Fondazione Eni Enrico Mattei

Global Warming, Uncertainty and Endogenous Technical Change: Implications for Kyoto

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NOTA DI LAVORO 61.2001

SEPTEMBER 2001

CLIM – Climate Change Modelling and Policy

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This paper is part of the research work being carried out by the Climate Change Modelling and Policy Unit at Fondazione ENI Enrico Mattei. We would like to thank C. Carraro, F. Bosello, and P. Buonanno for their helpful comments and suggestions. We thank Z. Yang who kindly provided us with the RICE model software.

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SUMMARY

The purpose of the present paper is to describe the role of uncertainty and technical change in an environmental context. Which impact does ecological uncertainty have on physical and R&D investments' decisions? How are pollution trajectories modified when uncertainty is taken into account? To reply these questions we modify the ETC-RICE model described in Buonanno *et al.* (2000) by embedding in it the "hazard rate function" approach as in Bosello and Moretto (1999). With such a model we are also able to study some consequences of the implementation of the Kyoto agreement under different policy options - i.e. with or without different degrees of introduction of one of the so-called "flexibility mechanisms" (specifically, the Emissions Trading) - in order to assess its impact on agents' behaviour in terms of domestic abatement, consumption, physical and environmental investment, trading of emissions rights (quantity and price). The results show that uncertainty strongly influences agents' behaviour; in particular, agents calm down the increase of temperature via lower emissions. In addition, R&D expenditures are a mean exploited in order to trigger the "engine of growth" only when environmental endogenous technical change is allowed. However, even if uncertainty may stimulate technical change, long-run growth is negatively affected by its presence as predicted by the theory (e.g. Clarke and Reed 1994; Tsur and Zemel 1996; and Bosello and Moretto 1999).

Keywords: Climate Change, Endogenous Technical Change, Uncertainty

JEL Classification: D8, D9, F18, O2, O3, Q2

NON TECHNICAL SUMMARY

The bio-physical aspects of a large number of environmental phenomena are still highly uncertain. The great scientific debate on the evolution of global temperature or on ozone depletion are just two examples of the relevant role of uncertainty. This physical, chemical, and biological uncertainty, that we term *ecological uncertainty* (Pindyck, 2000, pag. 235), makes it difficult to evaluate the costs and benefits associated with environmental policy interventions as well as the effectiveness of instruments to control greenhouse gas emissions.

Different aspects of uncertainty have been considered so far. Many models have been built in order to evaluate the *cost of uncertainty*. A "common" approach is to try to quantify the value of "early knowledge", that is, the economic value of resolving the uncertainties about climate change sooner rather than later. Another perspective is given by the possibility offered by some models to evaluate the *outcome* of a given action under different future scenarios which can be chosen by the user. Finally, a third approach to uncertainty is to describe how an uncertain, but possible, future and irreversible event can influence present decisions. In this approach the uncertainty stems from the agents' ignorance on the level of global temperature required to trigger a "catastrophic" event that, once occurred, brings about a dramatic fall in the social welfare (utility levels). The approach generally followed is to incorporate in an Integrated Assessment Model a hazard rate function linking an environmental (usually endogenous) variable of the model to a "survivor probability", which is in turn used to weight the utility level pre-catastrophe and the so-called "utility post-catastrophe". Specifically, after the catastrophic event, the utility is usually fixed to a certain level occurred in the past, or (in a more extreme version) to a nil value.

To our knowledge, no attempt has been made to date to embed the above described "hazard rate" framework in a model dealing explicitly with endogenous technical change. However, this is a very important issue, as illustrated by Carraro and Hourcade (1998). Uncertainty may well influence the agents' decisions regarding R&D expenditures, both environmental and not. According to Bosello and Moretto (1999), for instance, in presence of *backstop* technologies uncertainty works in favour of low polluting production methods. But does this conclusion still hold in presence of endogenous technical change? How does uncertainty affect investment decisions? How are pollution trajectories modified in this respect?

In order to try to answer these questions, we follow the "hazard rate function" approach as implemented by Bosello and Moretto (1999) and incorporate it into the ETC-RICE model described in Buonanno, Carraro, Castelnuovo, and Galeotti (2000) and Buonanno, Carraro, and Galeotti (2000). This is a simple climate model with endogenous environmental technical change, obtained by integrating Nordhaus and Yang (1996)'s RICE model with the insights from Nordhaus (1997) and Goulder and Mathai (2000). With such model we are also able to study some consequences of the implementation of the Kyoto agreement under different policy options, i.e. with or without different degrees of introduction of one of the so-called "flexibility mechanisms" (specifically, the Emissions Trading). Hence, with this work we also try to investigate how the imposition of ceilings on emissions (termed "Kyoto constraints") modifies the behaviour of the agents in terms of domestic abatement, consumption, physical and environmental investment, as well as how uncertainty influences the trading of emissions rights (quantity and price), when allowed.

The results show that uncertainty strongly affects agents' behaviour. In particular, agents are more cautious when there is the possibility of a catastrophe, and produce less in order to reduce the increase of temperature via lower emissions. In words, uncertainty is costly: total abatement costs are larger than in the case with perfect information regarding the future scenario. In addition, under uncertainty, R&D expenditures are a mean exploited in order to trigger the "engine of growth" only when environmental endogenous technical change in allowed. However, even if uncertainty may stimulate technical change, long-run growth is negatively affected by its presence as predicted by the theory (e.g. Clarke and Reed 1994; Tsur and Zemel 1996; and Bosello and Moretto 1999).

The structure of the paper is as follows. Section 2 presents the modelling framework regarding uncertainty. Sections 3 briefly describes the ETC-RICE model, and how we modify it in order to take into account environmental uncertainty. Section 4 discusses the main simulation results. We present comparisons among models (without and with uncertainty) whose environmental technology (energy efficiency) evolves either exogenously (á la Nordhaus and Yang, 1996) or endogenously (as done by Goulder and Mathai, 2000). We then investigate a situation with uncertainty either without or with endogenous environmental technology. Finally, section 5 provides some policy conclusions and describes directions of future research.

CONTENTS

GLOBAL WARMING, UNCERTAINTY AND ENDOGENOUS TECHNICAL CHANGE: IMPLICATIONS FOR KYOTO

1. Introduction

The bio-physical aspects of a large number of environmental phenomena are still highly uncertain. The great scientific debate on the evolution of global temperature or on ozone depletion are just two examples of the relevant role of uncertainty. This physical, chemical, and biological uncertainty, that we term *ecological uncertainty* (Pindyck, 2000, pag. 235), makes it difficult to evaluate the costs and benefits associated with environmental policy interventions as well as the effectiveness of instruments to control greenhouse gas emissions.

The fact that natural developments do not follow linear evolutionary trends makes it even more difficult to take into account the role of uncertainty. In fact, natural developments are characterised by radical changes that may dramatically modify living and economic conditions. Moreover, natural phenomena may also be "irreversible". That is, the possibility of catastrophic events induced by global warming cannot be excluded a priori (see IPCC, 1996a,b,c). In this respect, Fisher (2000, pag.192) points out that "There is some possibility of essentially irreversible catastrophic impact, as would result for example from the disintegration of the West Antartic ice sheet and consequent rise in sea levels of 5-6 m. Recent findings suggest that this possibility is more serious, and perhaps closer in time, than economists (and others) have realised (Kerr, 1998). Moreover, it seems plausible that the probability of such an event is positively related to the level of greenhouse gas concentrations in the atmosphere. In other words, the risk ought to be endogenous in a model of the optimal control of greenhouse gas emission."[1]

Consequently, the so called Integrated Assessment Models (IAM) need to be able to capture "jumps" and irreversibilities in order to predict and avoid dangerous divergence from equilibrium paths.

Different aspects of uncertainty have been considered so far. Many models have been built in order to evaluate the *cost of uncertainty*. A "common" approach is to try to quantify the value of "early knowledge", that is, the economic value of resolving the uncertainties about climate change sooner rather than later (see Manne and Richels, 1992; Peck and Teisberg, 1993; Manne, 1996; Nordhaus and Popp, 1997).

[1] A similar view was expressed by Nordhaus (1999, pag.10): "The major concern, in my view, is the potential for abrupt and unforeseen changes in climate, particularly on a regional level. A major concern, for example, is reversal of thermohaline circulation, which could lead to enormous climatic shifs in Europe. This and similar 'catastrophes' are genuinely frightening prospects, but we have no reliable way of assessing their likelihood at present."

Another perspective is given by the possibility offered by some models to evaluate the *outcome* of a given action under different future scenarios which can be chosen by the user. Models like FUND (Tol, 1997), PAGE (Plambeck and Hope, 1996), ICAM (Dowlatabadi and Kandlikar, 1995), and CONNECTICUT (Yohe, 1996) belong to this category.

Finally, a third approach to uncertainty is to describe how an uncertain, but possible, future and irreversible event can influence present decisions. In this approach the uncertainty stems from the agents' ignorance on the level of global temperature required to trigger a "catastrophic" event that, once occurred, brings about a dramatic fall in the social welfare (utility levels). Catastrophic environmental outcomes due to stock pollutants have been analysed both in the *theoretical* and in the *applied quantitative* economic literature. From a theoretical point of view, many authors (Cropper, 1976; Heal, 1984; Clarke and Reed, 1994; Larson and Tobey, 1994; Tsur and Zemel, 1996; Torvanger, 1997) have established a relationship between an environmental indicator (pollution, level of temperature, aggregated extraction) and the probability of a catastrophe: in particular, the closer is the environmental indicator to a certain threshold, the higher is the probability of the catastrophic event. Several papers have analysed the role of ecological uncertainty in connection with global warming with the help on numerical models (see Nordhaus, 1994; Yohe, 1996; Gjerde, Grepperud, and Kverndokk, 1999; Bosello and Moretto, 1999). The approach generally followed is to incorporate in an IAM a hazard rate function linking an environmental (usually endogenous) variable of the model to a "survivor probability", which is in turn used to weight the utility level pre-catastrophe and the so-called "utility post-catastrophe". Specifically, after the catastrophic event, the utility is usually fixed to a certain level occurred in the past, or (in a more extreme version) to a nil value.

To our knowledge, no attempt has been made to date to embed the above described "hazard rate" framework in a model dealing explicitly with endogenous technical change. However, this is a very important issue, as illustrated by Carraro and Hourcade (1998). Uncertainty may well influence the agents' decisions regarding R&D expenditures, both environmental and not. According to Bosello and Moretto (1999), for instance, in presence of *backstop* technologies uncertainty works in favour of low polluting production methods. But does this conclusion still hold in presence of endogenous technical change? How does uncertainty affect investment decisions? How are pollution trajectories modified in this respect?

In order to try to answer these questions, we follow the "hazard rate function" approach as implemented by Bosello and Moretto (1999) and incorporate it into the ETC-RICE model described in Buonanno, Carraro, Castelnuovo, and Galeotti (2000) and Buonanno, Carraro, and Galeotti (2000). This is a simple climate model with endogenous environmental technical change, obtained by integrating Nordhaus and Yang (1996)'s RICE model with the insights from Nordhaus (1997) and Goulder and Mathai (2000). The result is what we called ETC-U-RICE (Endogenous Technical Change with Uncertainty-RICE). With such model we are also able to study some consequences of the implementation of the Kyoto agreement under different policy options, i.e. with or without different degrees of introduction of one of the so-called "flexibility mechanisms" (specifically, the Emissions Trading). Hence, with this work we also try to investigate how the imposition of ceilings on emissions (termed "Kyoto constraints") modifies the behaviour of the agents in terms of domestic abatement, consumption, physical and environmental investment, as well as how uncertainty influences the trading of emissions rights (quantity and price), when allowed.

The structure of the paper is as follows. Section 2 presents the modelling framework regarding uncertainty. Sections 3 briefly describes the ETC-RICE model, and how we modify it in order to take into account environmental uncertainty. Section 4 discusses the main simulation results. We present comparisons among models (without and with uncertainty) whose environmental technology (energy efficiency) evolves either exogenously (á la Nordhaus and Yang, 1996) or endogenously (as done by Goulder and Mathai, 2000). We then investigate a situation with uncertainty either without or with endogenous environmental technology. Finally, section 5 provides some policy conclusions and describes directions of future research. Needless to say, the results show that uncertainty strongly affects agents' behaviour. In particular, agents are more cautious when there is the possibility of a catastrophe, and produce less in order to reduce the increase of temperature via lower emissions. In words, uncertainty is costly: total abatement costs are larger than in the case with perfect information regarding the future scenario. In addition, under uncertainty, R&D expenditures are a mean exploited in order to trigger the "engine of growth" only when environmental endogenous technical change in allowed. However, even if uncertainty may stimulate technical change, long-run growth is negatively affected by its presence as predicted by the theory (e.g. Clarke and Reed 1994; Tsur and Zemel 1996; and Bosello and Moretto 1999).

2. One way of dealing with Uncertainty

As pointed out by Fisher (2000), one aspect of environmental uncertainty concerns *catastrophes*. The possibility of catastrophic outcomes due to global warming cannot be completely dismissed. But what do we mean by "catastrophe"? And how can agents take into account the possibility of facing a catastrophic event? Bosello and Moretto (1999) provide an answer to these two questions. In their paper they use three diverse IAMs (RICE, CETA, and MERGE) and run simulations for different variables over the period 1990-2100 (or more). They define a *catastrophe* an event after which the utility level of the world regions dramatically drops either to zero or back to the 1990 values. The problem for the agents is that they are aware of the fact that they *could* face a catastrophic event, but they do not know precisely *if* and *when* the catastrophe will take place. Therefore, in solving their optimisation problem, agents maximise the discounted sum of a utility function which looks as follows:

$$U(n,t) = SP(t)U(n,t)_{bc} + [1 - SP(t)]U(n)_{ac} \quad (1)$$

where $U(n,t)_{bc}$ stands for "Utility before a catastrophe", and $U(n)_{ac}$ indicates "Utility after a catastrophe", as indicated above. The indexes n and t refer to regions of the world and to time, respectively. In particular, while $U(n,t)_{bc}$ is a function evolving over time, $U(n)_{ac}$ is a constant. Notice that each region n face a different convex combination $U(n,t)$ in every period t, but has in common the "survivor probability" *SP(t):* i.e. we assume that all agents share and use the same information about world catastrophic events. The survivor probability identifies the probability of a catastrophic event *not* taking place up to t, and in Bosello and Moretto (1999) is taken to be an endogenous scalar. In fact, it is given by the following exponential distribution:

$$SP(t) = exp[-HR(t)] \tag{2}$$

where *HR(t)*, "Hazard Rate" function, is a cumulative function that provides the link between the survivor probability and the (endogenous) level of temperature measured on the planet at a certain moment.[2] Due to higher emissions following from increasing production, which brings about higher concentrations of GHGs into the atmosphere, thus entailing temperature increases, the survivor probability is negatively correlated with hazardous behaviour by polluting countries.

Technically speaking, the hazard rate function is defined by Bosello and Moretto (1999) as follows:

$$HR(t) = HR(t-1) + [\varphi_0 + \varphi_1 \dot{T}(t)]\eta[max(0, T(t) - T_0)]^{\eta-1} \quad \text{for} \quad \dot{T}(t) > 0 \tag{3}$$

$$= 0 \qquad \text{otherwise}$$

where $\dot{T}(t) \equiv \dfrac{\Delta T(t)}{T(t-1)}$ represents the rate of change of the temperature level T(t), while φ_0, φ_1, and η are coefficients. It is immediate to see that the higher the temperature, the more "hazardous" is the behaviour of the agents in the economy.[3] This is due to the simple link existing between level of pollution, carbon concentration, and temperature level: the more GHGs are emitted due to production activities, the more global warming is anthropologically created.

According to equation (3), when the coefficient $\varphi_1 \neq 0$, agents adjust, at each time t, their emission control effort according to the temperature level at time t *and* to its rate of change. Hence, it is not only the current level of temperature at time that influences how the beliefs are formed, but rather it is the historical evolution of the temperature that matters (i.e. the speed at which the climate has been changing over several decades).[4]

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[2] For a more complete treatment of hazard functions see Kiefer (1988).

[3] It is worth to note that, given the production activities undertaken by the regions, in our simulations, the temperature level results to be always monotonically increasing with both an exogenous and an endogenous emissions-output ratio is embedded in the model. Therefore, the above hazard rate never collapse to zero. For pictures regarding the temperature patterns, see Figure 1 and 2.

[4] In their paper, Bosello and Moretto (1999) distinguish between two different cases. In the first one, the coefficient φ_1 is equal to zero; as a consequence, the historical path of the temperature level does not affect the Hazard Rate. The uncertainty stemming from this particular case is termed by the authors as "exogenous". In the second one, in which $\varphi_1 \neq 0$, the uncertainty is labelled as "endogenous". The uncertainty we consider in our work is the one that they call "endogenous". We think this is a richer and more interesting specification, because we believe that agents indeed exploit the whole set of available information in order to make optimal choices.

We embed into the ETC-RICE model (see Buonanno, Carraro, Castelnuovo, and Galeotti, 2000; Buonanno, Carraro, and Galeotti, 2000) the equations presented above. In particular we set η equal to 2.5 (the current level of temperature does influence the Survivor Probability) and $\varphi_1 > 0$ (the past temperature level does affect positively agents' beliefs). Moreover, in order to have the sharpest difference between the situation "before catastrophe" and the scenario "after catastrophe", and consequently to highlight clearly how uncertainty influences agents' choices, we select to choose a utility level *after* the catastrophe equal to zero (irreversible event). This last choice brings us to simplify the objective function (1) as follows:

$$U(n,t) = SP(t)U(n,t)_{bc} \tag{1'}$$

Computation wise, given our choice regarding the type of uncertainty we consider and the functional form of the Hazard Rate function we have adopted, we must calibrate the two coefficients φ_0 and φ_1. Given that we have two unknowns, we need to identify two assumptions in order to have a just-identified system. The two assumptions are (i) the level of catastrophe probability equal to 4,8% in year 2090, and (ii) the level of the catastrophe probability in years 2010-2020 lower than 0,1%, a value that can be considered as plausible for the occurrence of a catastrophic event in the next decade.[5] Hence, after embedding into the ETC-RICE model the framework relative to environmental uncertainty, we calibrated the two coefficients φ_0, φ_1 - following assumptions (i) and (ii) - by considering the so-called "Business-As-Usual" policy option, which is a scenario in which no efforts on emissions are undertaken by any region. The results of our calibration experiments, together with the other values featuring the environmental uncertainty as above described, are summarised in the following table:

Table 1

$U(n)_{ac} = 0$
$\eta = 2.5$
$\varphi_0 = 0.0015$
$\varphi_1 = 0.001$

[5] The first value derives from Nordhaus (1994), who asked a panel of experts to define subjectively the probability of a catastrophe in year 2090 in case an increase of 3° C were experienced. Nordhaus' definition of catastrophe is a loss of world GDP of more than 25%. The same estimate has been used among others by Manne (1996) and Gjerde et al. (1999) in similar studies. Explanations for the assumption underlying the second number are provided by Bentley (1997).

3. The ETC-RICE model with Uncertainty

In order to study the relationship between environmental uncertainty and endogenous technical change, we embed the analytical apparatus above described into the ETC-RICE model as formulated in Buonanno, Carraro, Castelnuovo, and Galeotti (2000) and more roughly in Buonanno, Carraro, and Galeotti (2000). This is an IAM based on the well known RICE model by Nordhaus and Yang (1996) and enriched with insights from Goulder and Mathai (2000)'s partial equilibrium model of knowledge accumulation.[6] Buonanno, Carraro, Castelnuovo, and Galeotti (2000) and Buonanno, Carraro, and Galeotti (2000) assume that innovation is brought about by R&D spending which contributes to the accumulation of the stock of existing knowledge. Following an approach pioneered by Griliches (1979, 1984), they assume that the stock of knowledge is a factor of production, which therefore enhances the rate of productivity (see also Weyant, 1997). Besides this channel, however, knowledge also serves the purpose of reducing, *ceteris paribus*, the level of carbon emissions. Thus, in their formulation, R&D efforts prompt both environmental and non-environmental technical progress, although with different modes and elasticities.

The key modifications to the RICE model are summarised in the following formulas:

$$Q(n,t) = A(n,t)K_R(n,t)^{\beta_n}[L(n,t)^{\gamma}K_F(n,t)^{1-\gamma}] \tag{4}$$

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

In the production function (4) the stock of knowledge K_R has a region-specific elasticity equal to β_n *(n=1,…6)*. Note that to the extent that this coefficient is positive, the output production process is characterised by increasing returns to scale, in line with current theories of endogenous growth. Also, note that while the authors allow for R&D-driven technological progress, they maintain the possibility that technical improvements can also be determined exogenously (the path of *A* is the same as that specified in the original RICE model). In (5) knowledge reduces the emissions-output ratio (hereafter simply referred to as "sigma") with an elasticity of α_n, which also is region-specific; the parameter χ_n is a scaling coefficient, whereas σ_n is the value to which the emission-output ratio tends asymptotically as the stock of knowledge increases without limit.[7] The stock accumulates in the usual fashion:

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[6] A similar idea regarding endogenous technical change and knowledge accumulation is in Nordhaus (1997).

[7] To be precise, sigma is equal to $E(n,t)/[(1-\mu(n,t))Q(n,t)]$, the ratio between emissions and "non abated" output.

$$K_R(n,t+1) = R\&D(n,t) + (1-\delta_R)K_R(n,t) \tag{6}$$

where *R&D* are the expenditures in research and development and δ_R is the rate of knowledge depreciation. Some resources are absorbed by R&D spending. That is:

$$Y(n,t) = C(n,t) + I(n,t) + R\&D(n,t) \tag{7}$$

In summary, Buonanno, Carraro, Castelnuovo, and Galeotti (2000) and Buonanno, Carraro, and Galeotti (2000)'s formulation introduces R&D as a further policy variable of the model which on the one hand contributes to output productivity and, on the other hand, affects the emission-output ratio, and therefore the overall level of pollution emissions.[8]

When simulating the model in the presence of emission trading, two other equations are added to the RICE model:

$$Y(n,t) = C(n,t) + I(n,t) + R\&D(n,t) + p(t)NIP(n,t) \tag{7'}$$

which replaces equation (7) and

$$E(n,t) = Kyoto(n) + NIP(n,t) \tag{8}$$

where *NIP(n,t)* is the net demand for permits and *Kyoto(n)* are the emission targets set in the Kyoto Protocol for the signatory countries, while these targets coincide with the BAU levels for the non-signatories. According to (7'), resources produced by the economy must be devoted, in addition to consumption, investment, and research and development, to net purchases of emission permits. Equation (8) states that a region's emissions may exceed the limit set in Kyoto if permits are bought, and vice versa in the case of sales of permits. Note that *p(t)* is the price of a unit of tradable emission expressed in terms of the numéraire output price. Moreover, there is an additional policy variable to be considered in this case, i.e. net demands for permits *NIP*.

Another important feature of the model regards the game played by the agents. Each country plays a non-cooperative Nash game in a dynamic setting, which results in a Open Loop Nash equilibrium (see Eyckmans and Tulkens, 1999). This is a situation where in each region the planner maximises its utility subject to the individual resource and capital constraints and the climate module for a given emission (i.e. abatement) strategy of all the other players.[9] Under the possibility of emission trading, the

[8] For details regarding parameter calibration and data requirements, see the quoted papers.
[9] As there is no international trade in the model, regions are interdependent through climate variables.

sequence whereby a Nash equilibrium is reached must be revised as follows. Each region maximises its utility subject to the individual resource and capital constraints, now including the Kyoto constraint, and the climate module for a given emission (i.e. abatement) strategy of all the other players and a given price of permits *p(0)* (in the first round this is set at an arbitrary level). When all regions have made their optimal choices, the overall net demand for permits is computed at the given price. If the sum of net demands in each period is approximately zero, a Nash equilibrium is obtained; otherwise the price is revised in proportion to the market disequilibrium and each region's decision process begins again.

Incorporating into the ETC-RICE model environmental uncertainty as described by equations (1'), (2), and (3) we obtain the ETC-U-RICE model.[10] The ETC-U-RICE model is used to perform simulations considering the following three different cases:

- absence vs. presence of uncertainty with exogenous environmental technical change (exogenous sigma). In this case accumulated R&D investments affect productivity, but not the (exogenously evolving) emissions-output ratio. This simulation is run in order to understand by how much R&D spending as well as on the other policy variables are affected by the presence of uncertainty;
- absence vs. presence of uncertainty with endogenous environmental technical change (endogenous sigma). This simulation is run in order to understand how different decisions are taken on R&D spending, as well as on the other policy variables, when we introduce uncertainty in a model with environmental R&D spending;
- exogenous vs. endogenous environmental technical change in presence of uncertainty. This last simulation is run in order to study the behaviour of the agents when shifting from an uncertain world with non-environmental R&D investments to one with environmental ones, under uncertainty.

Simulations will concern four different scenarios: Business-As-Usual (no abatement undertaken), Kyoto (Kyoto constraints are active from the 2010 on, but no trading allowed among any region), Et-A1 (trading allowed only among Annex 1regions), Et-All (trading allowed among all the countries without any constraint).

[10] In this respect, the assumption of equal survivor distribution among agents can be seen as the outcome of a two-period dynamic game where, in the first period agents set *SP(t)* and in the second period they play the Open-Loop Cournot – Nash game. Intuitively , as in the first period all agents know that in the second period the emissions trajectories would be chosen to maximise the discount value of utility (1') with *SP(t)* as scalar, they would minimise competition losses agreeing upon a common survivor distribution.

4. Simulations results

In this section we present the results of our simulations. As already indicated, we deal with three different set-ups: exogenous sigma (in absence or presence of uncertainty), endogenous sigma (in absence or presence of uncertainty), and exogenous vs. endogenous sigma (in presence of uncertainty). In the presentation of the results, we are forced to select a few variables because of space considerations. In particular, we concentrate on emissions, abatement costs, R&D spending, price and disequilibrium in the permit market, and GNP level.

4.1 Exogenous sigma: absence vs. presence of uncertainty

For this case our benchmark model is the ETC-RICE with exogenous environmental technical change and without uncertainty. Here R&D expenditures just prompt the productivity of the regions, without affecting the emissions-output ratio. Hence, accumulated R&D flows enter as input in the production function, but do not improve the relationship between production and pollution. Moreover, the absence of uncertainty implies that agents maximise the discounted value of their utility functions such as the one described in equation (1'), without considering the probability of facing a catastrophe. Formally, this is done by setting *SP(t)* = 1 in every period.

Our simulations show that when we pass from the benchmark model to the one with uncertainty each agent tends to be cautious and reduces the production in each region, in order to lower the overall level of emissions, keeping in this way as high as possible the survivor probability. Figure 3 shows how overall emissions at a world wide level are lower when uncertainty is considered: in every analysed policy option, this seems to be a common feature. The more cautious behaviour by the agents has been verified also by Gjerde et al. (1999), even though they find that even a fairly substantial long-term catastrophe risk does not have much of an impact on the desired emissions path in the short to medium term unless the discount rate is low. Notice that the behaviour of the agents is *not* the same shown by the RICE model with uncertainty, as underlined by Bosello and Moretto (1999). The authors underline how in the RICE model agents show a quite paradoxical behaviour in the short-run, by augmenting their emissions when uncertainty is embedded in the framework.

Which are the main reasons for the discrepancy existing between our result and Bosello and Moretto's? Our intuition is that the difference in the nature of the equilibrium reached by the agents in the game (cooperative in RICE, at least in Bosello and Moretto (1999)'s exercises, while á la Nash in our simulations) matters quite a lot in determining the emissions path.[11] In particular, Bosello and Moretto explain while in presence of a Social Planner the short-run global level of emissions may raise when uncertainty is taken into account.[12] However, even when emissions are reduced as a result of a cooperative solution, it is intuitive to think about the possibility of having a lower emission path for players involved in a game á la Nash. In fact, in the Open Loop-set-up of the game, each player reduces the level of emissions - in order to increase the *SP(t)* – not being aware about the positive externality that she provides to Society as a whole. On the other hand, she does not consider the reduction of global pollution caused by the other agents' efforts; hence, the abatement effort undertaken by each agent in this situation may turn to be (at least in the short-run) larger than the (Socially) optimal one. It should be clear enough how the type of equilibrium of this six-players game matters quite a lot in determining the optimal abatement effort and, consequently, the level of emissions overtime.[13]

The differences in the emissions levels are mirrored by Total Abatement Costs (defined here as the domestic abatement costs) sustained by the six regions when moving away from the benchmark case. As portrayed in Figure 4, in case of uncertainty, the need to reduce emissions brings to face larger Abatement Costs.

R&D expenditures are reduced when we add uncertainty to the model; this is not surprising, since this kind of investment does not have any influence on the emissions-output ratio. Accumulated R&D spending, in this context, just augments the productivity of the regions and, consequently, the level of global pollution. When agents have the need to reduce emissions in order to raise the Survivor Probability, they decide to cut the R&D investments, as shown in Figure 5.

An interesting outcome of our simulation regards the price of emission permits. When trading is solely allowed among developed countries, the price *goes down* when we move away from the benchmark case (see Figure 6). The intuition for this result is the following: as long as uncertainty induces a more cautions behaviour by the agents (reduces emissions vis a vis an increase in Abatement Costs), there is less incentive to demand permits to pollute, and more incentive to offer permits, as it is predictable by looking at equation (8), which regulates the demand and supply schedules of the market. Therefore, the pressure from the demand-side of the permits' market is now less intense, and this fact drives down, *ceteris paribus*, the permits' price. On the other hand, also the supply curve shifts rightward, driving the price down. But which is the predominant effect? By looking at the equilibrium quantities, we can see that the shift of the demand schedule is larger than the one of the supply curve, as indicated in Figure 7 (the price-quantity diagram is depicted in Figure 8). However, the difference here described seems to fade out as time goes by. This happens because the marginal impact of one additional unit of pollution on the Survivor Probability is great when the temperature is low; therefore, there is a huge stimulus to reduce the demand of permits to pollute, as well as to augment the supply. As

[11] Bosello and Moretto (1999) find relevant differences between the reaction of the agents in the RICE model when uncertainty is introduced, and the reactions of the agents in other Integrated Assessment Models (e.g. CETA, MERGE). They provide further intuitions on the causes of the paradoxical behaviour of the RICE agents in their article.

[12] Bosello and Moretto (1999), page 27.

[13] Formal proof is available by the authors upon request.

temperature increases, the marginal influence of one more unit of pollution on the Survivor Probability is smaller; this brings agents to go back to the permits' market in order to purchase permits (or to offer less emission rights).

Instead, when we enlarge the number of countries admitted to trade on the market, we see that the price *augments* as uncertainty is taken into account, as shown in Figure 9. This may be due to the differences of relative abatement costs between *Annex I* countries and *non Annex*, because of introduction of uncertainty in the model.

Given all what we have commented so far, it is straightforward to state that GNP growth is less sharp when uncertainty is taken into account. The fact that the production activities imply the creation of GHGs emissions plays a key role in understanding why the uncertainty over future possible catastrophic events is harmful for long-run growth. Indeed, in presence of uncertainty, agents act in order to avoid facing a catastrophe; in our model, this is done by slowing down production, which brings to a inferior level of pollution. Figure 10 shows the differences in GNP levels when passing from a situation with no-uncertainty to a situation with uncertainty.

We can summarise our findings with the following proposition:

Proposition 1. When uncertainty is considered, the behaviour of agents is more cautious. In particular, emissions are reduced, and this brings about higher abatement costs. As long as R&D expenditures are not in favour of the environment, the optimal level is reduced, thus not helping very much to trigger the "engine" of growth. Given the shift of both demand and supply schedules, price of permits is lower when trading is allowed among developed countries only. When trading is enlarged to the whole set of regions in the model, price raises when uncertainty is taken into account. Finally, since production is cut down, long-run growth result to be less intense.

4.2 Endogenous sigma: absence vs. presence of uncertainty

Results are differ in the case of an endogenous emissions-output ratio. Here our benchmark model is the ETC-RICE with endogenous environmental technical change and without uncertainty. The key difference with respect to the model with exogenous sigma is that now R&D expenditures are both a component of the production function (via Knowledge) *and* have a positive impact on environment. In other words, the more R&D investments a firm undertakes, the less pollution is created by the production process, *ceteris paribus*. This is why, when passing from ETC-RICE to ETC-U-RICE, simulations show how R&D expenditures are (roughly) *augmented in the short-run*: the sign is the opposite of the one found in the exogenous sigma study (compare Figure 5 with Figures 11-16). The intuition for this result is the following: in order to reduce the negative impact of uncertainty on the utility level, agents have to keep as high as possible the survivor probability. To do so, they aim at reducing emissions as much as they can, maintaining at the same time as high as possible the level of production (recall that consumption, strictly and positively related to the level of production, is the sole argument of the utility function to be maximised by the agents). Hence, they increase the R&D spending in order to improve the emissions-output ratio, lowering in this way the probability of having a catastrophe. However, R&D returns to scale are decreasing, and this brings to a smooth shift of resources from R&D spending to consumption. Moreover, the fact that in this model there is no room for any form of bequest suggests that agents want to consume all the available resources before dying. This is another reason why consumption gradually "substitutes" R&D spending in the agents' optimal allocation. The fact that with uncertainty R&D investments are higher than in the case with no-uncertainty in the *short-run* explains why, once the initial effort has been sustained (and a certain *low* level of emissions per produced unit of GNP has been reached), agents consume more and *invest less* in R&D in the *long-run*. Even if the parabolic path of the difference between R&D expenditures in case of no-uncertainty and uncertainty seems to be shared by every region, the timing of the agents' decisions is different. In this particular case, this reflects the differences existing between regions as far as environmental technology is concerned. Hi-tech regions (e.g. see Figure 12 for Japan) have of course a minor need to invest in R&D spending than technologically poor one (e.g. see Figure 14 for China), because of R&D decreasing returns to scale.

Given that in this model there is no *explicit* distinction between non-environmental and environmental R&D, the fact that firms boost R&D expenditures in order to better off the emissions-output ratio brings also to an increase in productivity. Indeed, when uncertainty is taken into account, the GNP of each region is larger when sigma is endogenous (as shown in Figure 17); this suggest that R&D expenditures here play a key role in triggering the "engine of growth". Anyhow, it has to be clarified that uncertainty is harmful for long-run growth. When passing from a situation with no-uncertainty to a situation with uncertainty, GNP levels are smaller both in case of exogenous and in case of endogenous sigma, as shown in Figure 18.

As already explained above, the reduction in emissions when passing from the benchmark model to the ETC-U-RICE set-up (see Figure 19) is therefore due both to a slightly lower overall GNP and to more environmental friendly production. However, the Total Abatement Costs augments when uncertainty is accounted for, as shown in Figure 20.

When emissions trading is allowed among the Annex I countries, we observe the same outcome already commented for the exogenous sigma case. Price of emission rights goes down when we move away from the benchmark case (see Figure 21), and this is still due to the combined shift of both demand and supply schedules. In fact, even though R&D expenditures shape a better sigma, pollution lowers expected future utility when uncertainty is considered, therefore there is less incentive to demand permits to pollute, and more incentive to offer them. Once again, the demand shift is larger than the supply one (as understandable by looking at the variation in the equilibrium quantities, as shown in Figure 22). Finally, by enlarging the market to the whole world, we can once again observe the increase of permit price in case of uncertainty (see Figure 23). So, as an attempt to summarise the most important findings relatively to this second set-up, we can write the following proposition:

Proposition 2. When also environmental R&D spending is considered, uncertainty in the model stimulates firms to allocate resources in order to improve the emissions-output ratio – at least in the short- run - so being able to produce more GNP, ceteris paribus. In this case, growth is boosted also by this decision variable. However, uncertainty still affects negatively the development of each country, given its link with the reduced expected utility per period that agents observe.

4.3 Presence of uncertainty: exogenous vs. endogenous sigma

To conclude, we now focus on the comparison between the results coming from the ETC-U-RICE model with exogenous emissions-output ratio path (our benchmark, here), and the same model with endogenous sigma*, given the presence of uncertainty* in the framework analysed. As already pointed out, the policy variables in both of these models are the same; the difference is due to the impact that *R&D* investments have in each one of them. When sigma is exogenous, R&D spending just affects productivity, while when it is endogenous, research and development influences both productivity and emissions-output ratio.

It is easy to foresee that the wider exploitation that R&D expenditures have in the endogenous environmental technical change case drives the six regions under study to perform better results. Indeed, this is confirmed by the figures obtained with our simulations. As already seen, a comparison of the GNP levels shows how in the endogenous case growth is more robust (see again Figure 17). This is possible because R&D spending results to be higher in the endogenous case (see Figure 24), leading the regions to a better emissions-output relationship. Due to this improvement from an environmental point of view, the incentive for purchasing tradables is lower, while the supply augments, driving downward the equilibrium price in each period. This holds in both the Et_A1 scenario, and the Et_All one (see Figure 25 and 26). These results are obtained also by Buonanno, Carraro, Castelnuovo, and Galeotti (2000). Hence,

Proposition 3. Given uncertainty, the wider application of R&D spending when sigma is endogenous is a source of positive growth of the six regions in the model. This implies an optimal re-allocation of resources which brings to have lower internal abatement channel and smaller trading of import permits. In other words, R&D spending trigger endogenous environmental technical change, and allows regions to produce the same output as in the exogenous sigma case with lower pollution.

5. Conclusions

In this paper we used a simple climate model, obtained by integrating the ETC-RICE model by Buonanno, Carraro, Castelnuovo and Galeotti (2000) and Buonanno, Carraro, and Galeotti (2000), with the specification concerning environmental uncertainty proposed by Bosello and Moretto (1999). Our goal was to evaluate how the optimal choices of the agents in our stylised economy are affected by the introduced possibility of having "the end of the world" at a certain, unknown, point in time.

Our findings are the following. When uncertainty is considered, the behaviour of the agents is more cautious. This conclusion seems to be in line with those of Schelling (1992), Bosello and Moretto (1999), and Gjerde, Grepperud, and Kverndokk (1999).

Emissions are reduced by cutting down production, thus growth is less intense. This is why uncertainty is costly, as mirrored by the higher level of Total Abatement costs faced by the agents. As long as R&D expenditures are not environmental-friendly, they are optimally reduced, and do not help very much to trigger the "engine" of growth. The fact that emissions are very dangerous in case of uncertainty brings agents to demand less (or offer more) permits, driving downward their price (at least as long as the developing countries are not admitted to trading rights to pollute).

When also *environmental* R&D spending is considered, conclusions turn out to be different. Uncertainty in the model stimulates firms to re-allocate resources in order to improve the emissions-output ratio, so being able to produce more GNP, ceteris paribus. In this case, growth is indeed boosted by "green" research and development.

This brings us to conclude that the presence of uncertainty renders even more important the key-variable R&D spending when this is also environmental. Hence, a possible policy suggestion is to work in order to create a "fertile field" for environmental R&D investments, as well as researchers have done for the non-environmental ones (see about the latter point Barro and Sala-i-Martin (1996), and Kremer, 2000).

Notice that the results we reached may be sensitive to the particular specification of the discount rate we adopted. As Portney and Weyant (1999), and Azar and Sterner (1996) suggest, there is disagreement about the "true" value of a discount rate when there is the need to evaluate pros and cons of projects extending into the far future. That is why a sensitivity analysis focused on the discount factor in order to assess the robustness of our findings is already in our agenda.

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FIGURE 1
UNCERTAINTY WITH EXOGENOUS SIGMA:TEMPERATURE

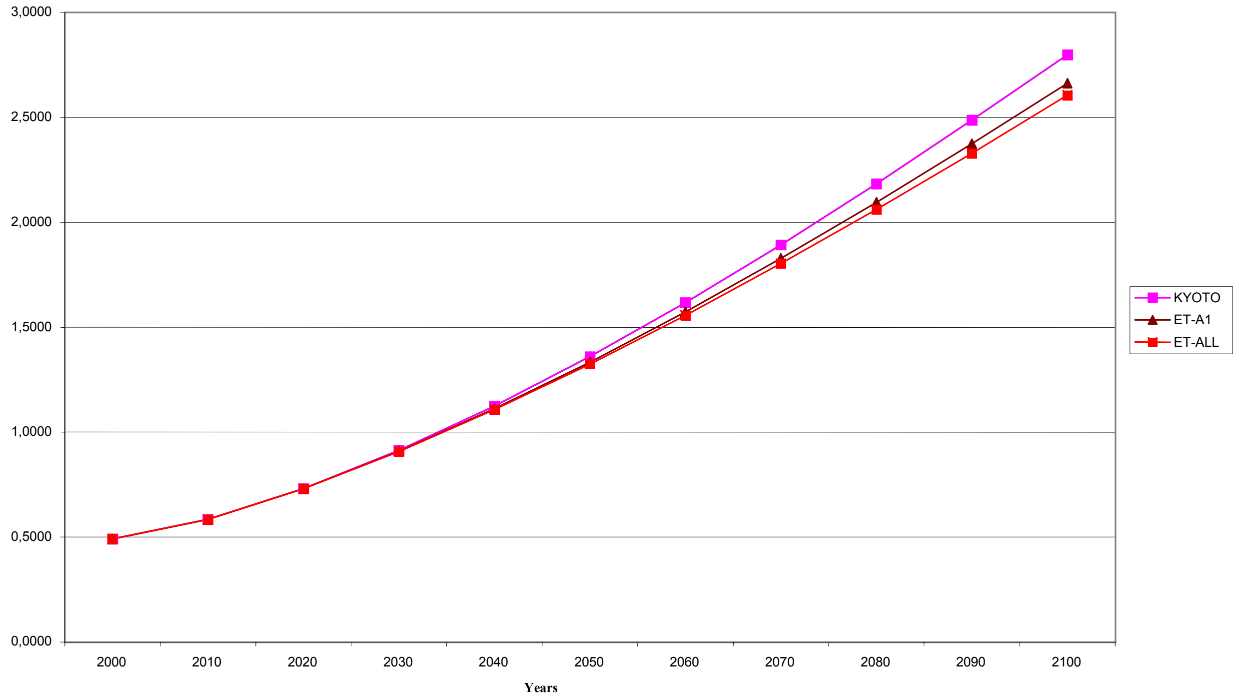

FIGURE 2
UNCERTAINTY WITH ENDOGENOUS SIGMA: TEMPERATURE

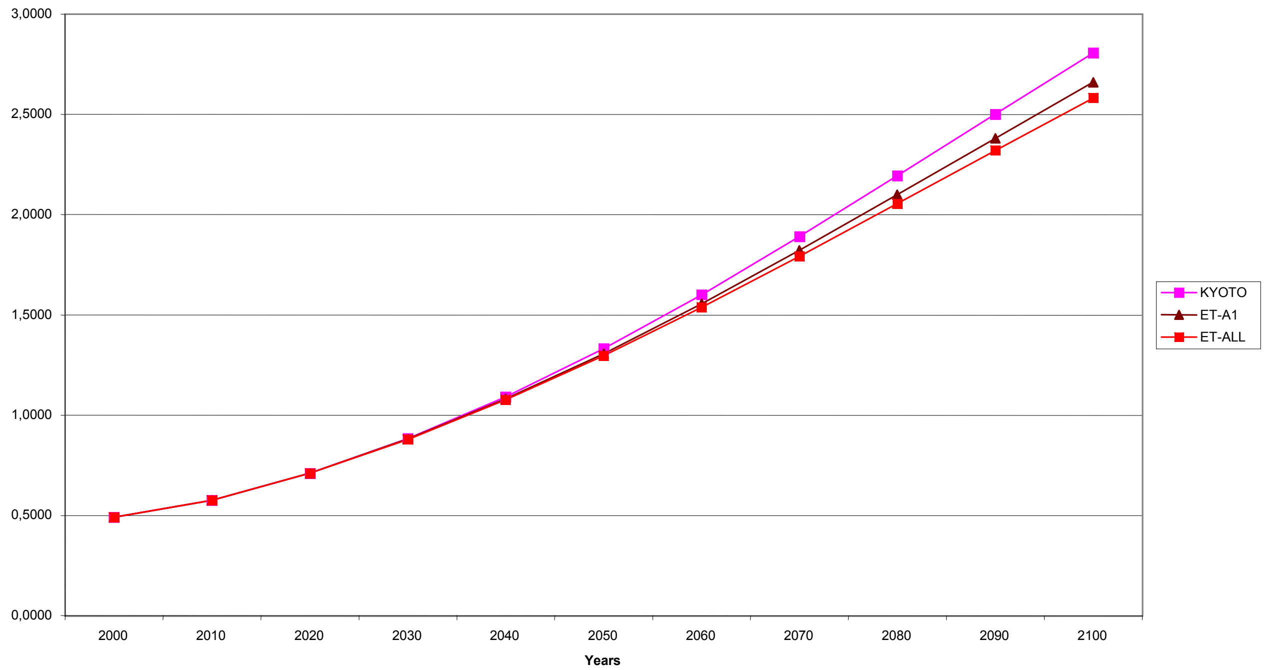

FIGURE 3
NO UNCERTAINTY VS. UNCERTAINTY WITH EXOGENOUS SIGMA: DIFFERENCES INOVERALL WORLD WIDE EMISSIONS

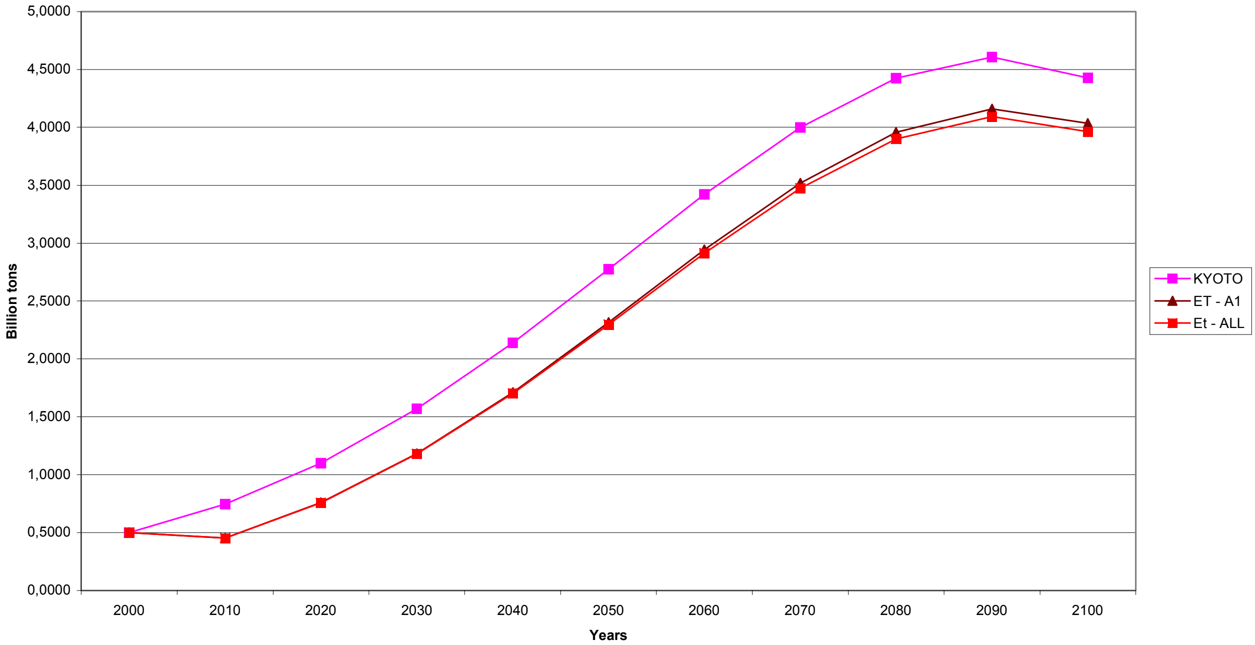

FIGURE 4
NO UNCERTAINTY VS UNCERTAINTY WITH EXOGENOUS SIGMA: DIFFERENCES IN TOTAL ABATEMENT COST (PERIOD 2010 - 2100)

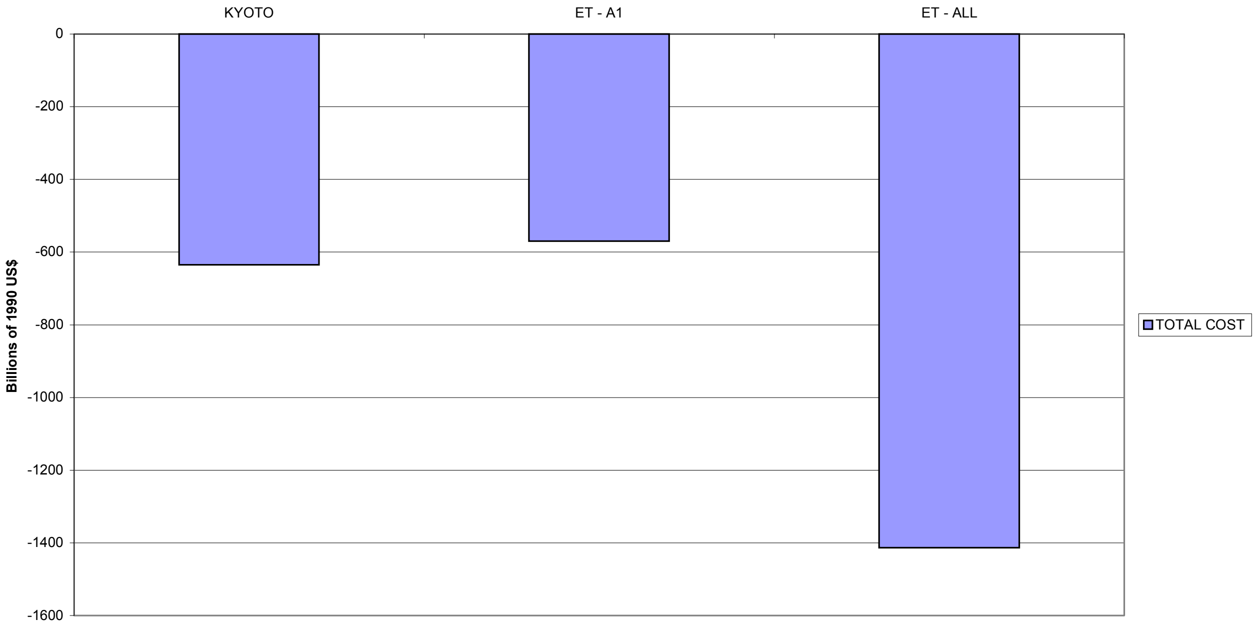

FIGURE 5
NO UNCERTAINTY VS UNCERTAINTY WITH EXOGENOUS SIGMA:
DIFFERENCES IN TOTAL R&D EXPENDITURES
(period 2010 - 2100)

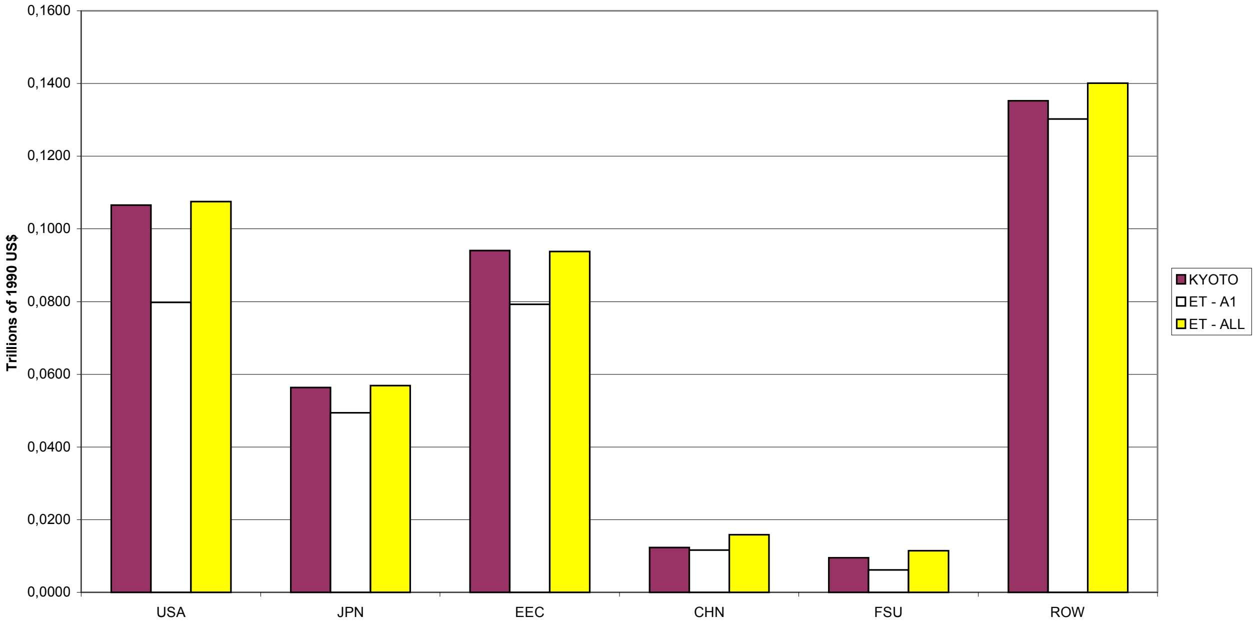

FIGURE 6
NO UNCERTAINTY VS UNCERTAINTY WITH EXOGENOUS SIGMA:
PRICE OF PERMITS IN ET - A1 POLICY OPTION

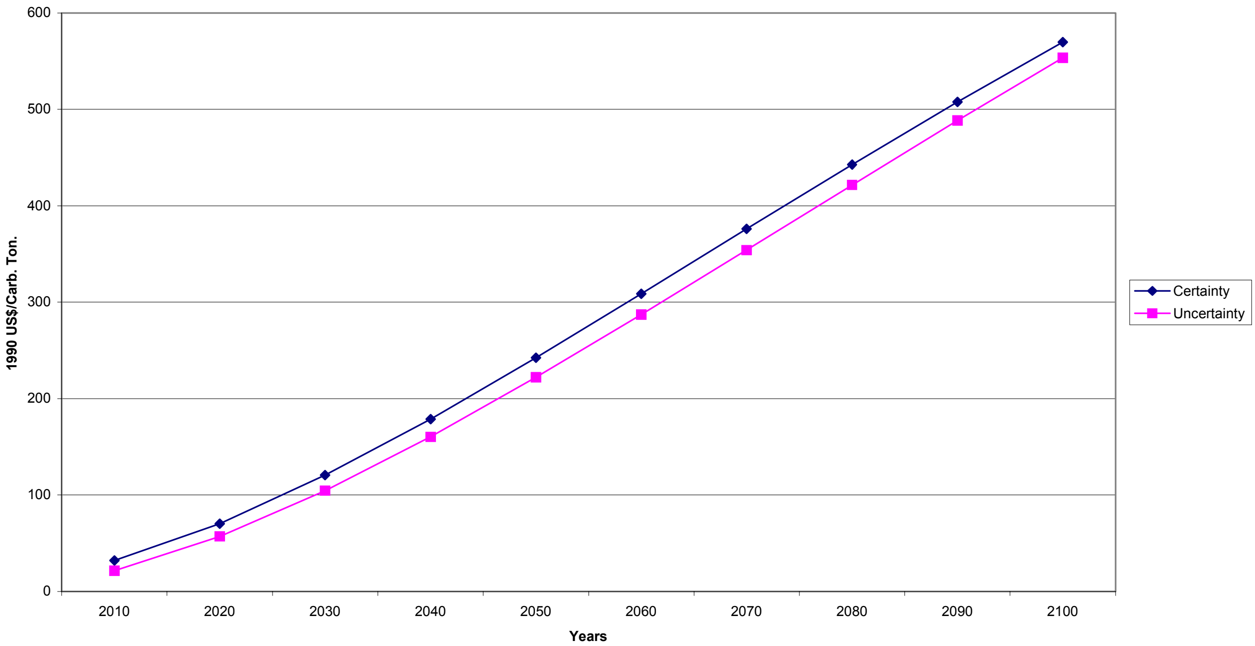

FIGURE 7
NO UNCERTAINTY VS UNCERTAINTY WITH EXOGENOUS SIGMA:
DIFFERENCES IN EQUILIBRIUM QUANTITIES ON PERMIT MARKET IN ET - A1 POLICY OPTION

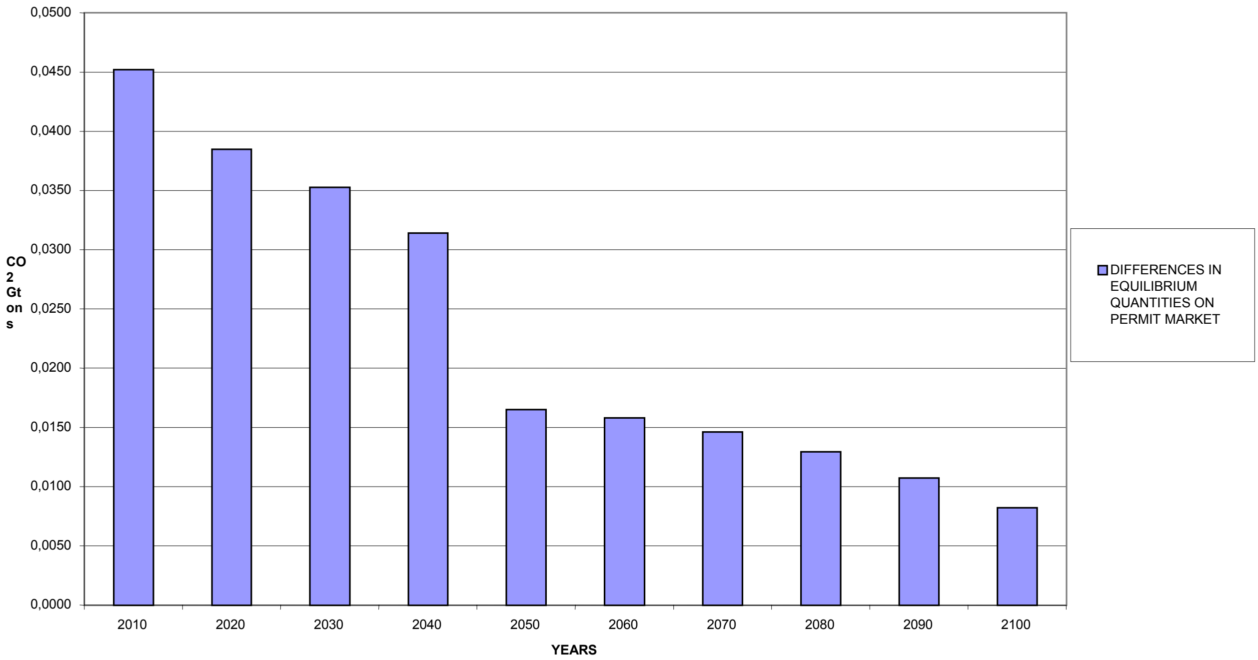

FIGURE 8

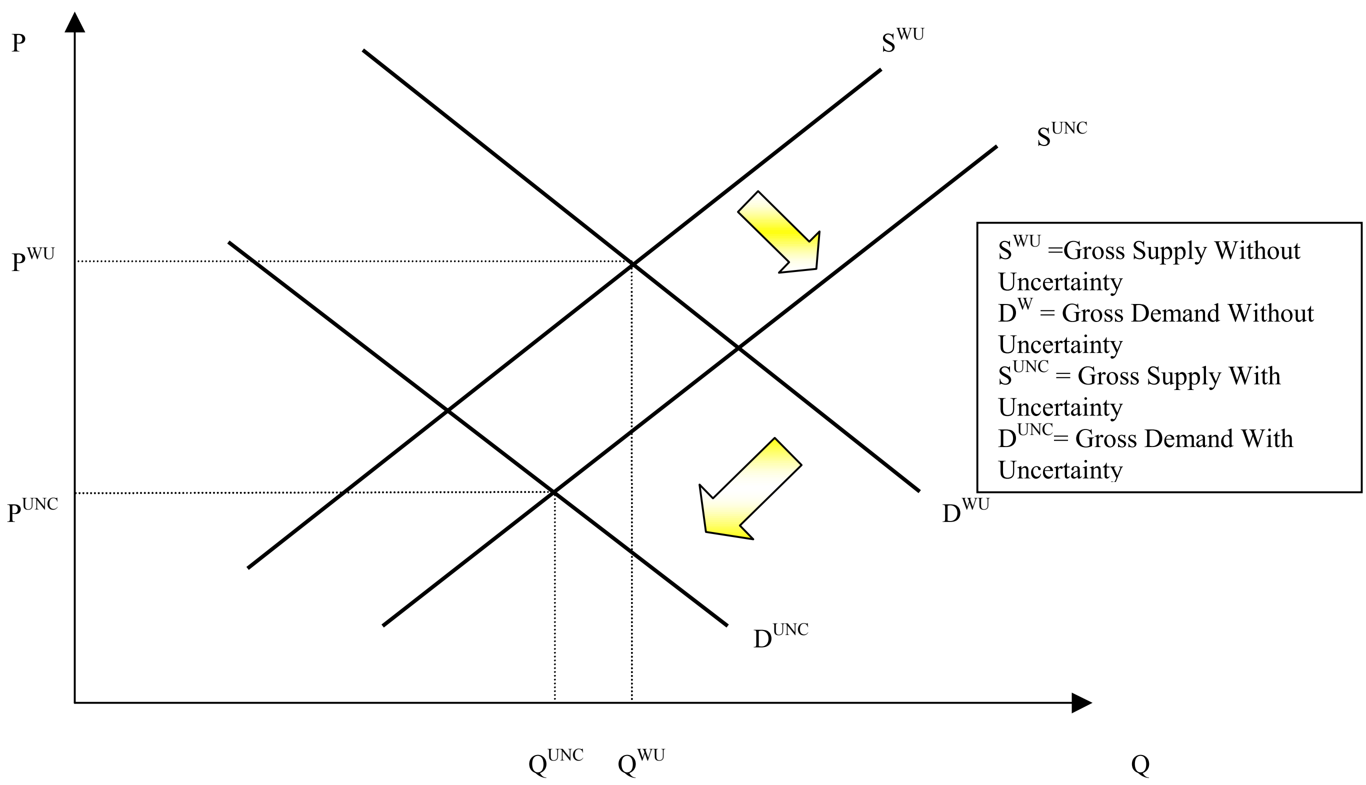

FIGURE 9
NO UNCERTAINTY VS UNCERTAINTY WITH EXOGENOUS SIGMA:
PRICE OF PERMITS IN ET _ ALL POLICY OPTION

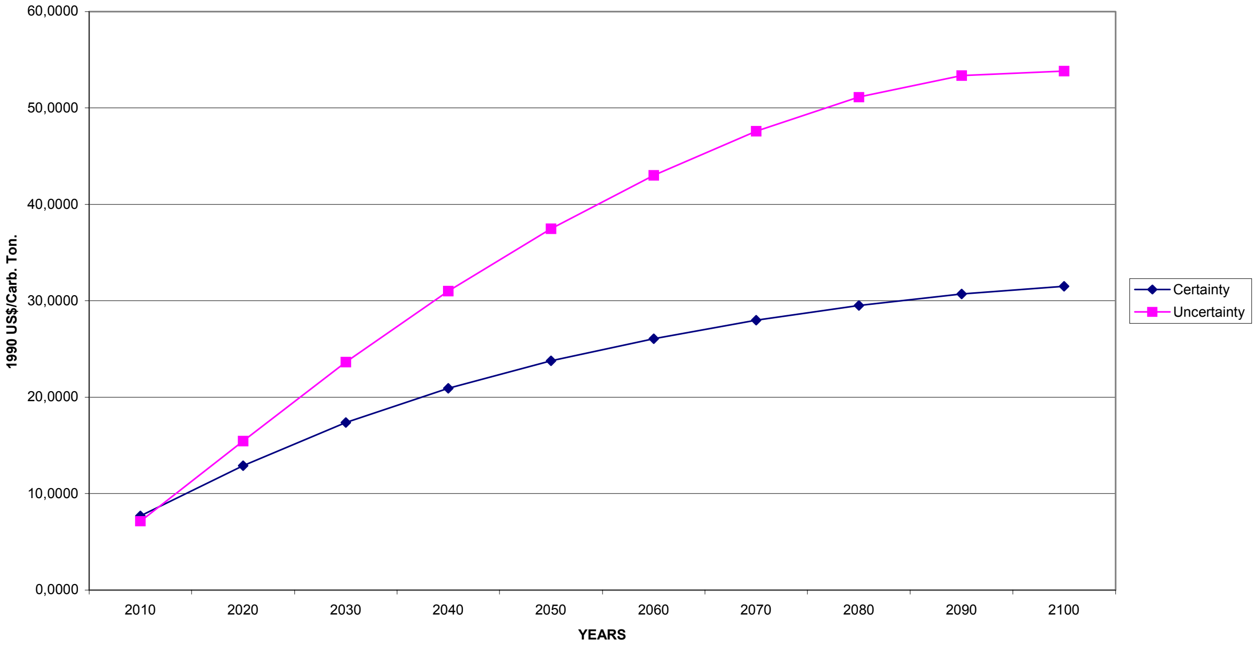

FIGURE 10
NO UNCERTAINTY VS UNCERTAINTY WITH EXOGENOUS SIGMA:
TOTAL GNP DIFFERENCES (period 2010 - 2100)

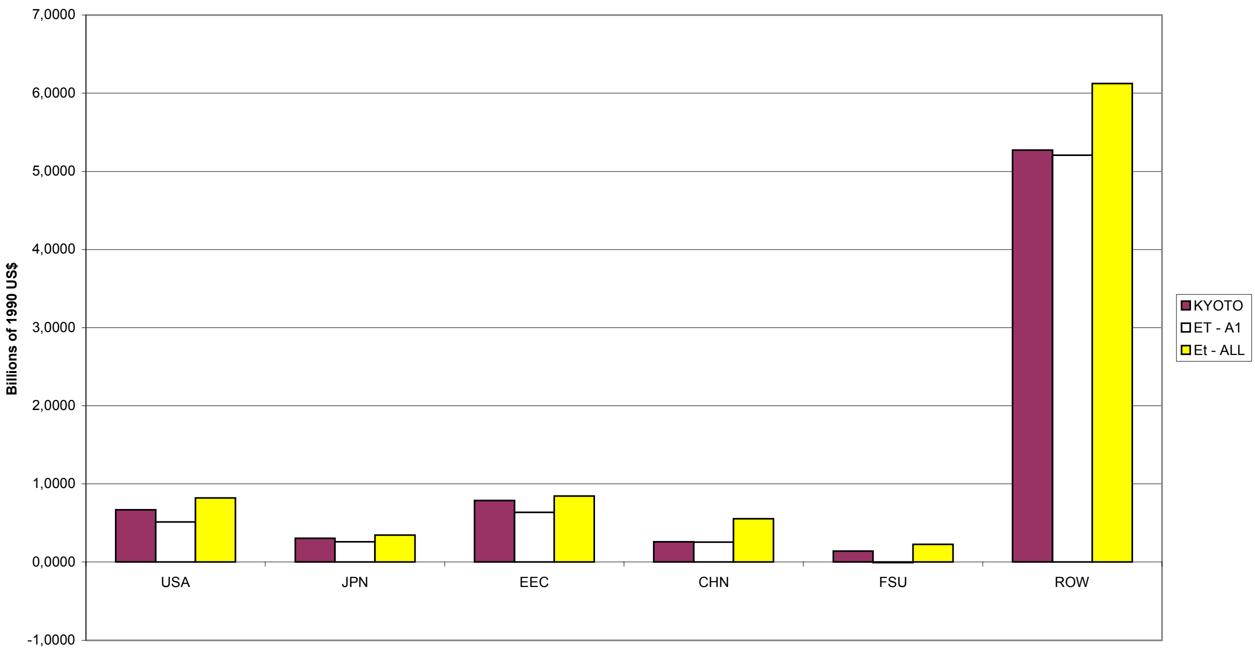

FIGURE 11
USA: NO UNCERTAINTY VS UNCERTAINTY WITH ENDOGENOUS SIGMA: DIFFERENCES IN TOTAL R&D EXPENDITURES

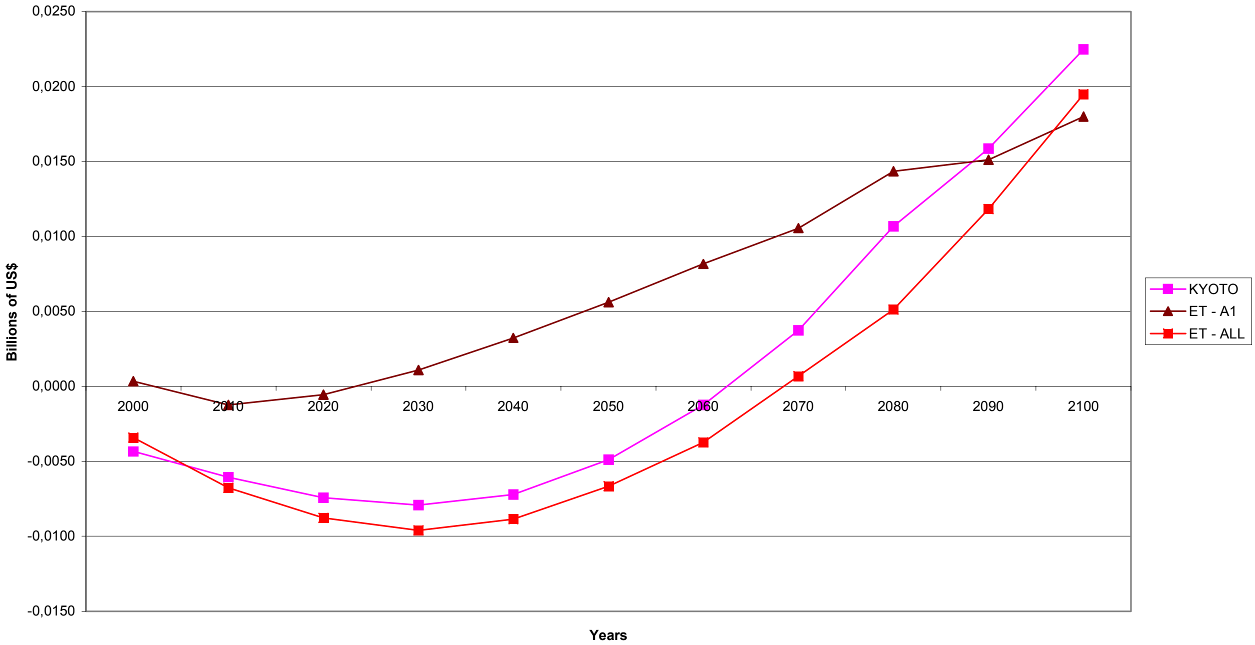

FIGURE 12
JAPAN: NO UNCERTANTY VS UNCERTAINTY WITH ENDOGENOUS SIGMA: DIFFERENCES IN TOTAL R&D EXPENDITURES

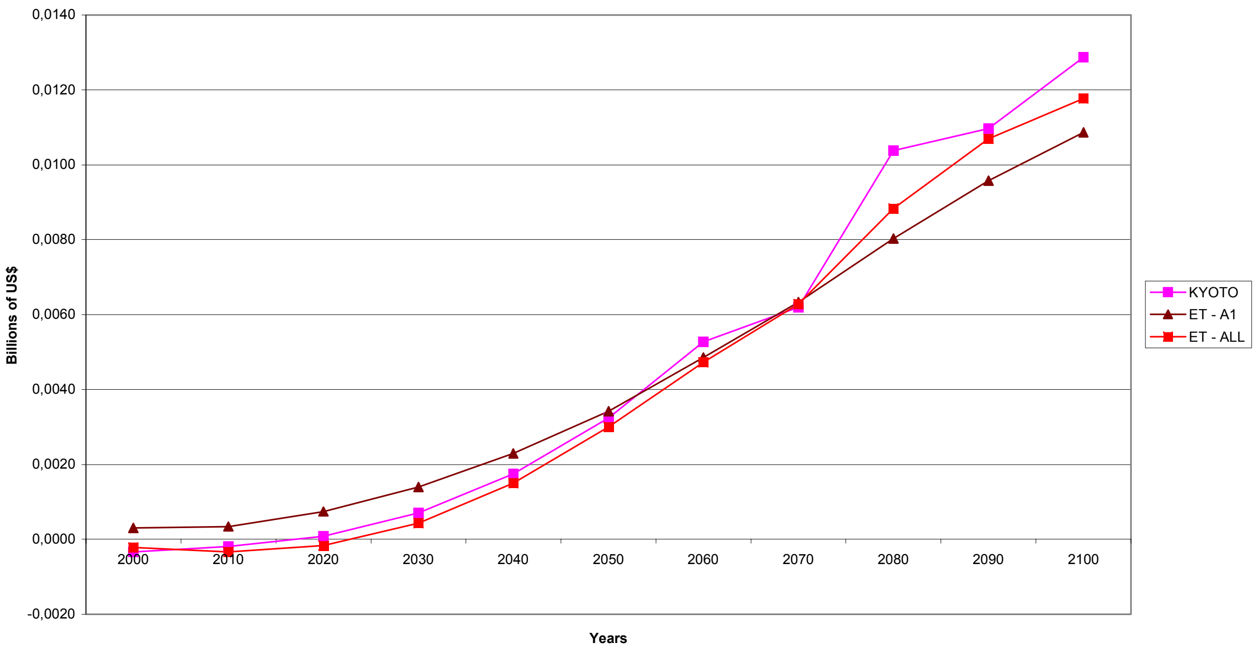

FIGURE 13
EEC: NO UNCERTAINTY VS UNCERTAINTY WITH ENDOGENOUS SIGMA:
DIFFERENCES IN TOTAL R&D EXPENDITURES

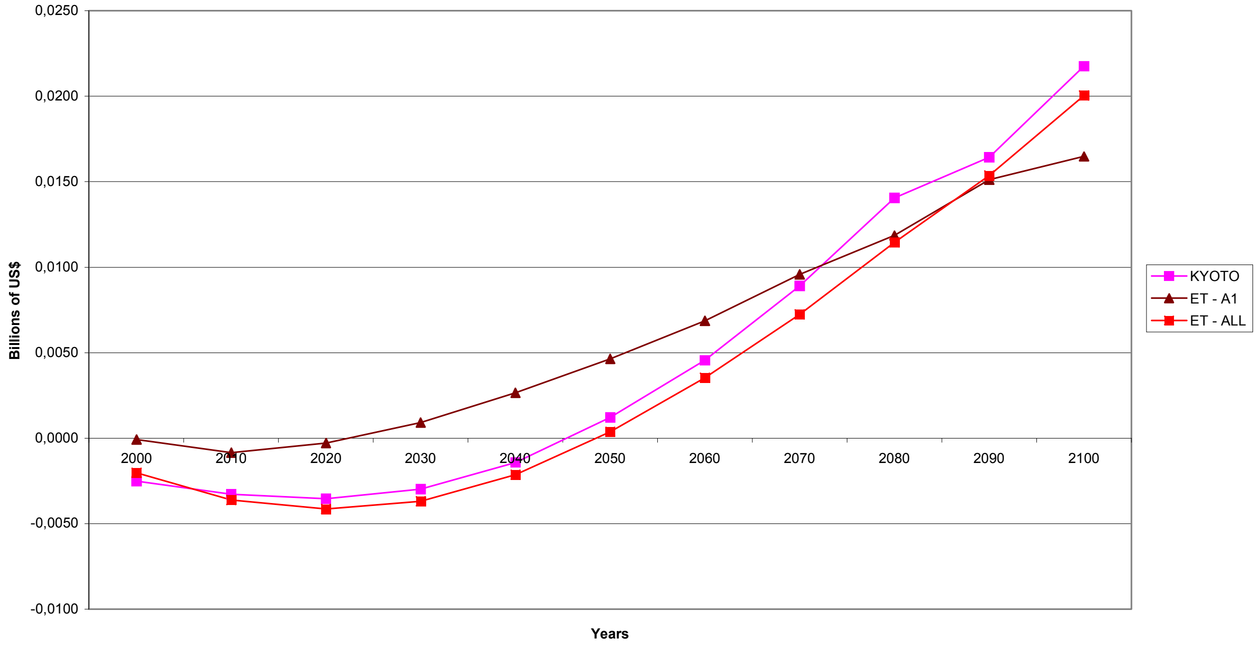

FIGURE 14
CHINA: NO UNCERTAINTY VS UNCERTAINTY WITH ENDOGENOUS SIGMA:
DIFFERENCES IN TOTAL R&D EXPENDITURES

FIGURE 15
FSU: NO UNCERTAINTY VS UNCERTAINTY WITH ENDOGENOUS SIGMA: DIFFERENCES IN TOTAL R&D EXPENDITURES

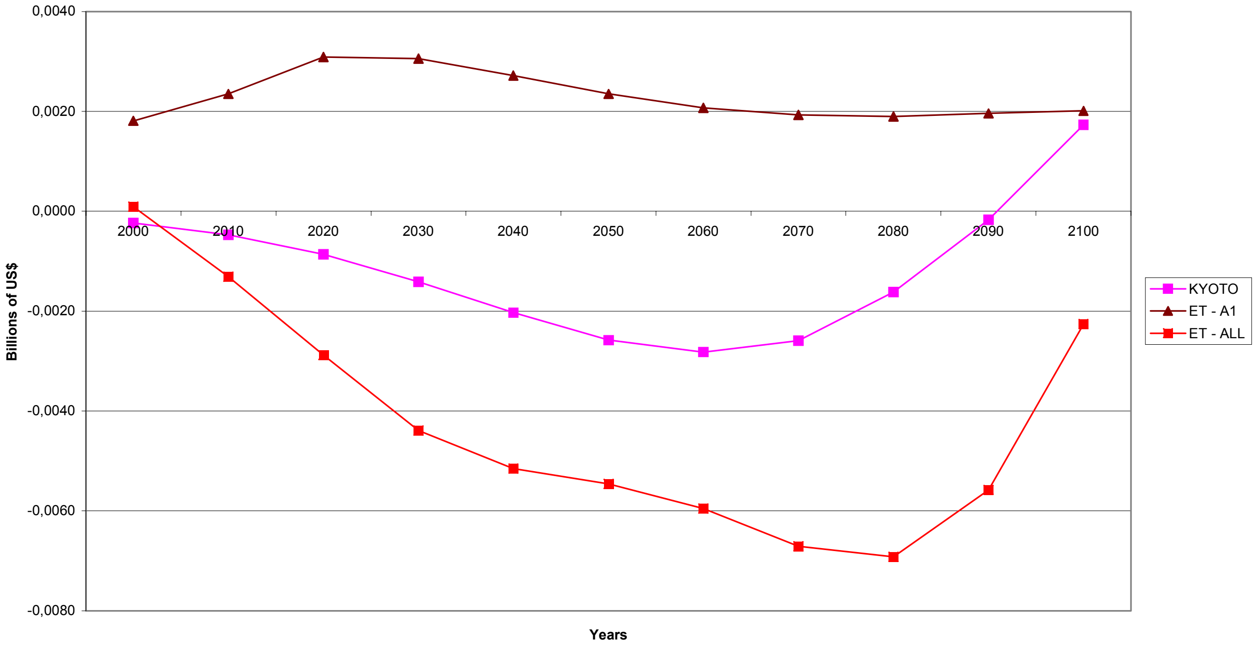

FIGURE 16
ROW: NO UNCERTAINTY VS UNCERTAINTY WITH ENDOGENOUS SIGMA: DIFFERENCES IN TOTAL R&D EXPENDITURES

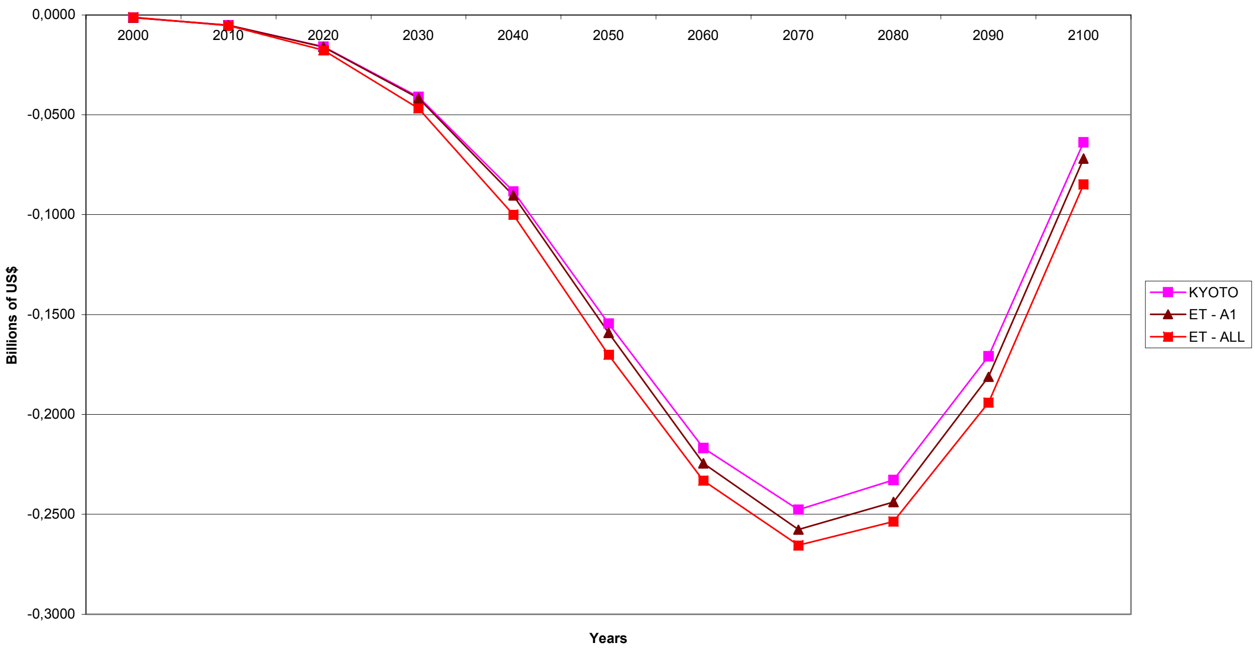

FIGURE 17
EXOGENOUS VS ENDOGENOUS SIGMA WITH UNCERTAINTY:
TOTAL GNP DIFFERENCES (period 2010 - 2100)

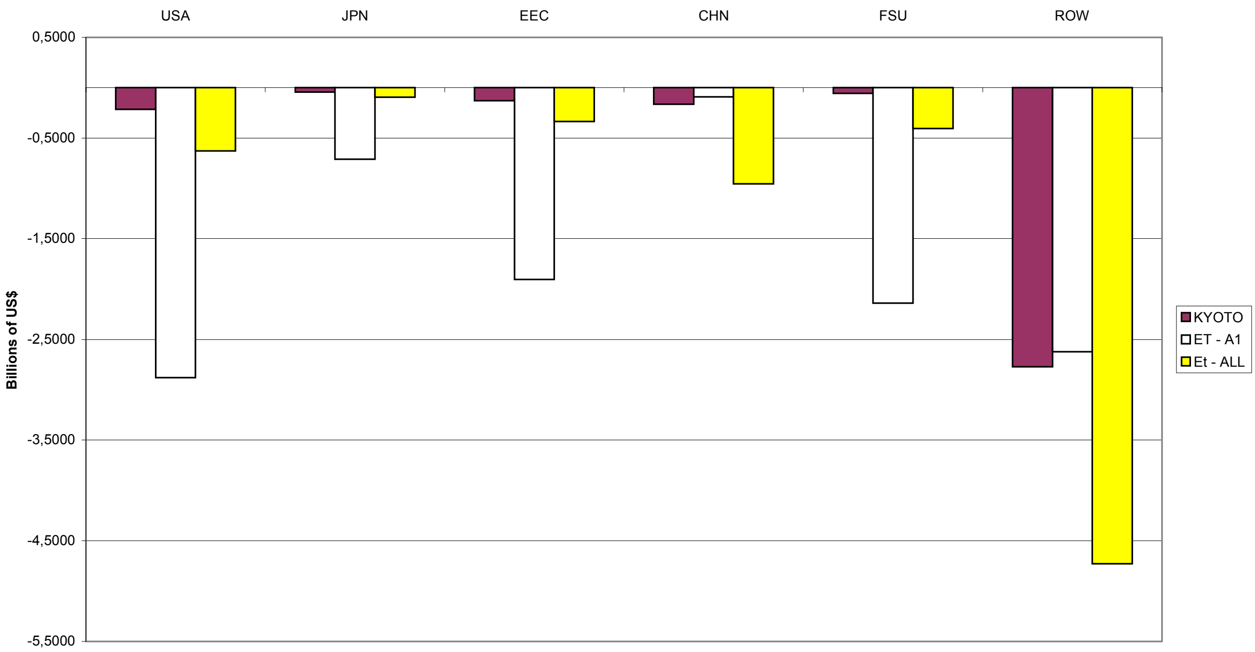

FIGURE 18
TOTAL GNP LEVEL (PERIOD 2010 - 2100)

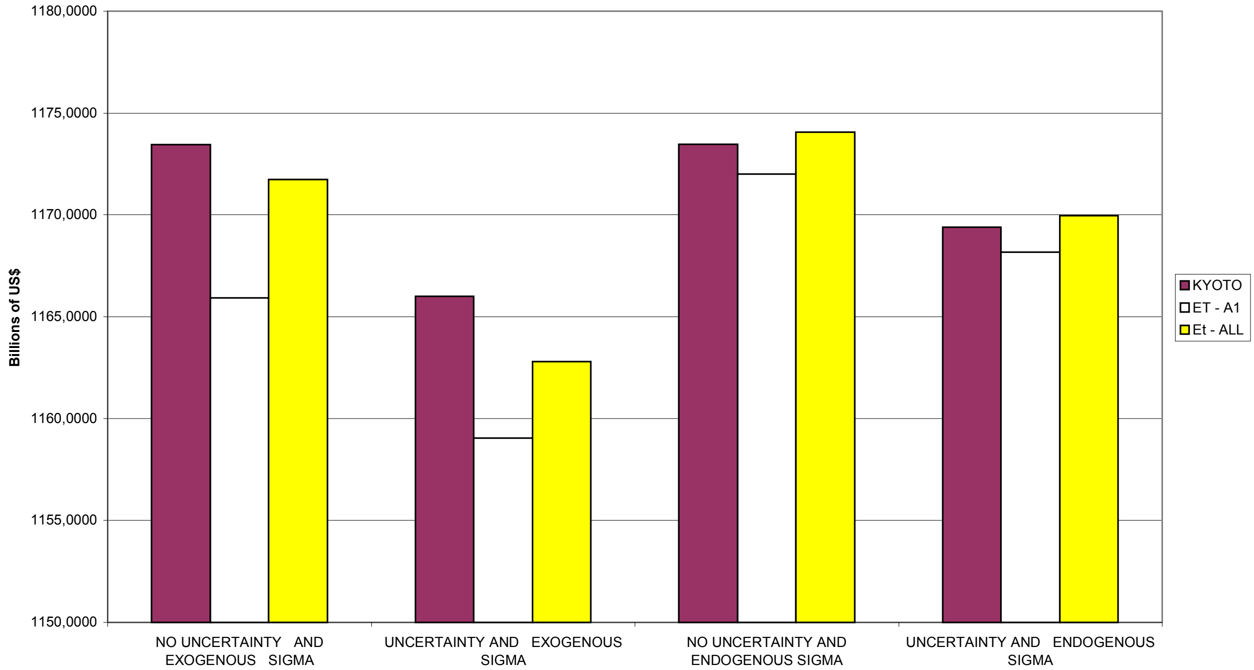

FIGURE 19
NO UNCERTAINTY VS UNCERTAINTY WITH ENDOGENOUS SIGMA :
DIFFERENCES IN OVERALL WORLD WIDE EMISSIONS

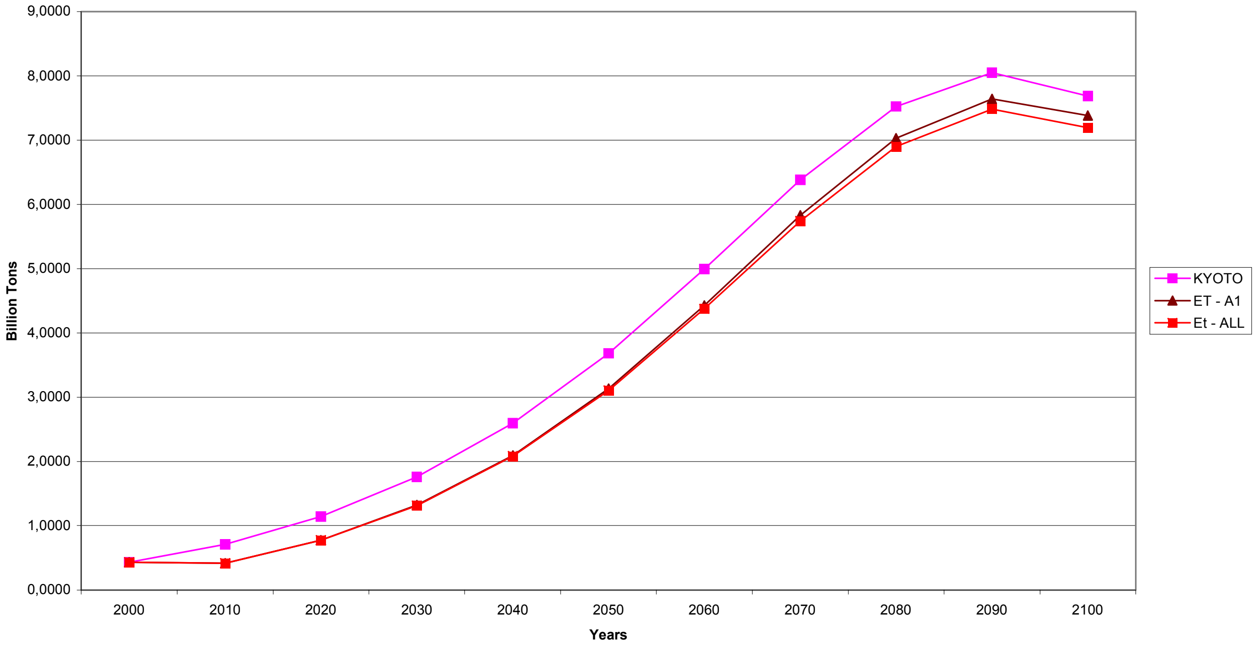

FIGURE 20
NO UNCERTAINTY VS UNCERTAINTY WITH ENDOGENOUS SIGMA:
DIFFERENCES IN TOTAL ABATEMENT COST (PERIOD 2010 - 2100)

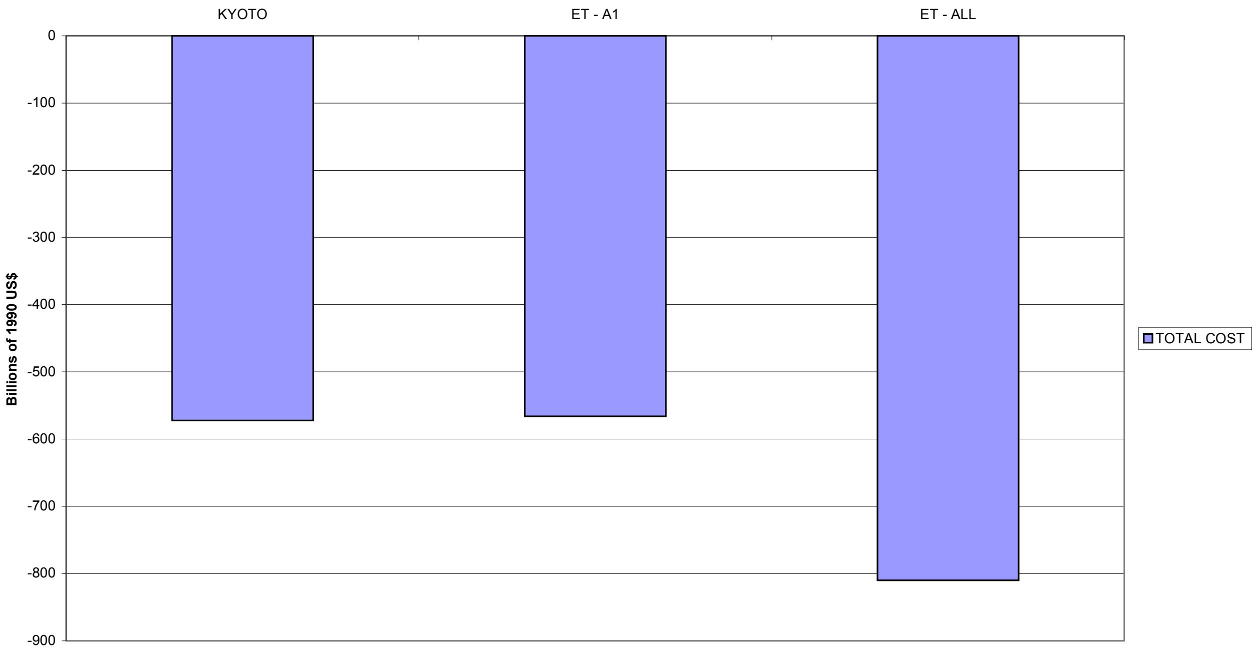

FIGURE 21
NO UNCERTAINTY VS UNCERTAINTY WITH ENDOGENOUS SIGMA:
PRICE DIFFERENCES IN ET - A1 POLICY OPTION

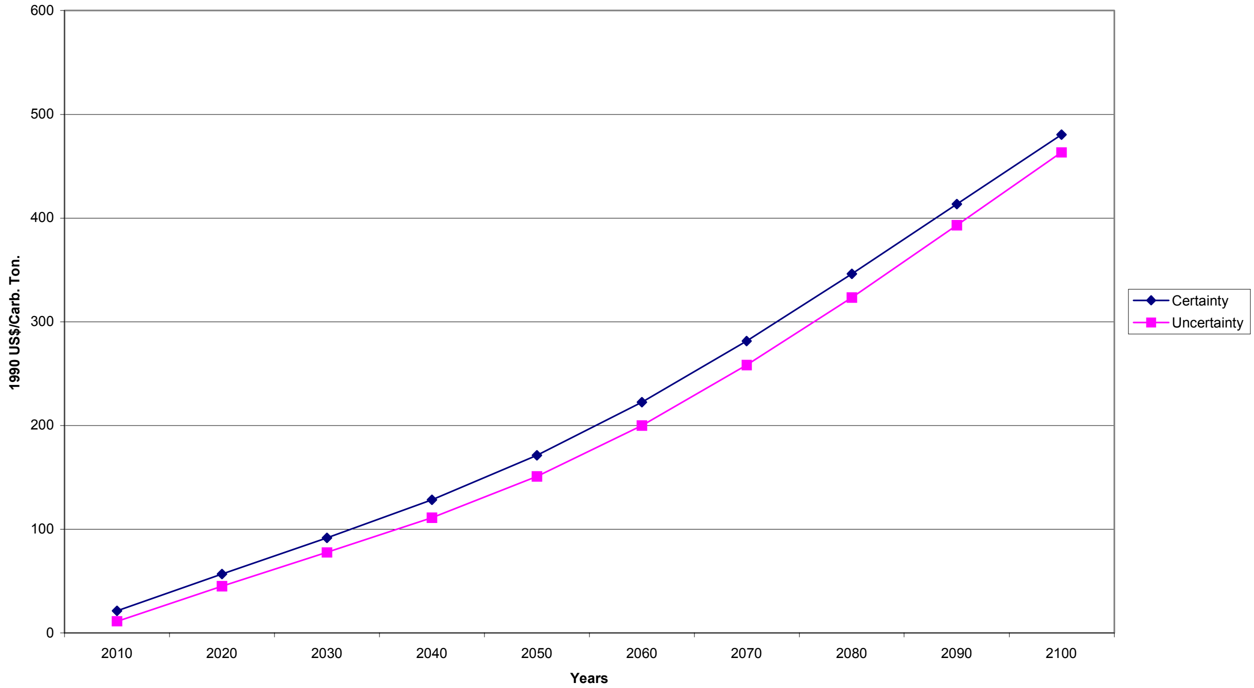

FIGURE 22
NO UNCERTAINTY VS UNCERTAINTY WITH ENDOGENOUS SIGMA:
DIFFERENCES IN EQUILIBRIUM QUANTITIES ON PERMIT MARKET IN ET - A1 POLICY OPTION

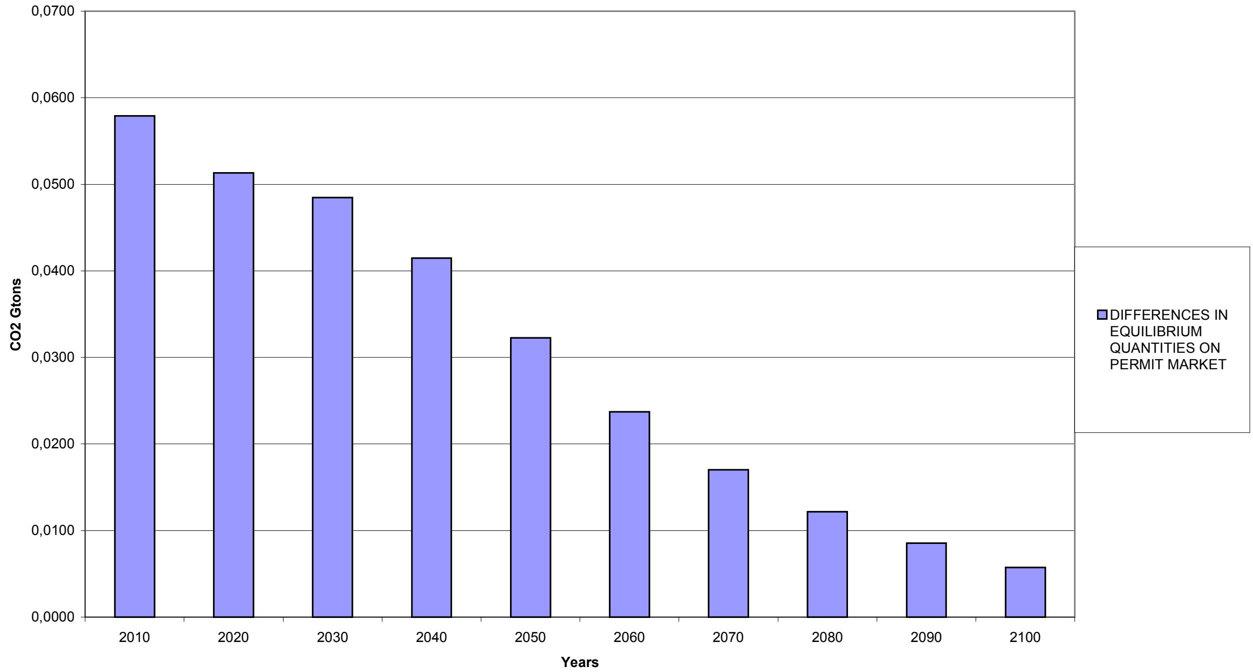

FIGURE 23
NO UNCERTAINTY VS UNCERTAINTY WITH ENDOGENOUS SIGMA:
PRICE OF PERMITS IN ET - ALL POLICY OPTION

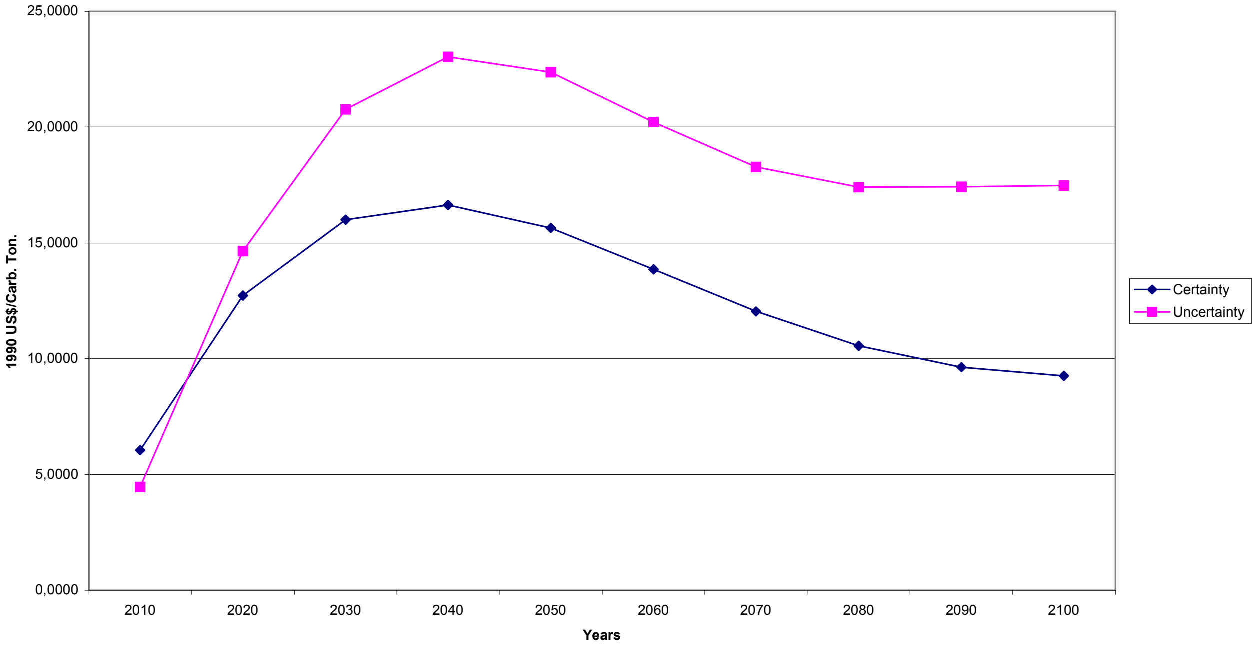

FIGURE 24
EXOGENOUS VS ENDOGENOUS SIGMA WITH UNCERTAINTY:
DIFFERENCES IN TOTAL R&D ENPENDITURES (period 2010 - 2100)

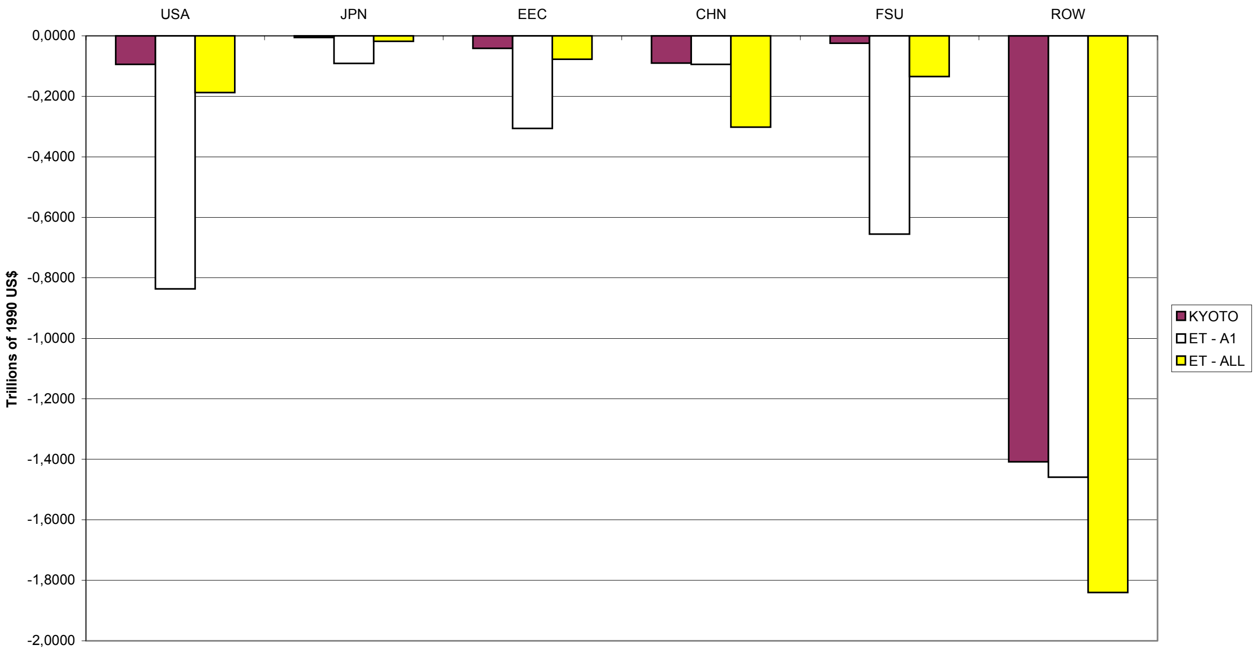

FIGURE 25
EXOGENOUS VS ENDOGENOUS SIGMA WITH UNCERTAINTY:
PRICE OF PERMITS IN ET - A1 POLICY OPTION

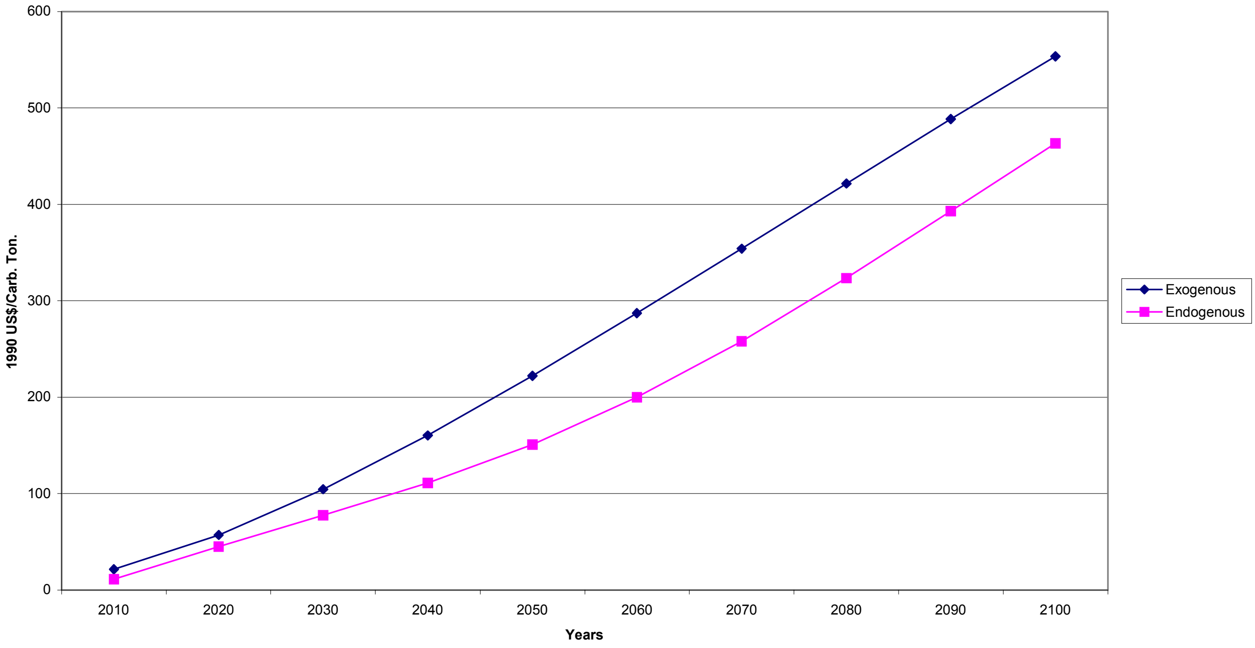

FIGURE 26
EXOGENOUS VS ENDOGENOUS SIGMA WITH UNCERTAINTY:
PRICE OF PERMITS IN ET - ALL POLICY OPTION

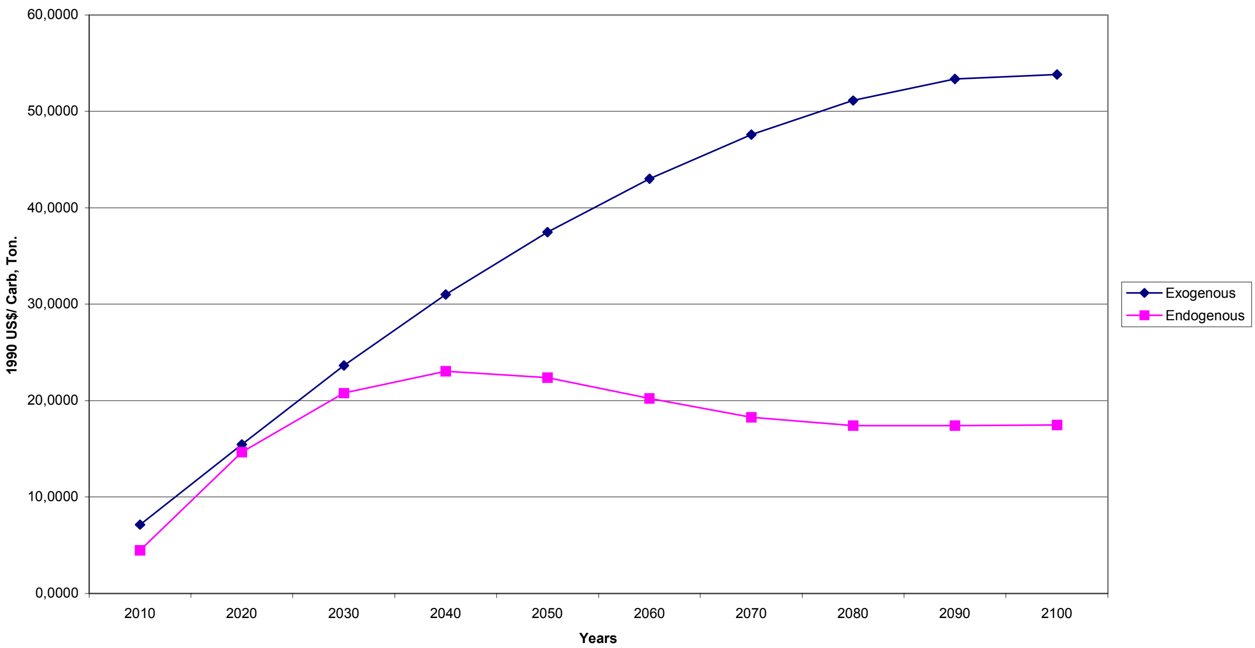

FIGURE 27
NO UNCERTAINTY VS UNCERTAINTY WITH EXOGENOUS SIGMA:
DIFFERENCES IN EQUILIBRIUM QUANTITIES ON PERMIT MARKET ET - ALL POLICY OPTION

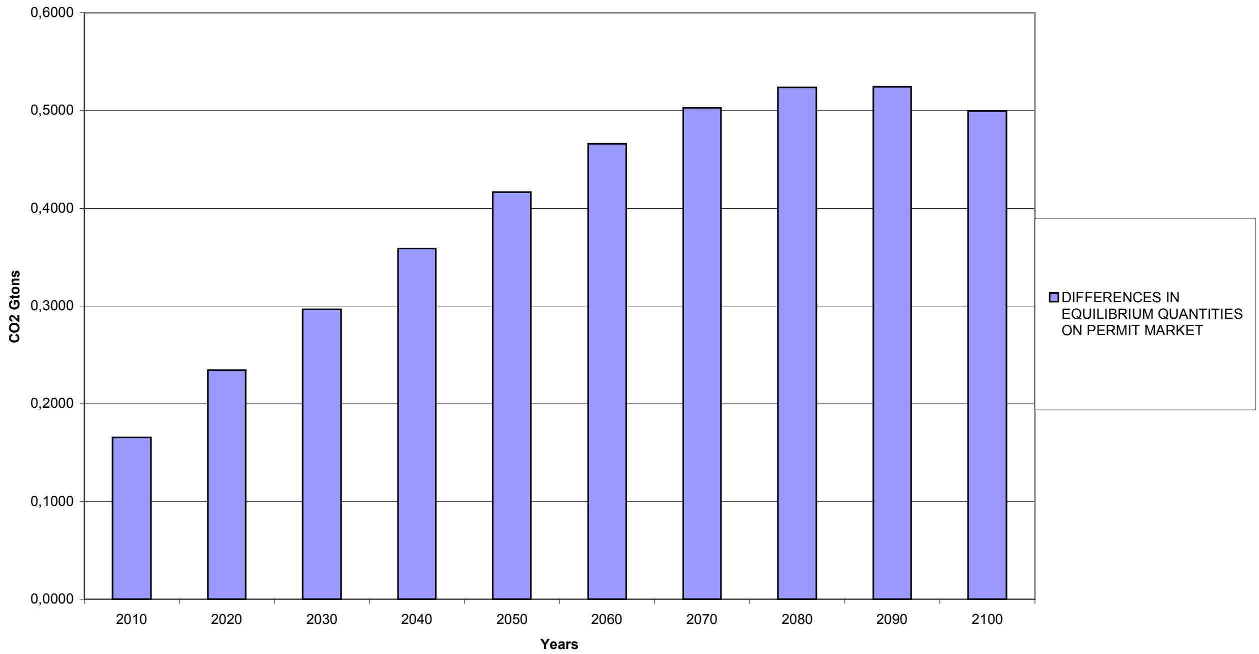

FIGURE 28
NO UNCERTAINTY VS UNCERTAINTY WITH ENDOGENOUS SIGMA: DIFFERENCES IN EQUILIBRIUM QUANTITIES ON PERMIT MARKET IN ET - ALL POLICY OPTION