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Beyond Kyoto: Identifying the Long-term Options

by

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Abstract

Widespread political support indicates that the process towards the Kyoto Protocol is still alive, notwithstanding the uncertainty about its coming into force (notably because Russia still hesitates to ratify). However, whatever Russia's strategy, the US decision not to ratify Kyoto has weakened the Kyoto Protocol and undermined its environmental effectiveness. At the same time, general consensus has emerged that the Kyoto Protocol represents only a first step towards the broader aim of minimising the danger of climate change. Climate change can only be effectively defeated if a large number of countries, including the major CO₂-emitters, coordinate their efforts to reduce GHG emissions. In order to improve the future prospects of climate policy, numerous strategies and proposals have recently been discussed. This paper contributes to this research field by designing and analysing a number of politically relevant and realistic regimes for future emission abatement commitments, as opposed to previous research studies which were mainly based on ad-hoc assumptions, as e.g. the "Kyoto forever" hypothesis. The implications for the main economic variables of six different future commitments scenarios will be assessed and analysed. In particular, participation incentives will be discussed and some suggestions for the design of future negotiation targets will be proposed.

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Beyond Kyoto: Identifying the Long-term Options

1 Introduction

Widespread political support indicates that the Kyoto Protocol may come into force within the next months. More than 120 countries have already ratified the agreement. Despite the withdrawal of the US in March 2001, the Kyoto process seems to be alive. New important issues have been raised at COP 8 in Delhi and at the World Summit on Sustainable Development in Johannesburg. Some more progress has been achieved also at COP 9 in Milan. Nonetheless, uncertainty about the coming into force of the Protocol still exists, notably because Russia still hesitates to ratify. In addition, whatever Russia's decision, the Bonn/Marrakech accords have weakened the Kyoto Protocol. What therefore is the future of climate policy?

There are two approaches to address this question. In the first one, participation incentives are the main focus of the analysis which thus is devoted to the identification of policy strategies and policy architectures (i.e. the design of an international climate agreement) that provide adequate incentives for the participation of most world countries in the cooperative effort to control GHG emissions (see, for example, Aldy, Barrett and Stavins, 2003; and Buchner and Carraro, 2003a,b; 2004). A second approach is devoted to explore what emission reduction commitments should be adopted by participating countries beyond 2012 (i.e. after the first commitment period of the Kyoto Protocol). On this issue, see for example Pershing and Tudela (2003) or Berk *et al.* (2001).

In this paper, the two approaches are linked. On the one hand, this paper analyses both the economic and environmental consequences of different scenarios on beyond Kyoto commitments. On the other hand, it identifies the implications of these commitments for countries' participation incentives. In other words, this paper recognises that future commitments are an important dimension of the incentive scheme that could be designed to induce more countries to participate in a climate agreement. Therefore, the objective of this paper is to analyse the relationship between future commitments, their environmental effectiveness, and their implications on the intertemporal and geographical distribution of the economic burden of reducing emissions.

In order to achieve the above objective, this paper provides an assessment of the implications for the main economic variables – and for climate policy in particular – of six different scenarios on future emission abatement commitments. What is the price of carbon in the different scenarios? What the abatement costs? In which scenario is climate friendly technical progress adequately stimulated? What scenario enhances countries' participation incentives? To answer these questions, an integrated climate-economy model is

necessary. This paper uses FEEM-RICE, a regional dynamic model of the world economy in which technical change is endogenous and responds to environmental policies. The model represents an extended version of Nordhaus and Yang's (1996) RICE model and is basically a single sector multiple countries optimal growth model. Both endogenous and induced technological change are explicitly modelled and international technological spillovers are quantified.

The structure of the paper is as follows. The next section will describe the alternative scenarios on future commitments that will be examined in this paper. In particular, we will provide motivations for the different scenarios, trying to cover both optimistic and pessimistic predictions on climate change control. Section 3 will present the results of our analysis. It will identify the consequences of the US decision not to comply with the Kyoto Protocol in each different scenario. In addition, section 3 will also analyse the incentives for the US, as well as for other countries, to meet different types of emission targets, i.e. to participate in future climate agreements. Finally, Section 4 will draw the conclusions and outline future research directions.

2 Scenarios for future commitments in climate change control

As widely recognised, the Kyoto Protocol represents only a first step towards GHG emission control and leaves a lot of open questions regarding future measures to combat climate change. For example, the emission reduction targets established by the Kyoto Protocol are specified only for the first commitment period, up to 2012. Nothing is known yet about emissions targets after 2012. In addition, the number of countries participating in the agreement is far from complete. The US and Australia defected from the Protocol, and other major developing countries are still out of the climate coalition. In particular, the Kyoto Protocol, without the US and Russia, covers only about 40% of global emissions.

At the same time, the domestic climate strategy currently implemented by the US does not seem to represent a long-term alternative to the Kyoto Protocol, since its main piece – the voluntary GHG intensity reduction target of –18% by 2012 – implies that actual emissions are allowed to grow by 12% over the same period (Claussen, 2003). In addition, a domestic climate policy is unlikely to be the only approach to climate change control in the US. If the US realises that a large amount of GHGs emission abatement must be undertaken and that these emission reductions are too costly if undertaken through domestic measures only, then they may decide to re-enter the game, either within the Kyoto framework or outside it.

As a consequence, the future of climate policy still seems to be quite uncertain, and potential developments are intensely debated throughout the world¹. Depending on the different future scenarios, the consequences

¹ For a discussion of different proposals, see for example Baumert et al (2002), CNRS/LEPII-EPE et al. (2003), Aldy et al. (2003), Aldy, Barrett and Stavins (2003), OECD/IEA (2002).

of recent decisions can significantly change (e.g. the US withdrawal from the Kyoto Protocol). In order to find out what implications these possible policy developments could have, we will investigate six different “Post-Kyoto” scenarios.

The six scenarios possess some common features. In particular, all scenarios assume that the absolute emission reductions defined in the Kyoto Protocol will be achieved by the Annex B_{US} countries by 2010 (first commitment period)². The US is assumed to achieve its –18% emission intensity target in order to slow the growth of GHG emissions per unit of economic activity over the next 10 years³. Developing countries have no target in the first commitment period.

Common assumptions also characterise the second commitment period (2010-2020).⁴ We assume that the international and domestic pressures for climate change control induce countries to strengthen further their efforts in international climate policy. In particular, we assume that both the remaining Annex B countries and the US agree by 2020 to reduce emissions by an additional 10% compared to the level of emissions achieved in 2010.⁵ The –10% objective for developed countries was indicated as the most likely for the second commitment period by a panel of 44 experts interviewed by Böhringer and Löschel (2003).⁶ In order to account for the need of developing countries to continue their economic and social development, and to catch up with the industrialised world, developing countries still do not have to comply with emission reduction targets. This assumption is also in line with recent research studies which conclude that an inclusion of developing countries in international climate change control is not likely before 2020. For example, expert judgements presented in Böhringer and Löschel (2003) reveal that in the second commitment period up to 2020 “...in 75% of the policy-relevant scenarios developing countries do not commit themselves to binding targets.” (p. 9)

² The Kyoto Protocol imposes absolute reduction targets, i.e. a reduction of absolute GHG emissions by a specified percentage.

³ In order to replicate the US strategy as precise as possible, our model computes the –18% intensity reduction in 2010 compared to the year 2000. Climate policy in terms of emission intensity targets is typically expressed as percentage reductions from some base year level. In the US context, greenhouse gas intensity is given by the ratio of greenhouse gas emissions to economic output. For a detailed discussion of the US proposal, see for example De Moor et al. (2002), Goulder (2002), Viguier (2002).

⁴ With the exception of Scenario 1 and 2.

⁵ When evaluating the economic implications of likely scenarios for the second commitment period, Böhringer and Löschel (2003) find that the global adjustment costs to accomplish the Post-Kyoto target of a 10% reduction in world carbon emissions (in their case with respect to the business-as-usual emissions in 2020) are likely to be moderate due to comprehensive “where-flexibility”. Also Frankel (2002) advocates small additional emission cuts for the Annex B in the second budget period in order to go towards the broader, long-term target of worldwide average of a conversion on a common formula for per-capita emissions.

⁶ The –10% target in the second commitment period belongs to all scenarios with the exception of Scenario 1 and 2. See below.

Then, different assumptions characterise the different scenarios from 2020 onwards. In the next sub-section, we will briefly describe the six scenarios on future emission abatement commitments in detail, as well as the motivations upon which they are based. Table 1 provides a synthesis of the six scenarios.

All scenarios will be analysed by using a modified version of Nordhaus' RICE model in which endogenous and induced technical change are explicitly modelled⁷. In our version of Nordhaus' model, called FEEM-RICE, technical change performs a twofold role: on the one hand, via increasing returns to scale, it yields endogenous growth; on the other hand, by affecting the emission/output ratio, it accounts for the adoption of cleaner and energy-saving technologies.

In the model, six countries/regions – United States (US), Europe (EU), Japan (JPN), Former Soviet Union (FSU), China (CHN) and Rest of the World (ROW) – optimally set the intertemporal values of three strategic variables: investments, R&D expenditure, and abatement rate. Given the interdependency of these countries' decisions, the equilibrium value of these variables is the solution of a dynamic open-loop Nash game between the six countries/regions.

Some important assumptions qualify our results. First, all countries are assumed to adopt cost-effective environmental policies. In particular, cost-effective mechanisms (e.g. emissions trading) are chosen over “command-and-control” measures in order to guarantee an efficient implementation of environmental targets. Therefore, according to the specific scenario and period, the countries belonging to the same climate coalition are assumed to implement a perfectly competitive emissions trading scheme. Second, our analysis focuses only on CO₂. There are other man-made greenhouse gases, and some of them are also taken into account by the Kyoto Protocol. Moreover, both the Bonn Agreement to the Kyoto Protocol and the subsequent Marrakech deal emphasise the role of sinks in meeting the Kyoto targets.

2.1 Six scenarios on the future of climate policy

A number of “Beyond Kyoto” scenarios have been discussed in the economic literature and in the policy debate. Here, we analyse six of them and describe their implications on the behaviour and performance of the different world regions. Table 1 summarises the main features of the six scenarios. The consequences of the six scenarios will be compared to those of the standard “Kyoto forever” hypothesis, which is usually assumed in most climate policy analysis. Figure 1 to 5 summarise the effects of the six scenarios on the

⁷ The FEEM-RICE model has already been used in Buonanno, Carraro, Castelnuovo and Galeotti (2001), Buonanno, Carraro and Galeotti (2002), Buchner, Carraro and Cersosimo (2002), Buchner, Carraro, Cersosimo and Marchiori (2002) and Buchner and Carraro (2003). A brief description is contained in the Appendix.

equilibrium number of emission permits, the price of permits, abatement costs, R&D investments and total CO₂ emissions.

Table 1: A summary of the six scenarios

Expected emissions			
	2010	2020	from 2020 onwards
Scenario 1 “Kyoto Forever without US”			
Annex B _{US}	Kyoto target: -5.2%	2010 level	2010 level
US	-18% intensity target	business-as-usual	business-as-usual
Developing countries	business-as-usual	business-as-usual	business-as-usual
Scenario 2 “Kyoto Forever without US only in the first commitment period”			
Annex B _{US}	Kyoto target: -5.2%	2010 level	2010 level
US	-18% intensity target	Kyoto constraint	2020 level
Developing countries	business-as-usual	business-as-usual	business-as-usual
Scenario 3 “Annex B cooperation only until 2020”			
Annex B _{US}	Kyoto target: -5.2%	-10%	“Business-as-Usual”
US	-18% intensity target	-10%	
Developing countries	business-as-usual	business-as-usual	
Scenario 4 “Enhanced permanent global cooperation”			
Annex B _{US}	Kyoto target: -5.2%	-10%	“Enhanced cooperation” ¹
US	-18% intensity target	-10%	
Developing countries	business-as-usual	business-as-usual	
Scenario 5 “Stabilisation at 550 ppmv”			
Annex B _{US}	Kyoto target: -5.2%	-10%	Stabilisation at 550 ppmv in 2100 with emission targets allocated according to sovereignty rule
US	-18% intensity target	-10%	
Developing countries	business-as-usual	business-as-usual	
Scenario 6 “-70% emission target”			
Annex B _{US}	Kyoto target: -5.2%	-10%	-70% emission target in 2050
US	-18% intensity target	-10%	-15% each decade
Developing countries	business-as-usual	business-as-usual	

¹ Targets deduced from the optimal cooperative intertemporal solution of the dynamic game among countries and strengthened by requiring an additional –10 % reduction.

- The first scenario: “Kyoto forever without the US”

The first scenario assumes a continuation of the current situation. After the US announced its defection from the Kyoto Protocol in March 2001, the remaining Kyoto countries – in particular the EU and Japan – have struggled to continue the Kyoto process and to convince Russia to participate in the Protocol. This scenario assumes that Russia ratifies the Kyoto Protocol in the very near future and that the targets embedded in the treaty can therefore be reached at the end of the first commitment period. Then, the Annex B_{US} countries decide to maintain their initial Kyoto targets and thus the corresponding emission level until the year 2100, whereas the US remains out of the Kyoto Protocol and adopts no effective climate policy. This scenario thus represents the situation in which the Annex B_{US} countries behave according to the “Kyoto forever” hypothesis, whereas the US and the developing countries have no binding emission constraints. All countries are assumed to adopt cost-effective environmental policies, and in particular, emissions trading is implemented among the Annex B_{US} countries.

This scenario has been extensively analysed in Buchner, Carraro and Cersosimo (2002). Let us recall what are its main implications. The US defection reduces the demand for permits and therefore the permit price. As a consequence, compliance costs for the remaining Annex B countries become much smaller. The lower abatement costs and permit price also reduce the incentives to invest in climate friendly technologies. The environmental effectiveness of the Kyoto Protocol becomes very low.

Russia suffers the main economic loss from the US defection, because of the fall of the price in the permit market and the corresponding decline in windfall profits.⁸ As a consequence, Russia also has a strong incentive to withdraw from the Kyoto Protocol, whereas developing countries have little incentives to join the Kyoto Protocol.

- The second scenario: “Kyoto forever without the US only in the first commitment period”

Currently, the US has decided to adopt its own domestic climate change policy, independently of the efforts undertaken in the context of the Kyoto Protocol. However, this strategy could be revised after 2010, either for domestic or for international political reasons. The simplest way by which the US might return into the international climate process would be to ratify Kyoto and to adopt the Kyoto targets from 2010 onward.

⁸ Some studies highlight feedback effects that can mitigate the fall in the permit price. Strategic market behaviours can indeed modify the size of the expected changes in prices and abatement costs. In particular, these changes are much smaller than initially suggested. For example, banking and monopolistic behaviour in the permit market (Manne and Richels, 2001; Den Elzen and de Moor, 2001a and 2001b; Böhringer and Löschel, 2001) or strategic R&D behaviour (Buchner, Carraro and Cersosimo, 2002) can offset the demand shift and reduce the decline of the permit price consequent to the US withdrawal from the Kyoto Protocol.

There are indeed several signs that Kyoto could again become an option for the US industries have initiated their own mitigation activities in order to remain competitive in the so-called Kyoto countries – also in the light of possible sanctions – and a number of US states have introduced their own GHG targets and climate activities. Also, the official US position could change after the next elections, and a new US administration could re-start the climate talks which at the moment seem to be stalled.

On the basis of these indications, in this second scenario we assume that the US decides to join the group of countries committed to the Kyoto Protocol in the second commitment period and afterwards. Continuity with Kyoto could be attractive for the countries that are already engaged in the Kyoto Protocol, i.e. the Annex B-US, since these countries already made a substantial investment in the Kyoto process (Bodansky, 2003).

Developing countries, as in “Kyoto forever”, are assumed not to adopt any emission target until 2050. Consequently, emissions in Annex B countries will be stabilised at about –5% w.r.t their 1990 value, whereas emissions in developing countries will keep growing. Figure 5 shows the evolution of total emissions in Scenario 2 and in the other scenarios as well.

In this scenario, the equilibrium number of permits is lower than in “Kyoto forever” only in the first commitment period, whereas they coincide afterwards. As a consequence, also the price of permits and abatement costs follow the same path as in “Kyoto forever”.

Figure 1: Equilibrium number of emission permits

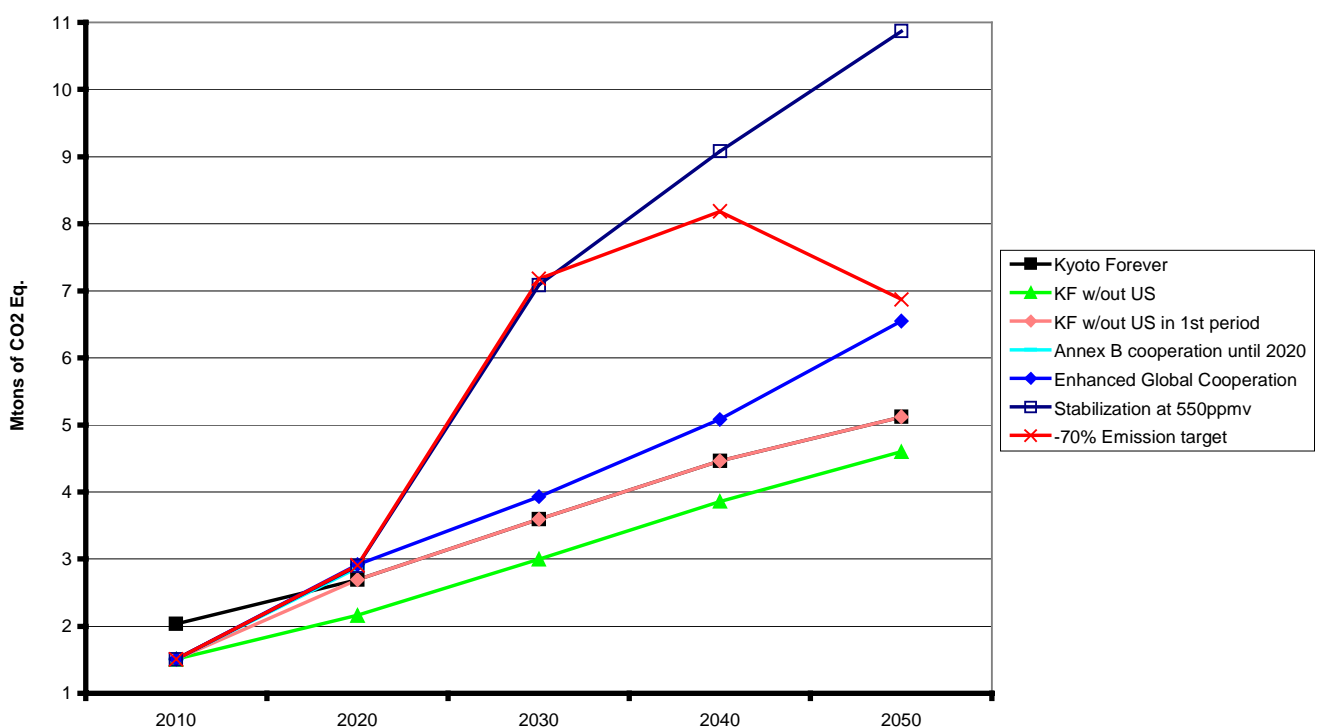


Figure 2: Price of emission permits

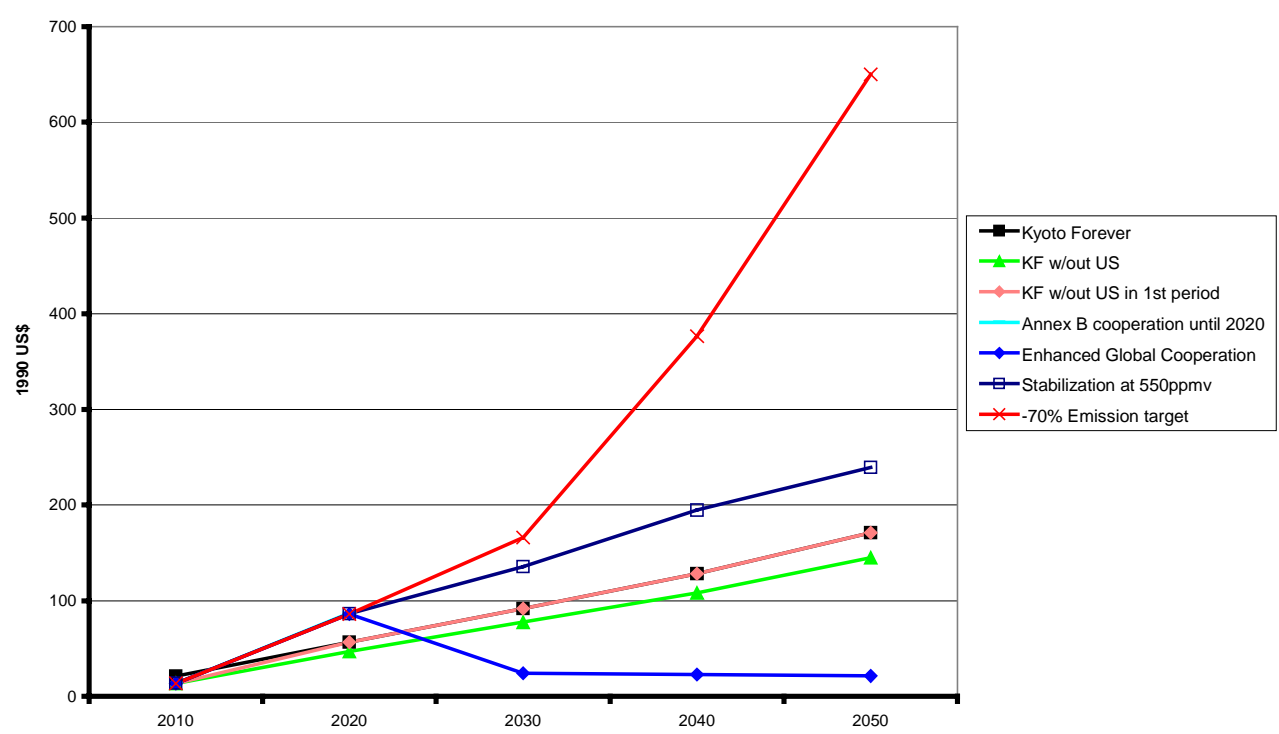


Figure 3: Total abatement costs

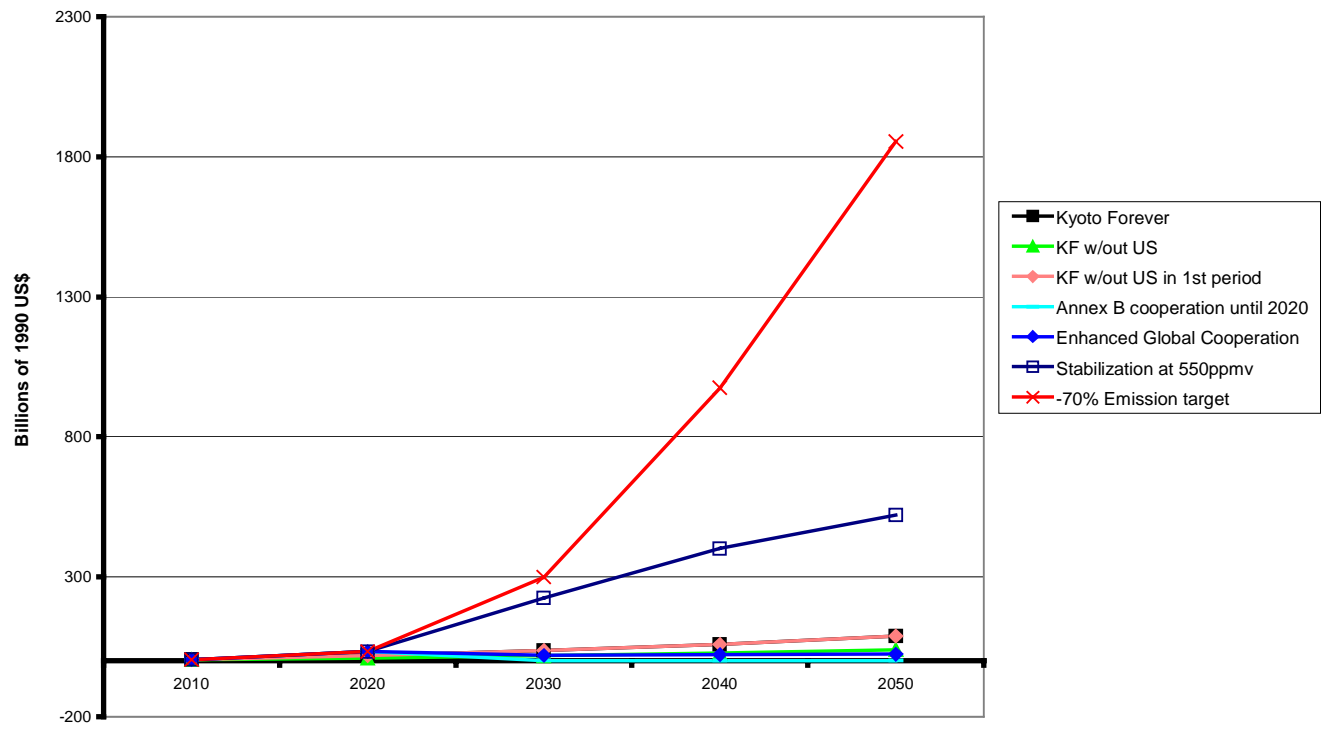


Figure 4: Total R&D investments

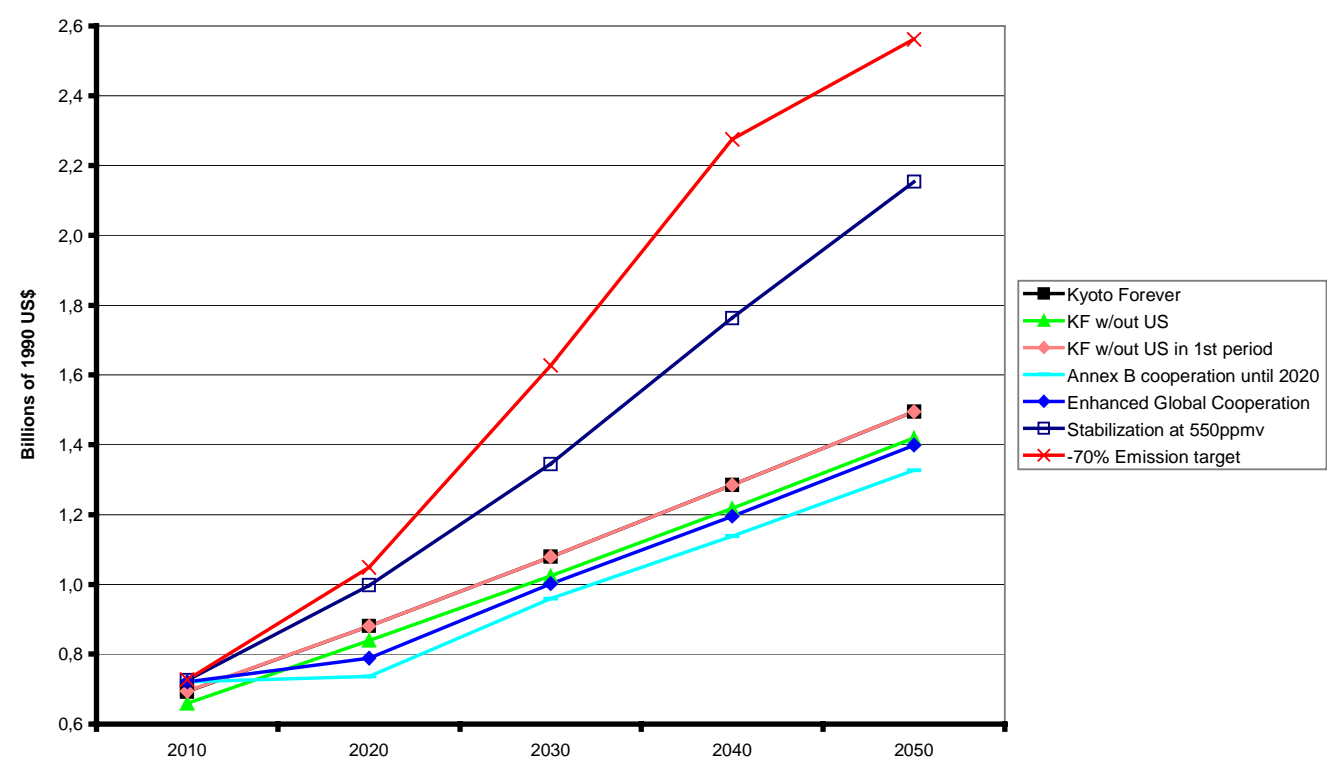
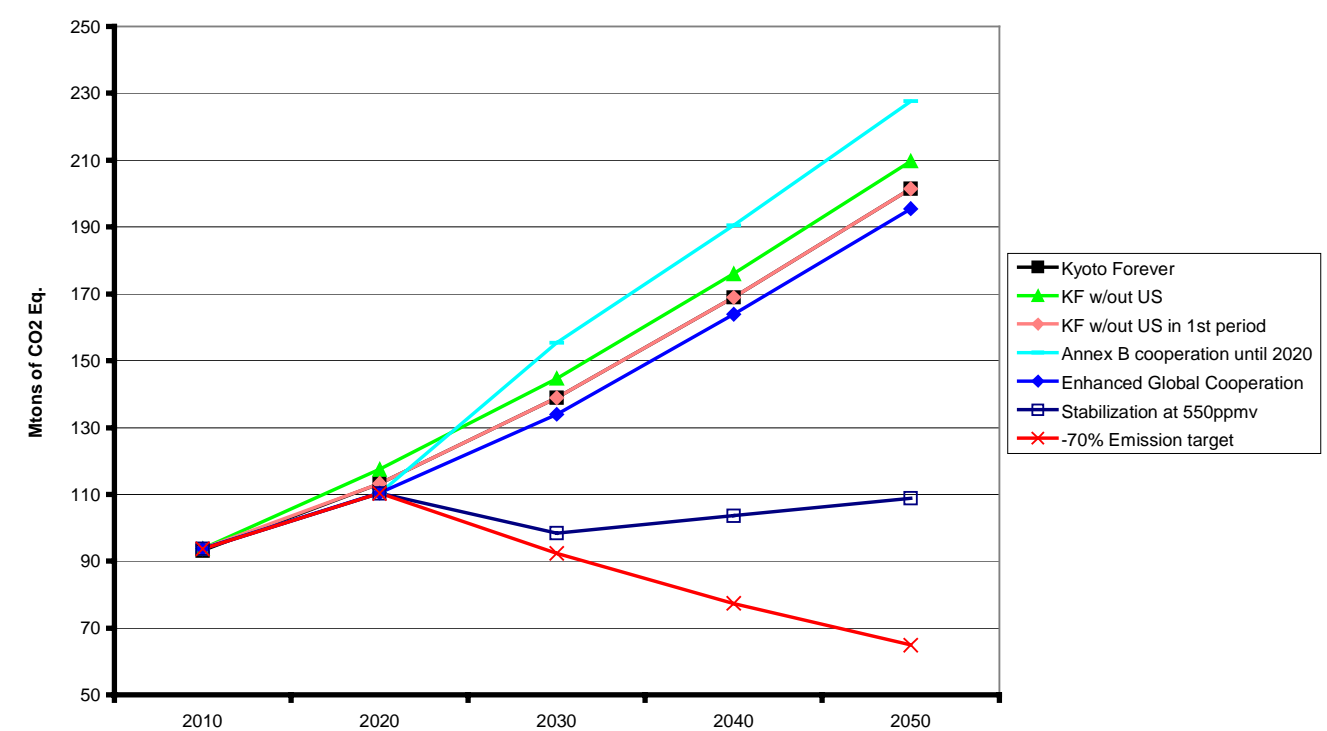


Figure 5: Total CO₂ emissions



- The third scenario: “Annex B cooperation only until 2020”

In the third scenario, the first two commitment periods coincide with the ones described at the beginning of this section, namely the Annex B_{US} countries achieve the Kyoto target in the first commitment period and the –10% target (w.r.t. 2010 emissions) in the second one. The US adopts its –18% intensity target in the first commitment period and the –10% absolute target (w.r.t. 2010 emissions) in the second one. Developing countries do not commit to any emission reductions.

After 2020, we assume that cooperation on climate change control collapses and emissions return to their business-as-usual (BAU) paths. This dramatic change of policy could be explained by a failure of international diplomacy to sustain cooperation, by an economic crisis that shifts countries’ priorities or by new scientific evidence on climate change that convince countries to postpone or cancel actions to reduce GHG emissions.

Indeed, given the uncertainties in the process of climate policy and the relatively low priority that is attached to climate change control by several key countries, a possible development in climate policy after the second commitment period could consist of the rejection after 2020 of any type of commitment to reduce GHG emissions. Obviously, this scenario seems to be a very pessimistic prediction of future climate policy. Nonetheless, the slow process towards the ratification of the Kyoto Protocol confirms one more time that climate policy is a complex area, characterised by long time horizons and scientific uncertainties, which pose special difficulties to political systems more suited to immediate concerns. At the same time, there are expectations that science will provide new information on climate change and develop new technologies that could make the emission of greenhouse gases rather harmless.

Given the characteristics of this scenario, both the permit price and total abatement costs are likely to be very low (see Figures 2 and 3). As a consequence, investments in mitigation technologies are likely to be very small and GHG emissions larger than in other scenarios (see Figures 4 and 5).

- The fourth scenario: “Enhanced permanent global cooperation”

The fourth scenario is based on the idea that Kyoto targets are largely sub-optimal – in the sense of not corresponding to the countries’ reduction incentives and inducing low carbon reduction – and that countries are likely to adopt targets closer to the optimal ones in the medium term. Therefore the two initial commitment periods are the same as in scenario 3. Then, after 2020, Annex B countries (including the US) and developing countries adopt what we call “enhanced permanent cooperation emission targets”. These are computed as follows. All countries cooperatively maximise their joint welfare with respect to their policy variables, including GHG emissions. This yields the optimal path of GHG emissions in all world regions in

the sense of cooperative outcome to all nations. Then all countries, on the basis of the precautionary principle and given the relatively low emissions reduction in their optimal strategy, commit to reduce their emissions by an additional 10% below the optimal emission trajectories from 2020 onward. Note that this amount of abatement is more than the nations' would do in their cooperative optimum, but can still be considered as relatively modest emission reduction commitments⁹.

Notice that in this scenario, given its global and cooperative nature, developing countries are also committed to reduce their GHG emissions. Targets for developing countries are set cooperatively with developed countries. As a consequence, emissions in developed countries are slightly larger than in "Kyoto forever", whereas they are smaller for developing countries. Total emissions are shown in Figure 5.

In this scenario, thanks to the participation of developing countries, the price of permits becomes quite low after 2020, thus reducing total abatement costs. This result is obtained despite the strong increase of the total permits traded (see Figure 1). The reason is that the participation of developing countries makes low cost abatement opportunities available. Therefore, both the supply and the demand of permits increase, implying a larger number of trades, with the supply increasing more than the demand (i.e., the supply curve shifts more than the demand curve).

- The fifth scenario: "Stabilisation at 550 ppm"

The fifth scenario recognises that one of the major problems with the Kyoto Protocol and with the above scenarios is the low reduction of total GHG emissions that can be achieved. Therefore, in this scenario we assume that all countries agree to undertake a substantial effort to control GHG emissions and to stabilise global GHG emissions at 550 ppmv in the year 2100¹⁰. This concentration goal is often used as a baseline hypothesis for models examining climate sensitivity. We assume linear convergence to 550 ppmv in 2100, starting in 2020.

Again, the two initial commitment periods are designed as in Scenario 3 and 4. From 2020 onwards, targets are calculated to achieve the 550 ppmv stabilisation goal. How is this global target allocated among the different world regions? Following again the suggestions of 44 experts (Cf. Böhringer and Löschel, 2003), we adopted the "sovereignty" equity rule, which requires that the emission entitlements are shared in proportion to emissions. This rule thus reflects the so-called "polluter-pays principle", indicating that the individual countries are responsible for their own contribution to global warming. Therefore, the emission

⁹ Note that we talk about the optimal strategies/scenarios to the nations in their cooperative outcome, not taking into account the externalities which would need to be internalised in order to make these strategies also socially optimal.

¹⁰ Parts per million by volume is a measure of concentration of gases in the atmosphere.

targets for 2030, 2040 and 2050 for all world regions, including the developing countries, are based on both the 550 ppmv stabilisation goal and the sovereignty rule.

The long-term stabilisation level of 550 ppmv is generally considered to be a reasonable goal, also adopted in the emission mitigation scenarios examined by the latest IPCC report (IPCC 2001). In particular, the analysis of Working Group III in the TAR suggests that achieving the aggregate Kyoto commitments in the first commitment period can be consistent with trajectories that achieve stabilisation at 550 ppmv at the end of the century (WGIII TAR, Section 2.5.2). This concentration level also coincides with a *doubling* of CO₂ atmospheric concentrations compared to pre-industrial levels. Stabilisation at such a level would imply a global warming up to 3°C with a change in the mean surface temperature in the range 1.6°C - 2.9°C by 2100. In this range, although the strongest impacts from climate change can be prevented, potentially serious damages attributable to climatic changes could still be entailed¹¹.

The target of not exceeding the 550 ppmv concentration level is also supported by the EU. The first significant EU proposal for a climate target for the post-2000 period, presented at the EU Council of Ministers in 1996, suggested stabilising the atmospheric concentrations of CO₂ at a level around twice the pre-industrial level of about 280 ppm, corresponding thus to the concentration target of 550 ppm.

In this scenario, abatement costs are considerably higher than in most of the other scenarios (Figure 3). As a consequence, the emission permit trading is increasing from the year 2020, thus inducing a very high price in the permit market (see Figure 1 and 2). The relevant abatement effort also induces strong investments in climate-related R&D (see Figure 4).

- The sixth scenario: “-70% emission target”

Lately, several politicians have expressed their concern for the dangers of climate change. In a recent announcement, the English Prime Minister Tony Blair proclaimed that Kyoto represents an enormous achievement, even though it is not sufficient to protect humanity from the impacts of climate change¹². In order to stop further damage to the climate, Blair proposed to aim at a 60% cut in carbon emissions by 2050, implementing thus each decade an emission reduction target of -10%, and advocated this target for all industrialised countries.

¹¹ In particular, the IPCC TAR (2001) points out that significant impacts associated with warming up to 3°C would not be prevented (e.g. loss of some unique vegetation systems, extensive coastal wetland loss, decreases in crop yields in most regions, and many adverse impacts to which developing countries are particularly vulnerable).

¹² The “Speech on Climate Change” given by the British Prime Minister Tony Blair on February 24th, 2003, is available at <http://www.britain-info.org/>

This reduction goal is based on the outcomes of a recent report by The Royal Commission on Environmental Pollution (2000) which found that a 60% reduction by 2050 was essential if the overall goal of stabilising GHG emissions at 550 ppm was to be achieved already by 2050. A few days after Blair's statement, also Chirac, the French President, echoed Blair's proposal and insisted on a strong commitment to reduce GHG emissions.

Therefore, this scenario is designed as follows. The two initial commitment periods are the same as in scenarios 3, 4 and 5. Then, starting from 2020, the so-called Kyoto countries – Japan, European Union and Russia – are supposed to achieve a total reduction in GHG emissions of –70% in 2050 with respect to their BAU emissions, following the recommendations of the UK plan. The other countries – the US and the developing regions – reduce their emissions between 2020 and 2050 by –15% each decade. These targets thus imply strong emission reductions also in the US and the developing countries. From 2050 onwards, when countries have achieved the ambitious emission levels, all nations are committed to maintain these emission levels.

The environmental consequences of this scenario are shown in Figure 5. A reduction in global emissions of almost 70% with respect to the Kyoto forever emission path can be obtained in 2050. Therefore, this last scenario aims at the strongest emission reductions among the proposed scenarios.

In order to achieve this goal, the demand for permits will be high, whereas the supply of permits, given the strong constraints also in developing countries, is expected to be low. Therefore, both the permit price and abatement costs are going to be very large (see Figure 2 and 3). Notice that, given the high level of the permit price in 2040 and 2050, the quantity of demand for permits is likely to decrease in these two decades (Figure 1). The reason is that other mitigation activities become more convenient and are implemented. For example, countries prefer to invest in new technologies to control their GHG emissions (see Figure 4).

3 Main policy implications of the six scenarios

As shown in Buchner, Carraro and Cersosimo (2002) among others, other countries, in addition to the US, have an incentive not to comply with the Kyoto Protocol. This is the case of Russia above all, whose benefits from participating in the Kyoto Protocol are largely reduced by the US defection. This conclusion was based on the “Kyoto forever” hypothesis. Does it still hold when we adopt more realistic scenarios on future emission abatement commitments? Does the US still face an incentive to implement its own domestic climate change strategy if assumptions on the future of climate policy are modified? What are the implications of different future commitment scenarios on the specific consequences of the US decision not to ratify Kyoto and on the incentives for the other countries to follow the US in defecting from the agreement?

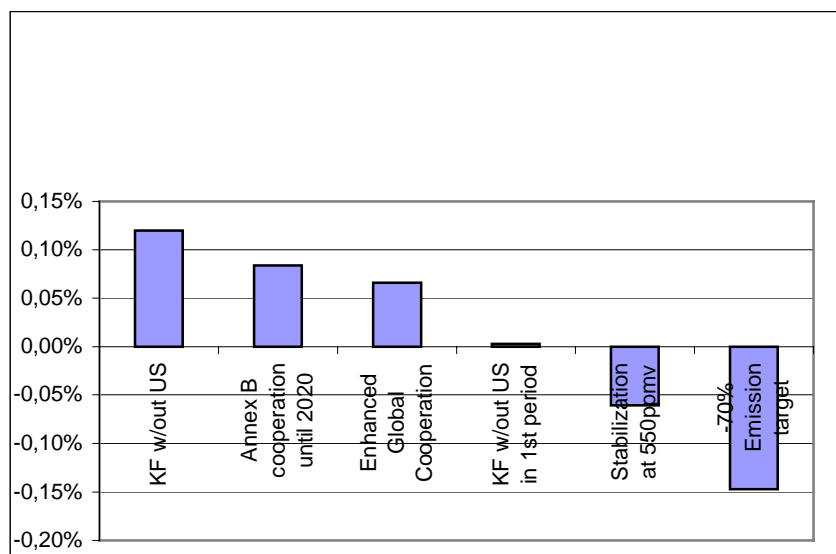
In order to answer these questions, we structure the discussion of the results on the six scenarios introduced in the previous section along four steps: First, we verify whether the US still has an incentive to defect from the Kyoto Protocol when future commitments change. In a second step, we investigate the consequences of the US decision under the different future commitments scenarios. Third, we would like to find out whether changes in future commitments modify Russia's incentive to defect from Kyoto. Finally, we address the same question for developing countries, i.e. whether they face new incentives to support or oppose the Kyoto Protocol in the different scenarios.

3.1 Participation incentives for the US

Figure 6 shows the present value of welfare changes in the US induced by changes in future emission reduction commitments. Welfare changes are computed with respect to the “Kyoto forever” scenario (where the US participates). In particular, Figure 6 confirms that the US faces the strongest free-riding incentives in the current situation, that is, it gets the highest welfare change in the scenario in which it remains outside the Kyoto Protocol also in the long-term.

However, Figure 6 also demonstrates that the US is able to achieve welfare gains from several policy scenarios that differ in the longer term from the current defection scenario, in particular because they include the US and lead to a better environmental effectiveness. This result is crucial for future negotiations on climate policy as it could change the US position.

Figure 6: US total welfare. Changes with respect to “Kyoto forever”



In particular, three alternative policy scenarios allow positive welfare changes for the US compared to “Kyoto forever”. The second-highest welfare gain for the US is obtained in scenario 3 which requires only relatively small US efforts up to 2020, and then no additional effort with respect to “business as usual”. In line with the current US behaviour, this scenario would imply an increased US effort only in the second commitment period from 2010 to 2020, thus requiring little emission reduction activities in the US.

Another particularly attractive case is the “Enhanced permanent global cooperation” scenario, in which there are again incentives for the US to defect from “Kyoto forever”. However, although the US withdraws from the Kyoto Protocol at the beginning, it starts to intensify its efforts on climate change control after the first commitment period. Comparing this scenario to the original Kyoto Protocol, the US would thus have incentives to participate in the longer term. This increases environmental effectiveness and lowers total abatement costs. If the US would have the possibility to choose between this climate scenario and the Kyoto Protocol when deciding again on climate policy, it would favour what we call “Enhanced permanent global cooperation”, namely they would accept to commit to future emission abatement targets, thus enhancing global participation and environmental effectiveness.

If the awareness on potential damages from climate change increases and international negotiations lead to ambitious future emission abatement targets, like the ones assumed in scenario 5 and 6, then the US would suffer welfare losses if it complies with these targets. In particular, the strongest losses would be induced by the most stringent climate policy, i.e. the -70% emission target. Faced with this alternative, the US do prefer to comply with the “Kyoto forever” scenario.

3.2 Consequences of the US withdrawal

In Buchner, Carraro and Cersosimo (2002), a number of reactions resulting from the US withdrawal from the Kyoto Protocol have also been identified. The US defection, by lowering the demand for emission permits, induces a fall in the permit price and consequently a reduction of the compliance costs. Taking into account the permit suppliers’ strategic behaviour and the effects on technological innovation induced by the US decision¹³. Buchner, Carraro and Cersosimo (2002) estimated a fall in the permit price by almost 35% (with respect to. “Kyoto forever”) in 2010. This implies a reduction in abatement costs, which lead to welfare

¹³ The reason for this result is two-fold: On one hand, the US withdrawal – by reducing the demand for emission permits and their price – lowers the incentives to undertake energy-saving R&D. As a result, the GHG emissions increase, implying that countries need to increase their demand for permits or reduce their supply of permits in order to fulfil their Kyoto commitments. On the other hand, the US decision – by lowering the R&D investments and triggering emission increases – leads to higher damages from climate changes. In order to cope with these damages and the corresponding lower growth rate of output, higher investments are needed which, by increasing the energy demand, again raise the emissions. Both of these feedback-effects on the demand and supply of permits increase the permit price. Nonetheless, the final permit price is still lower compared to the situation in which the US would have participated in the Kyoto Protocol.

gains in the permit-buying countries and to welfare losses in the permit-selling countries, most importantly in Russia. As a consequence, Russia's benefits from participating in the Kyoto Protocol are much lower while the cost of a possible Russian defection increases in the EU and in Japan, thus creating a situation in which Russia possesses a large bargaining power.

Do the consequences of the US decision not to ratify the Kyoto Protocol change when more realistic future commitments scenarios are considered? Let us start by analysing the effects of the US defection on the price of permits, on the corresponding demand and on total abatement costs under the six different scenarios on future abatement targets. In addition, given the important role of technological innovation and diffusion, let us analyse total R&D investments as well.

Results are shown in Figures 7 - 10. There is a preliminary result that we would like to stress. Consider the first scenario ("Kyoto forever" without the US). The US defection lowers the demand for permits and therefore the permit price. The level of the demand for permits lies about 25% below "Kyoto forever" (Figure 8) and the permit price is about 35% lower than in "Kyoto forever" in 2010 (Figure 7). These results coincide with those previously derived in Buchner, Carraro and Cersosimo (2002) and thus confirm the robustness of the model.

Let us consider the other scenarios. Results vary as a function of the stringency of future commitments. As expected, permit prices are highest in the more environmentally ambitious scenarios.

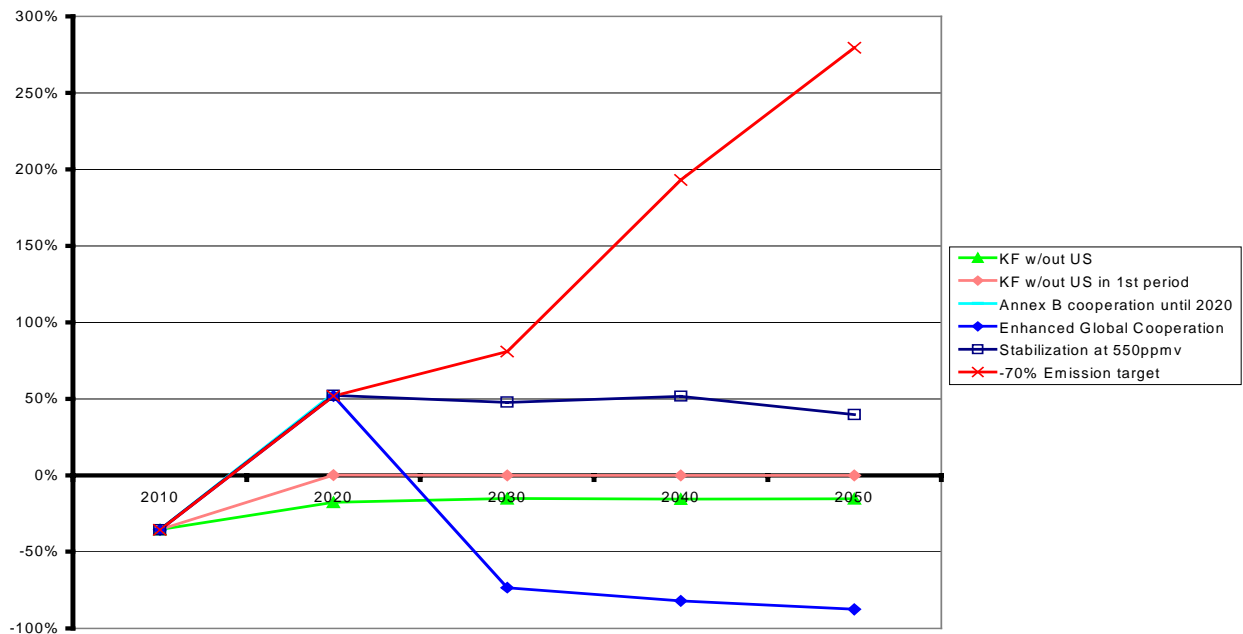
In 2020, the permit price varies from -18% to +52% w.r.t. "Kyoto forever". The lowest level of the permit price is induced by the scenario in which the US never agrees to adopt any emission reduction targets. Instead, if the US defects only in the first commitment period, then the demand for permits and their price would remain below the "Kyoto forever" level until 2020 and then (roughly) coincide with the one implied by "Kyoto forever". In the scenarios 3, 4, 5, and 6, the demand for permits grows, thus increasing the permit price, which achieves a value of about 50% above "Kyoto forever" in 2020. As emission reduction commitments increase for the entire Annex B countries in the second period, the demand for emission permits and their price strongly increase. The more than proportional growth in the permit price is induced by the market power of a few permit suppliers.

Abatement costs follow the path of the demand for emission permits and their price (Figure 9). In the first commitment period, compliance costs remain below the "Kyoto forever" level, but then they quickly increase and peak in 2020, achieving a level which is about 80% higher than in "Kyoto forever".

From 2020, four different developments can be observed, where permit prices range from a reduction by almost 90% to an increase by 280% and changes in compliance cost range from -100% to more than 20

times w.r.t. “Kyoto forever” in 2050. Again the reason is the different stringency of future commitments in the four scenarios.

Figure 7: Price of permits. Changes with respect to “Kyoto forever”



In the “Enhanced permanent global cooperation” scenario, the large supply of emission permits triggered by global participation induces a strong decrease in the permit price after its peak in 2020. The permit price reaches in 2030 a value corresponding to less than 70% the “Kyoto forever” value (Figure 7), despite the slow increase in demand induced by the stronger global emission reduction requirements. The low price for carbon obviously also reduces unit abatement costs. Therefore the involvement of developing countries and of the US is crucial to minimise the total costs of achieving relevant global emission reductions. At the same time, environmental effectiveness is larger than in “Kyoto forever” (from 2020, emissions stabilise at about 3-4% below the “Kyoto forever” level). However, the low marginal compliance costs reduce the incentives to invest in climate-friendly technologies, because emission reductions can be cost-effectively achieved by trading emission permits (Figure 10).

The collapse of climate change control in the “Annex B cooperation only until 2020” scenario induces both an increase in global emissions (see Figure 5) and a strong fall in compliance costs (see Figure 9) w.r.t. “Kyoto forever”. In particular, costs coincide already in 2025 with the “Kyoto forever” level and attain the lowest levels among the proposed scenarios from 2030 onwards (almost 100% below “Kyoto forever”). The extremely low compliance costs, induced by the absence of abatement commitments beyond 2020, lower the

incentive to undertake climate-friendly R&D. This scenario is actually characterised by the lowest R&D investments, never exceeding the BAU level.

In the fifth climate scenario, the permit price remains roughly at the level of 2020, fluctuating around 50% above “Kyoto forever” and starting to slowly fall only from 2040. Given the rather stringent emission reduction requirements, the number of emission permits traded grows strongly after 2020 and maintains a positive growth path also in the future. Total abatement costs are also characterised by a positive trend. They increase until 2040, when compliance costs are almost four times higher than under “Kyoto forever”. Nonetheless, from 2040 abatement costs slowly decrease, as a consequence of the permit price dynamics. The high future abatement commitments have an impact also on R&D efforts. From the initial level of about 5% above “Kyoto forever” in 2010, R&D investments continue to increase over the following decades, achieving a positive variation of more than 40% in 2050.

Figure 8: Quantity traded of permits. Changes with respect to “Kyoto forever”

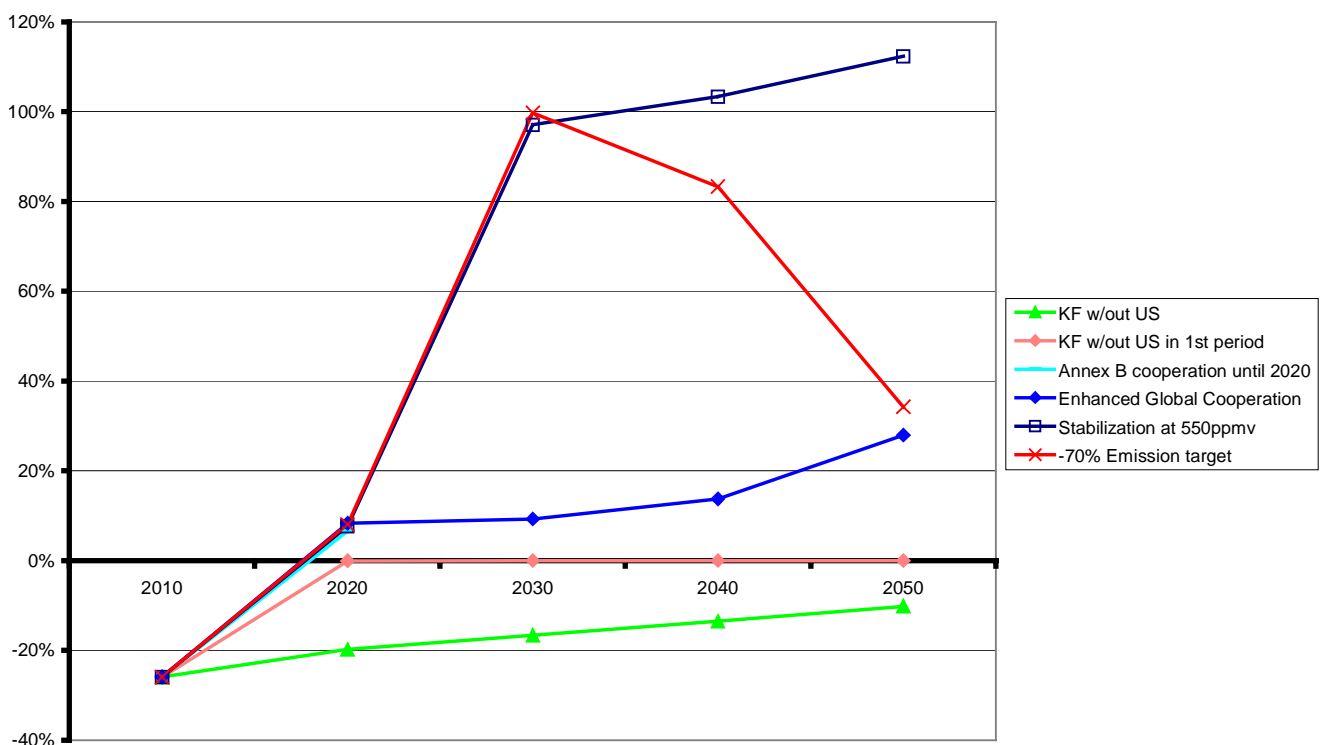


Figure 9: Abatement costs. Changes with respect to “Kyoto forever”

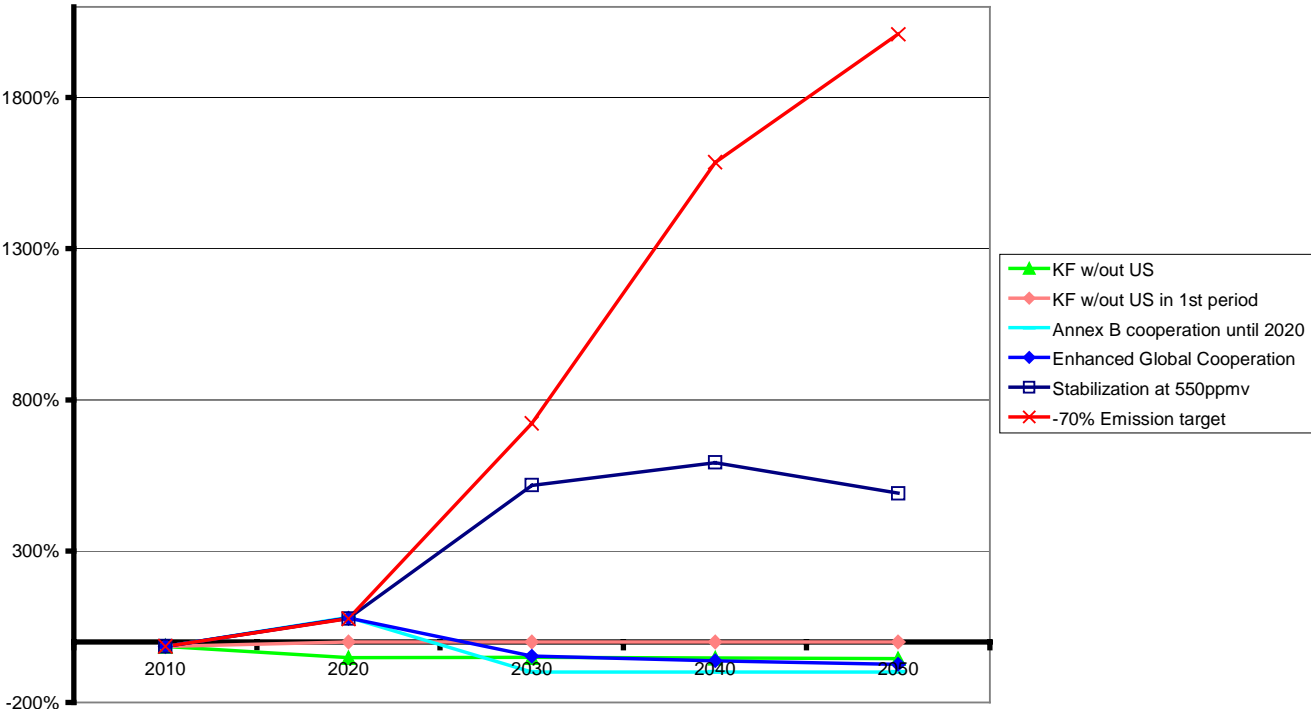
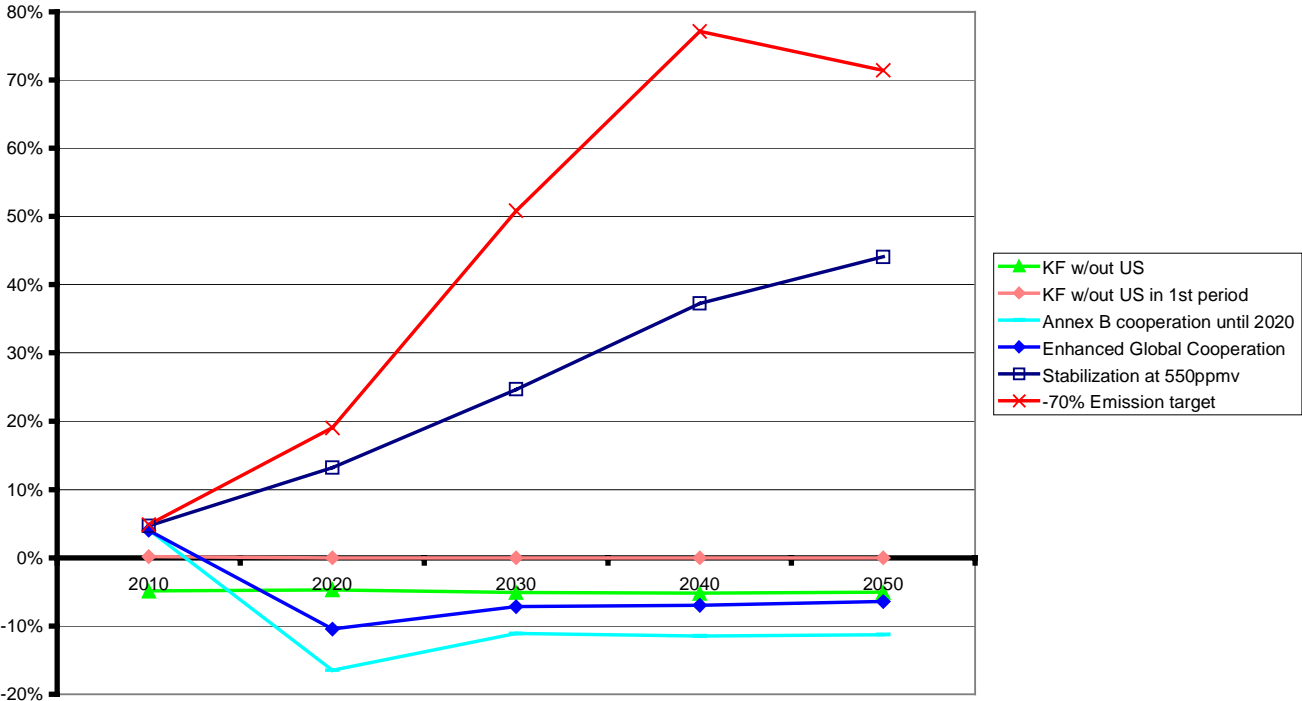


Figure 10: R&D investments. Changes with respect to “Kyoto forever”



The last scenario is designed to achieve a reduction in global emissions of about 70% in 2050. Given this ambitious abatement target, the quantity of emission permits traded sharply increases after 2020 and becomes twice the “Kyoto forever” level in 2030. However, traded emission permits then fall considerably and become 65% lower in the following two decades. The reason for this dynamics is shown in Figure 7. Already in 2030, the permit price reaches a value of more than 80% above the “Kyoto forever” price. Then it increases even more sharply and becomes about 280% larger than the “Kyoto forever” value in 2050. This high price level provides strong incentives for countries to invest in climate friendly R&D in order to cope with the convened abatement targets. As a consequence, this scenario is characterised by the highest R&D investments among the six scenarios. The growth of R&D investments is particularly strong from 2020 to 2040 (Figure 8). Nonetheless, abatement costs become very large after 2020 and grow exponentially (in 2050, total compliance costs are more than 20 times larger than in “Kyoto forever”).

This analysis shows the importance of considering the entire profile of policy scenarios. Different future commitments can substantially change participation incentives. For example, total abatement costs range from a reduction by almost 100% to an increase by more than 20 times the Kyoto forever level in 2050. The economic impacts of climate policy are both influenced by the stringency of future commitments and the involvement of the US and developing countries.

3.3 Participation incentives for Russia¹⁴

The role of Russia is evidenced by Figure 11, which shows the welfare loss induced by the US withdrawal from the Kyoto Protocol. In addition, Figure 11 seems to confirm that Russia prefers, like the other countries, scenarios in which future abatement targets are not very ambitious. Russia experiences its highest welfare gain (w.r.t. to the “Kyoto forever” case) in the “Annex B cooperation only until 2020” scenario. The reason is the economic costs induced by emission abatement, which are compensated by the revenue from selling emission permits.

¹⁴ The relationship between welfare and future commitments in the EU and Japan is similar to the one already shown for the US. The only difference concerns the “Kyoto forever w/out US” scenario, which obviously cannot be the most preferred one for the EU and Japan. The most preferred scenarios for the EU and Japan are scenarios 3 and 4. In both cases, the US is asked to assume the same responsibilities as the EU and Japan in terms of future emission abatement. In addition, in the “Annex B cooperation only until 2020” scenario, future targets are not very ambitious and therefore compliance costs are low in all the countries. Notice again that considerable welfare gains can be obtained in the “Enhanced permanent global cooperation” scenario. The EU and Japan, as well as the US, gain from moderate short term emission targets. The similarity of the preferences of the EU and Japan with those of the US depends on their role of demanders in the permit market. Russia, instead, is likely to be the largest permit supplier and therefore has different preferences over the six scenarios.

Consequently, the implementation of the “Enhanced permanent global cooperation” scenario provides Russia with some welfare gains, despite the considerable fall in the permit price after the year 2020. The permit prices decrease because of the moderate future targets and because China is assumed to start supplying permits after 2030. This higher supply reduces the revenue that Russia receives from selling permits (see Figure 12), notwithstanding that the demand for permits remains relatively high compared to the one in the “Kyoto forever” scenario. Given the low permit price and low revenue, Russia considerably reduces its investments in R&D, which becomes about 50% lower than in “Kyoto forever”. Therefore, investment costs are smaller, as well as other abatement costs. This more than offsets the revenue loss in the permit market.

In the remaining four scenarios, Russia loses in terms of welfare w.r.t to “Kyoto forever”. Only if the US joins the Kyoto coalition in 2010, then Russia faces a very small welfare loss. In the ambitious scenarios 5 and 6, high negative welfare changes occur to Russia as it is required to be active in climate change control as part of the Annex B_{US}. Despite the very high revenues from emissions trading, the interplay of the strong emission requirements and the participation of alternative, competitive permit suppliers, explains the welfare losses for Russia.

This suggests that a careful design of long-term climate policies could provide incentives for Russia to participate in an international agreement to control climate change. However, this is more likely to happen through a mitigation of Russia’s commitments rather than through the profits that Russia can make in the permit market.

Figure 11: Welfare in Russia. Changes with respect to “Kyoto forever”

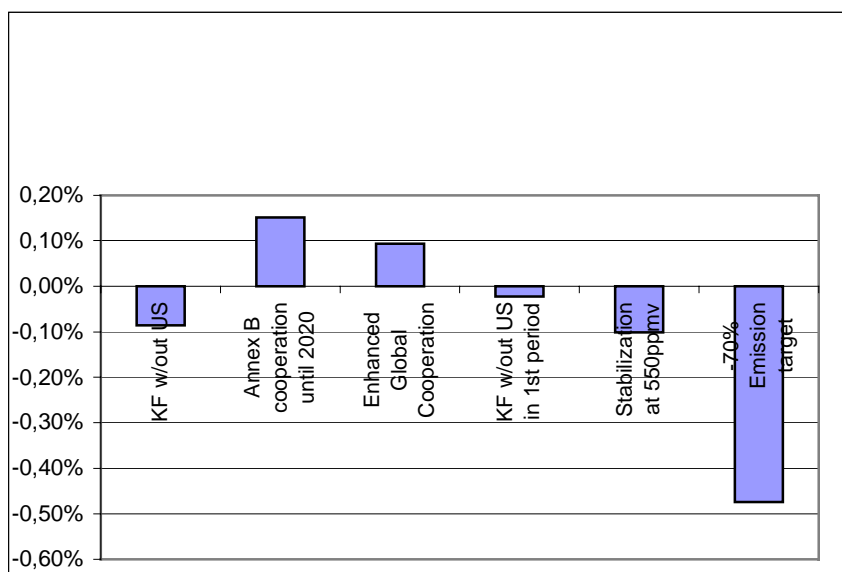
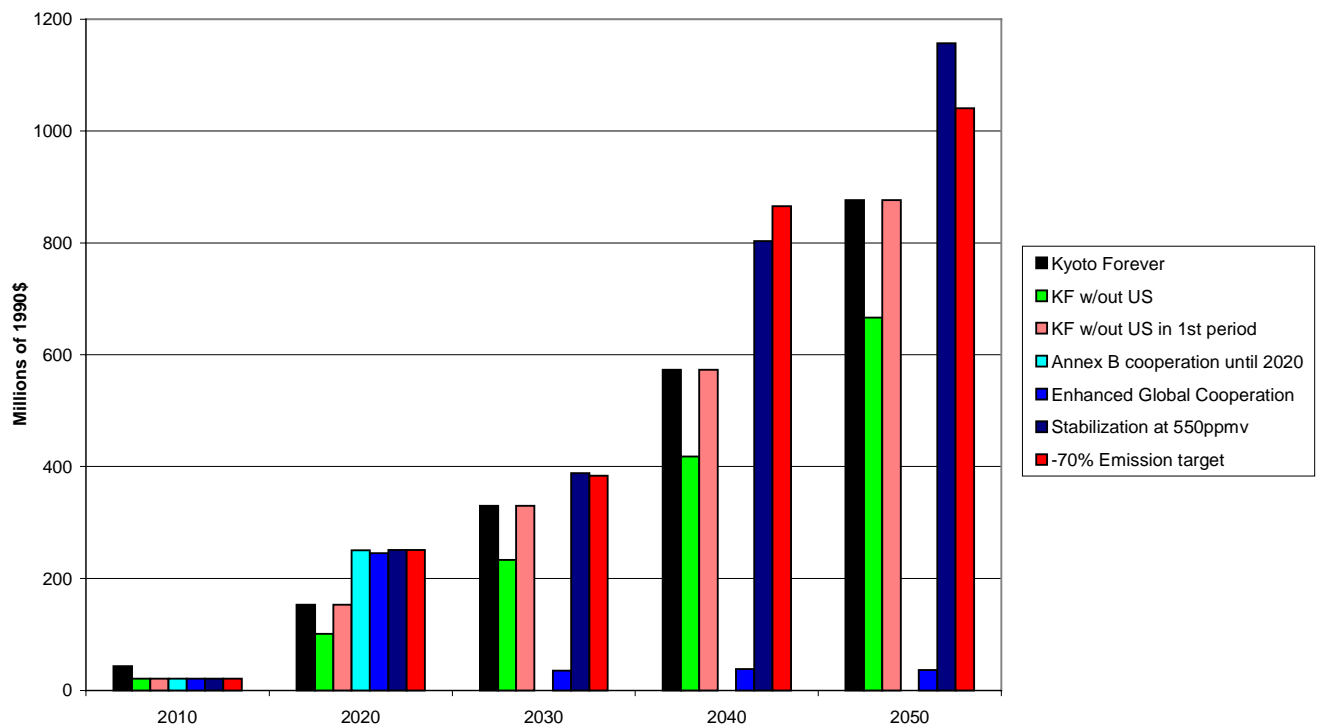


Figure 12: Russia's revenues from selling permits



3.4 Participation incentives for developing countries

Developing countries are assumed to face binding emission reduction targets only in three of the six scenarios. Therefore, these three scenarios yield some welfare losses for developing countries, because emission abatement is obviously costly. Developing countries, like all participants in a public good provision game, prefer scenarios in which they can free-ride on the other countries' emission abatement.

Figure 13 and 14 shows that both China and Rest of the World reveal similar preferences over the six scenarios. Both suffer the smallest, rather marginal, welfare losses in the “Enhanced permanent global cooperation” scenario, characterised by moderate emission targets for all countries. This scenario imposes the lowest burden on developing countries, giving them the possibility to contribute to climate change control while still paying adequate attention to their development priorities.

By contrast, welfare losses for developing countries could be quite relevant in the “550 ppmv” scenario and even higher in the “–70% emission target” scenario. Therefore, developing countries face strong free-riding incentives, in particular in climate scenarios characterised by ambitious emission targets.

Figure 13: Welfare in China. Changes with respect to “Kyoto forever”

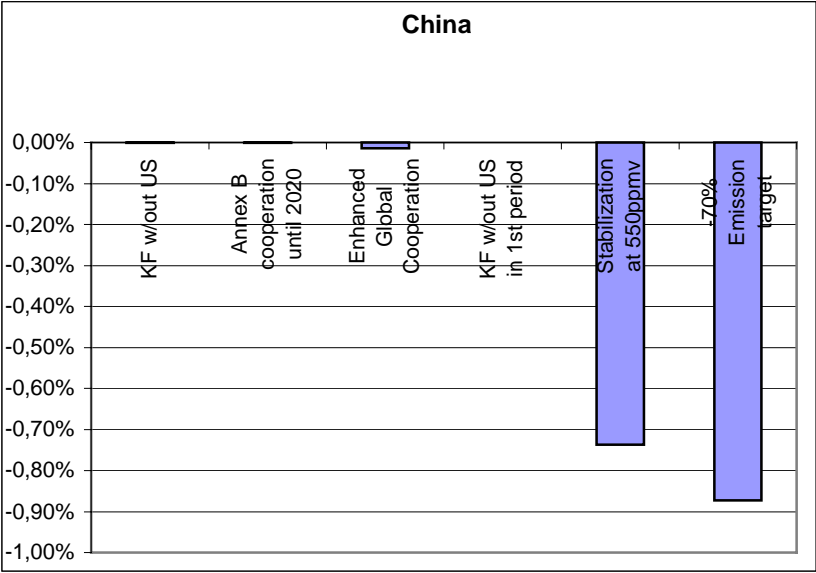
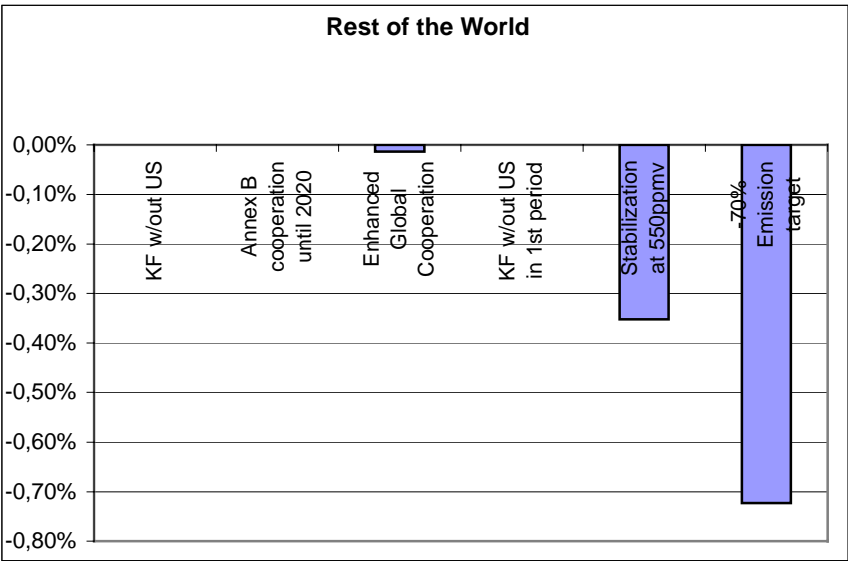


Figure 14: Welfare in the Rest of the World. Changes with respect to “Kyoto forever”



In the case of the Rest of the World, this is the consequence of both the ambitious emission targets and the corresponding costs of buying emissions permits in the permit market. By contrast, China, being a permit seller, can receive high revenues in both scenarios 5 and 6. This induces China to overinvest in climate friendly innovation in order to increase its sales in the permit market. However, the results obtained from our model suggest that China, like Russia, prefers moderate emission targets with low revenues from selling permits, rather than the symmetric case in which targets are ambitious and revenues are high.

4 Conclusions

The Kyoto Protocol represents only a first attempt to cope with the likely dangers of climate change. The proposed global emission reductions are small, no targets beyond 2010 have been set, and some major GHG emitters have not yet ratified the Protocol and are unlikely to do so in the near future.

Among the possible measures that could be adopted to enhance participation incentives in the Kyoto Protocol or a similar climate agreements, this paper has explored the role of future commitments beyond 2010. Future abatement targets can indeed be designed in order to address more effectively the climate change problem and at the same time to enhance participation incentives.

Our results confirm that the design of future long-term abatement commitments crucially affects the short-term incentives to participate in a climate agreement. A careful design of future commitments can actually provide incentives for the US to participate in the international cooperative effort to control climate change. Short term ambitious emission reduction targets are unlikely to make a come-back to the Kyoto Protocol attractive. More balanced scenarios can set the floor for a more successful long-term approach to climate change. They provide better incentives not only for the US, but also for Russia and the developing countries.

In particular, by deriving future emission reductions from countries' optimal abatement strategies, the so-called "Enhanced permanent global cooperation" scenario can help shaping the future evolution of climate policy. This scenario can achieve a good environmental effectiveness at low total compliance costs. In addition, it constitutes a Pareto improvement for all Annex B countries (always w.r.t the "Kyoto forever" scenario). Developing countries would suffer only relatively small welfare losses, but they would accept binding emission targets. This small loss could easily be overcome by the presence of ancillary benefits, both in the sense of environmental and economic secondary benefits, which are not yet captured by our model. The strategy to impose moderate targets on *all* countries, including the developing countries, can thus enhance participation incentives.

Our results confirm that there also exists a close relationship between future long-term commitments and present decisions on innovation and technical change. If emissions have to be much lower in the future, the permit price increases strongly, because of the high future demand for emission permits to meet future commitments. There exists a level of the permit price for which it is no longer appropriate for countries to increase their demand for permits. Instead, investments in climate-friendly R&D become more suitable to cope with the reduction requirements. Therefore, the higher the necessary future emission reductions, the higher are the expected compliance costs, and consequently the higher investments in research and innovation should be the. As a consequence, incentives to participate in a climate regime could be enhanced by increasing cooperation on climate related technological developments (Cf. Buchner and Carraro, 2004). As shown in the 2002-2003 part of our research for the ESRI collaboration project on environmental issues, this would reduce free-riding incentives and increase the likelihood of developing new technologies, notably energy technologies, which reduce the carbon intensity of economic systems.

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Appendix. The FEEM-RICE Model

The FEEM-RICE model is an extension of Nordhaus and Yang's (1996) regional integrated climate-economy RICE model of integrated assessment, which is one of the most popular and manageable integrated assessment tools for the study of climate change (see, for instance, Eyckmans and Tulkens, 2001). It is basically a single sector optimal growth model which has been extended to incorporate the interaction between economic activities and climate. One such model has been developed for each macro region into which the world is divided (USA, Japan, Europe, China, Former Soviet Union, and Rest of the World).

Within each region a central planner chooses the optimal paths of fixed investment and emission abatement that maximise the present value of that region's per capita consumption. Output (net of climate change) is used for investment and consumption and is produced according to constant returns Cobb-Douglas technology, which combines the inputs from capital and labour with the level of technology. Population is taken to be equal to full employment. Both population and technology levels grow over time in an exogenous fashion, whereas capital accumulation is governed by the optimal rate of investment. There is a wedge between output gross and net of climate change effects, the size of which is dependent upon the amount of abatement (rate of emission reduction) as well as the change in global temperature. The model is completed by three equations representing, respectively, emissions (which are related to output and abatement), carbon cycle (which relates concentrations to emissions), and climate module (which relates the change in temperature relative to 1990 levels to carbon concentrations).

In our extension of the model, technical change is no longer exogenous. Instead, the issue of endogenous technical change is tackled by following the ideas contained in both Nordhaus (1999) and Goulder and Mathai (2000) and accordingly modifying Nordhaus and Yang's (1996) RICE model. Doing so requires the input of a number of additional parameters, some of which have been estimated using information provided by Coe and Helpman (1995), while the remaining parameters were calibrated so as to reproduce the business-as-usual scenario generated by the RICE model with exogenous technical change.

In particular, the following factors are included: first, endogenous technical change affecting factor productivity is introduced. This is done by adding the stock of knowledge to each production function and by relating the stock of knowledge to R&D investments. Second, induced technical change is introduced, by allowing the stock of knowledge to affect the emission-output ratio as well. Finally, international technological spillovers are also accounted for in the model.

Within each version of the model, countries play a non-cooperative Nash game in a dynamic setting, which yields an Open Loop Nash equilibrium (see Eyckmans and Tulkens, 2001, for an explicit derivation of first

order conditions of the optimum problem). This is a situation in which, in each region, the planner maximises that region's social welfare subject to the individual resource and capital constraints and the climate module, given the emission and investment strategies (in the base case) and the R&D expenditure strategy (in the endogenous technological change case) of all other players.

The Standard Model without Induced Technical Change

As previously mentioned, it is assumed for the purpose of this model that innovation is brought about by R&D spending which contributes to the accumulation of the stock of existing knowledge. Following an approach pioneered by Griliches (1979, 1984), it is assumed that the stock of knowledge is a factor of production, which therefore enhances the rate of productivity (see also the discussion in Weyant, 1997; Weyant and Olavson, 1999). In this formulation, R&D efforts prompt non-environmental technical progress, but with different modes and elasticities. More precisely, the RICE production function output is modified as follows:

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

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

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

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

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

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

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

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

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

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

Induced Technical Change

In the second step of our model formulation, endogenous environmental technical change is accounted for. It is assumed that the stock of knowledge – which in the previous formulation was only a factor of production - also serves the purpose of reducing, *ceteris paribus*, the level of carbon emissions. Thus, in the second formulation, R&D efforts prompt both environmental and non-environmental technical progress, although with different modes and elasticities.¹⁵ More precisely, the RICE emission-output relationship is modified as follows:

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

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

¹⁵ Obviously, we could have introduced two different types of R&D efforts, respectively contributing to the growth of an environmental knowledge stock and a production knowledge stock. Such undertaking however is made difficult by the need to specify variables and calibrate parameters for which there is no immediately available and sound information in the literature.

Knowledge Spillovers

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

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

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

and:

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

where the stock of world knowledge:

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

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

Emission Trading

As mentioned above, throughout the analysis we assume the adoption of efficient policies. As a consequence, the model also includes the possibility of flexibility mechanisms. In particular we compare the two cases in which emission trading takes place amongst all original Annex I countries (including the US), first with one in which trading is allowed amongst Annex 1 countries without the US, and then one in which emission trading takes place amongst all Annex I countries without the US and Russia.

When running the model in the presence of emission trading, two additional equations are considered:

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

which replaces equation (3) and:

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

where $NIP(n,t)$ is the net demand for permits and $Kyoto(n)$ are the emission targets set in the Kyoto Protocol for the signatory countries and the BAU levels for the non-signatory ones. According to (3'), resources produced by the economy must be devoted, in addition to consumption, investment, and research and development, to net purchases of emission permits. Equation (6) states that a region's emissions may exceed the limit set in Kyoto if permits are bought, and vice versa in the case of sales of permits. Note that $p(t)$ is the price of a unit of tradable emission permits expressed in terms of the *numeraire* output price. Moreover, there is an additional policy variable to be considered in this case, which is net demand for permits NIP .

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