8
-1
-1,2
-1,4
-1,6
-1,8
-2
Percentage Variations
Kyoto Relative to BAU
Et-A1 Relative to BAU
Average Variations (2010-2050)

Figure 9

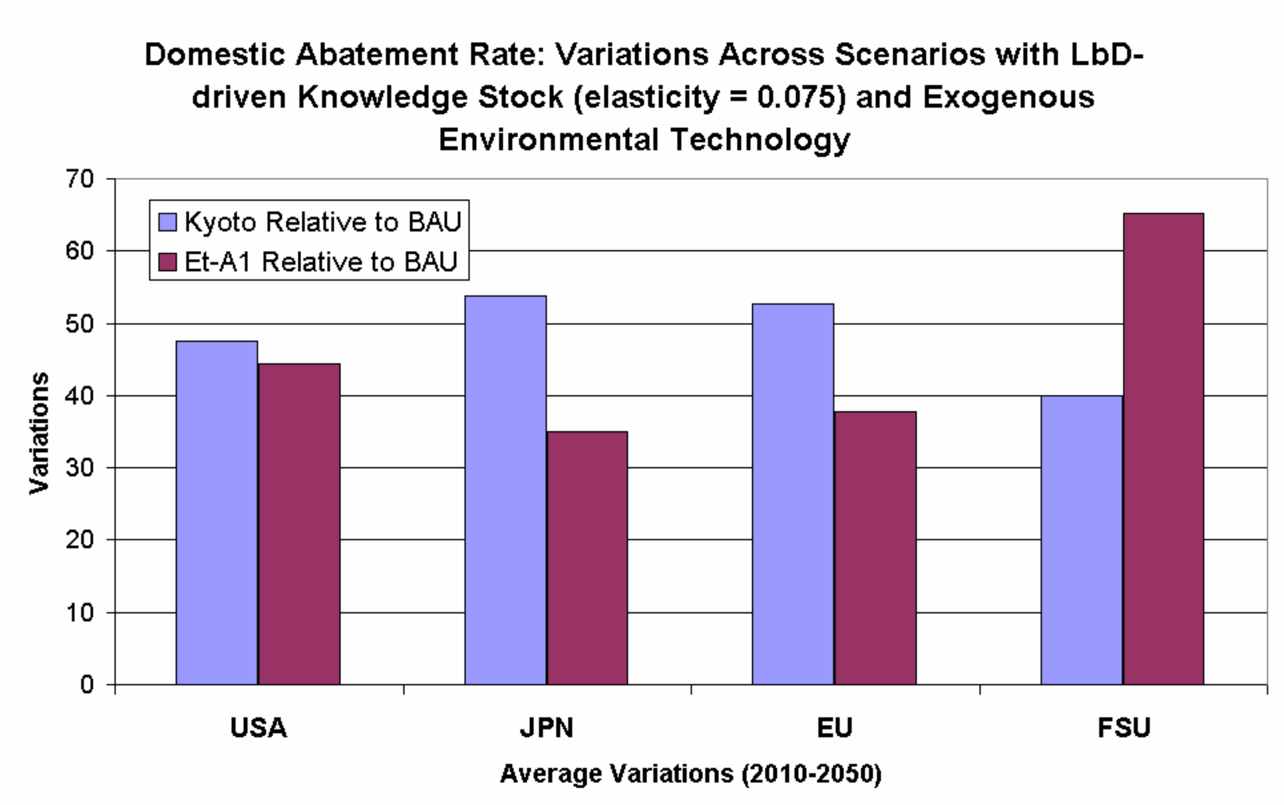


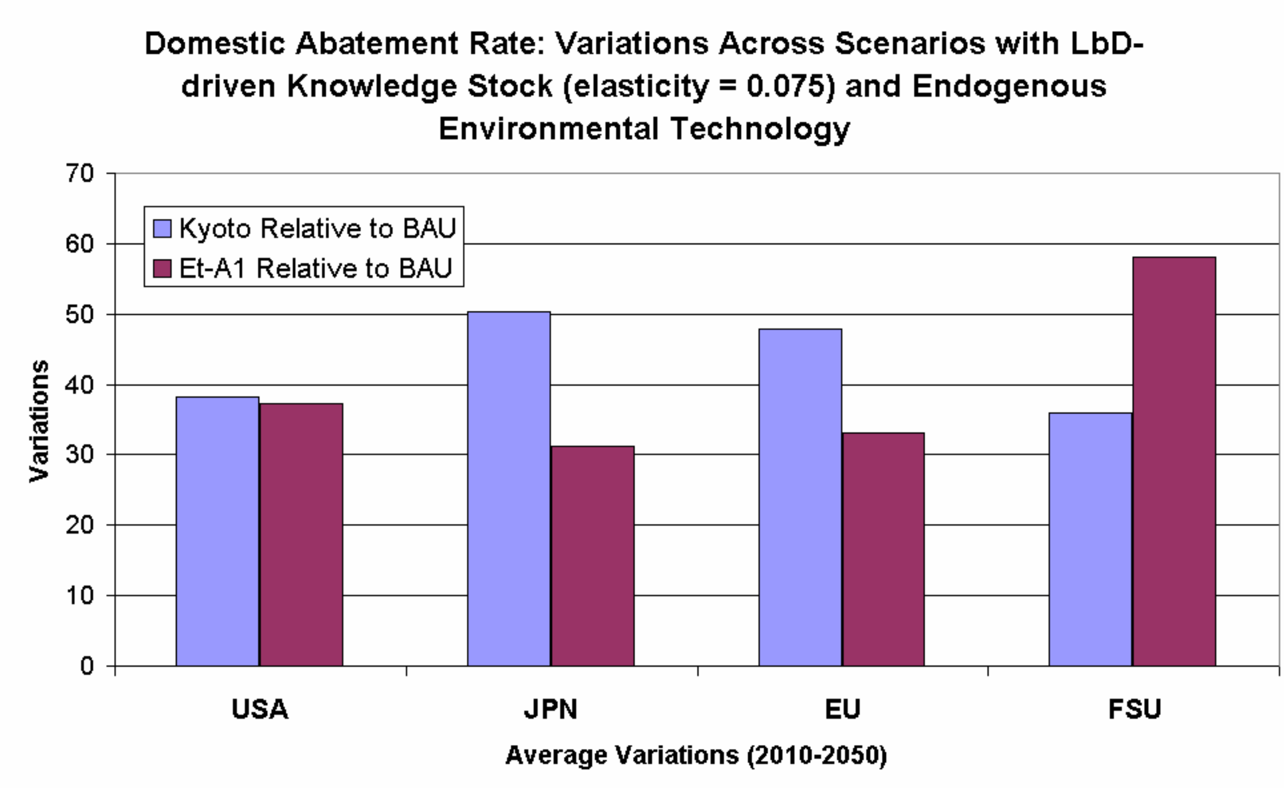
Physical Capital: Variations Across Scenarios with LbD-driven Knowledge Stock (elasticity = 0.075) and Exogenous Environmental Technology



Physical Capital: Variations Across Scenarios with LbD-driven Knowledge Stock (elasticity = 0.075) and Endogenous Environmental Technology

Figure 10


Domestic Abatement Rate: Variations Across Scenarios with LbD-driven Knowledge Stock (elasticity = 0.075) and Exogenous Environmental Technology
Kyoto Relative to BAU
Et-A1 Relative to BAU
Variations
0
10
20
30
40
50
60
70
USA
JPN
EU
FSU
Average Variations (2010-2050)


Domestic Abatement Rate: Variations Across Scenarios with LbD-driven Knowledge Stock (elasticity = 0.075) and Endogenous Environmental Technology
Kyoto Relative to BAU
Et-A1 Relative to BAU
Variations
0
10
20
30
40
50
60
70
USA
JPN
EU
FSU
Average Variations (2010-2050)

4.3 A Comparison between the Two Approaches

Goulder and Mathai (2000) explore the importance of policy induced technological change for the design of carbon abatement policies. By comparing R&D-based and LbD-based knowledge accumulation, they verify that the impact of induced technical change on the optimal abatement path varies. In particular, when knowledge is gained through R&D investments, the presence of immediately improving technology justifies a delay in abatement efforts, while when LbD is the source of knowledge the impact on the timing of abatement turns out being ambiguous. Notice that in their work a social planner has to face a constraint on carbon concentration (i.e. cumulated emissions), while in ours six different regions play a Nash-game taking into account caps on emissions. Goulder and Mathai (2000)'s and our framework are so deeply different, so rendering very difficult a direct comparison on the results. That is why, in drawing a comparison between R&D and LbD, we prefer to focus our attention on the variables we have focused our attention on so far, i.e. consumption, physical capital, and domestic abatement rate.

First of all, what we want to emphasize is that R&D and LbD are two conceptually different sources of Knowledge. Indeed, the first one is costly, but it endows firms with a control variable more (R&D expenditures), so rendering their problem more 'flexible'. Vice versa, Knowledge stemming from LbD is for free *ceteris paribus*, but firms do not have any specific control variable to manage it.

Nevertheless, our findings regarding the imposition of emissions constraints (with or without flexibility mechanism) are qualitatively speaking quite similar. In fact, it turns out that limits on emissions are welfare depressing, because they bring to clear reduction in the consumption enjoyed by the agents. Moreover, apart from some exception (USA and FSU), that imposition leads to a reduction in the stock of physical capital, and a logical increase of the domestic effort aimed at an environmental improvement. As expected, the flexibility mechanism (i.e. emissions trading) renders less costly to comply with the Kyoto Protocol.

Quantitatively speaking, some differences are worth to be underlined. First of all, the welfare losses seem to be more marked under LbD, both in the case of exogenous technical change and in the case with endogenous sigma. The intuition for this result is the following: when having to face the environmental constraints, under the R&D-driven hypothesis agents vary (also) the R&D expenditures levels in order to comply with Kyoto. This means that the (negative) impact of the environmental limits is optimally 'distributed' by the agents both on physical capital and on Knowledge, which have in this case different elasticities with respect to output. Instead, in the LbD-driven Knowledge framework, Kyoto's implications in terms of reduced production affect uniquely physical capital; in other words, agents have a degree of freedom less, so it is not surprising that they obtain an inferior result in terms of welfare.

The key role of physical capital is confirmed by the fact that with exogenous emission-output ratio the reduction of the accumulated fixed investments are less pronounced under R&D; this is so because of the impossibility of improving the environmental technology by augmenting the stock of Knowledge. Instead, when the emissions-output ratio is endogenous, capital plays the role of R&D, i.e. its reduction is less pronounced with respect to the R&D-driven Knowledge case because it causes the improvement of the environmental technology.

The fruitful interactions between R&D and domestic abatement rate implies that the latter is lower when agents may exploit the former; in other words, in presence of R&D agents undertake less domestic efforts with respect to the LbD case, in which of course those interactions are just not possible.

All what we have written above holds also in case of emissions trading, which so renders less costly the compliance of the Kyoto protocol, without affecting that much the relative importance of the agents' control variables.

5. Concluding Remarks

Current modeling practices in the climate change literature are intensifying efforts at endogenizing the process of technological change. The bottom-up tradition has typically considered the notion of Learning by Doing, incorporated through learning curves associated with each technology considered. Top-down models have instead experimented more with R&D-based knowledge formation processes meant to capture the idea of an endogenously evolving technology. While there are a few recent attempts to allow for a role of R&D in learning process specified by bottom-up models and to accommodate Learning by Doing in top-down models, it appears that no model has yet studied both formulations using the same conceptual framework.

In this paper we have extended Nordhaus and Yang's RICE model to allow for, besides emission trading, endogenous technical change. A crucial role is given to the stock of knowledge which accumulates either through deliberate, optimally selected, R&D activities, or through physical investment. In the latter case the stock of knowledge becomes equivalent to cumulative installed capacity. The model presented here, called ETC-RICE, specifies endogenous technical change (enhancing output production) together with or without induced technical change (reducing emissions-to-output). In all cases the state of technology, both environmental and not, can also evolve exogenously.

With these two versions of the model we ran a set a basic simulations under alternative regimes concerning emission trading within the context of the Kyoto Protocol.

Our results seem to support the conclusion that, although conceptually very different, R&D-driven and LbD-driven Knowledge frameworks may lead to qualitatively similar findings. In particular, what we find is that caps on emissions are welfare depressing, and the possibility to affect the environmental technology just offers a milder version of this depression. However, our quantitative outcomes lead us to think that R&D, being a costly but additional control variable exploitable by optimizing agents, may provide the agents with a better outcome with respect to a pure LbD framework, in which Knowledge accumulates for free but it may constrain agents to undertake optimal choices in a more ‘rigid’ set up.

In this paper we did not study forms of hybrid Knowledge formation, i.e. situations in which R&D and LbD are jointly present. We guess that a hybrid Knowledge formation could provide agents with a superior results, but empirical endeavors have to be undertaken before claiming so.

Naturally, much remains to be done within the research project of which the present paper is a further block. The next and more important task is to complete the transition to a more realistic model, the RICE99 model, which highlights a new production input, carbon energy, together with a price for it. Other aspects to allow for are knowledge spillovers, carbon sequestration, and climate change impacts.

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(l) This paper was presented at the Workshop “Growth, Environmental Policies and Sustainability” organised by the Fondazione Eni Enrico Mattei, Venice, June 1, 2001

(li) This paper was presented at the Fourth Toulouse Conference on Environment and Resource Economics on “Property Rights, Institutions and Management of Environmental and Natural Resources”, organised by Fondazione Eni Enrico Mattei, IDEI and INRA and sponsored by MATE, Toulouse, May 3-4, 2001

(lii) This paper was presented at the International Conference on “Economic Valuation of Environmental Goods”, organised by Fondazione Eni Enrico Mattei in cooperation with CORILA, Venice, May 11, 2001

(liii) This paper was circulated at the International Conference on “Climate Policy – Do We Need a New Approach?”, jointly organised by Fondazione Eni Enrico Mattei, Stanford University and Venice International University, Isola di San Servolo, Venice, September 6-8, 2001

(liv) This paper was presented at the Seventh Meeting of the Coalition Theory Network organised by the Fondazione Eni Enrico Mattei and the CORE, Université Catholique de Louvain, Venice, Italy, January 11-12, 2002

(lv) This paper was presented at the First Workshop of the Concerted Action on Tradable Emission Permits (CATEP) organised by the Fondazione Eni Enrico Mattei, Venice, Italy, December 3-4, 2001

(lvi) This paper was presented at the ESF EURESCO Conference on Environmental Policy in a Global Economy “The International Dimension of Environmental Policy”, organised with the collaboration of the Fondazione Eni Enrico Mattei , Acquafredda di Maratea, October 6-11, 2001

(lvii) This paper was presented at the First Workshop of “CFEWE – Carbon Flows between Eastern and Western Europe”, organised by the Fondazione Eni Enrico Mattei and Zentrum fur Europaische Integrationsforschung (ZEI), Milan, July 5-6, 2001

(lviii) This paper was presented at the Workshop on “Game Practice and the Environment”, jointly organised by Università del Piemonte Orientale and Fondazione Eni Enrico Mattei, Alessandria, April 12-13, 2002

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