

DISCUSSION PAPER SERIES

No. 6995

**MODELLING ECONOMIC IMPACTS
OF ALTERNATIVE INTERNATIONAL
CLIMATE POLICY ARCHITECTURES:
A QUANTITATIVE AND
COMPARATIVE ASSESSMENT OF
ARCHITECTURES FOR AGREEMENT**

Valentina Bosetti, Carlo Carraro, Alessandra
Sgobbi and Massimo Tavoni

***INTERNATIONAL TRADE AND
REGIONAL ECONOMICS***



Centre for Economic Policy Research

www.cepr.org

Available online at:

www.cepr.org/pubs/dps/DP6995.asp

**MODELLING ECONOMIC IMPACTS
OF ALTERNATIVE INTERNATIONAL
CLIMATE POLICY ARCHITECTURES:
A QUANTITATIVE AND
COMPARATIVE ASSESSMENT OF
ARCHITECTURES FOR AGREEMENT**

**Valentina Bosetti, Fondazione ENI Enrico Mattei and CMCC
Carlo Carraro, Fondazione ENI Enrico Mattei, Università di Venezia and CEPR
Alessandra Sgobbi, Fondazione ENI Enrico Mattei and CMCC
Massimo Tavoni, Fondazione ENI Enrico Mattei and Università Cattolica di
Milano**

Discussion Paper No. 6995
October 2008

Centre for Economic Policy Research
90–98 Goswell Rd, London EC1V 7RR, UK
Tel: (44 20) 7878 2900, Fax: (44 20) 7878 2999
Email: cepr@cepr.org, Website: www.cepr.org

This Discussion Paper is issued under the auspices of the Centre's research programme in **INTERNATIONAL TRADE AND REGIONAL ECONOMICS**. Any opinions expressed here are those of the author(s) and not those of the Centre for Economic Policy Research. Research disseminated by CEPR may include views on policy, but the Centre itself takes no institutional policy positions.

The Centre for Economic Policy Research was established in 1983 as an educational charity, to promote independent analysis and public discussion of open economies and the relations among them. It is pluralist and non-partisan, bringing economic research to bear on the analysis of medium- and long-run policy questions.

These Discussion Papers often represent preliminary or incomplete work, circulated to encourage discussion and comment. Citation and use of such a paper should take account of its provisional character.

Copyright: Valentina Bosetti, Carlo Carraro, Alessandra Sgobbi and Massimo Tavoni

CEPR Discussion Paper No. 6995

October 2008

ABSTRACT

Modelling Economic Impacts of Alternative International Climate Policy Architectures: A Quantitative and Comparative Assessment of Architectures for Agreement*

This paper provides a quantitative comparison of the main architectures for an agreement on climate policy. Possible successors to the Kyoto protocol are assessed according to four criteria: economic efficiency; environmental effectiveness; distributional implications; and their political acceptability which is measured in terms of feasibility and enforceability. The ultimate aim is to derive useful information for designing a future agreement on climate change control.

JEL Classification: C72, H23, Q25 and Q28

Keywords: climate policy, integrated modelling and international agreements

Valentina Bosetti
Fondazione Eni Enrico Mattei
Corso Magenta 63
20121 Milan
ITALY
Email: valentina.bosetti@feem.it

Carlo Carraro
Dipartimento di Scienze Economiche
Università di Venezia
San Giobbe 873
30121 Venezia
ITALY
Email: ccarraro@unive.it

For further Discussion Papers by this author see:
www.cepr.org/pubs/new-dps/dplist.asp?authorid=166883

For further Discussion Papers by this author see:
www.cepr.org/pubs/new-dps/dplist.asp?authorid=104121

Alessandra Sgobbi
FEEM
Corso Magenta 63
20121 Milan
ITALY
Email: alessandra.sgobbi@feem.it

Massimo Tavoni
Fondazione Eni Enrico Mattei
Corso Magenta 63
20123 Milan
ITALY
Email: massimo.tavoni@feem.it

For further Discussion Papers by this author see:
www.cepr.org/pubs/new-dps/dplist.asp?authorid=166881

For further Discussion Papers by this author see:
www.cepr.org/pubs/new-dps/dplist.asp?authorid=166886

* This paper is part of the research work being carried out by the Climate Change Modelling and Policy Research Programme of the Fondazione Eni Enrico Mattei and by the Climate Impacts and Policy Division of the EuroMediterranean Center on Climate Change. The authors grateful to Rob Stavins, Joe Aldy and the Harvard Project on International Climate Agreements for many helpful comments and enduring support. The collaboration with Scott Barrett, Jeff Frankel and David Victor has been fundamental for the successful development of the research project whose results are presented in this paper. Any remaining errors are the authors' sole responsibility.

Submitted 21 September 2008

1 Introduction

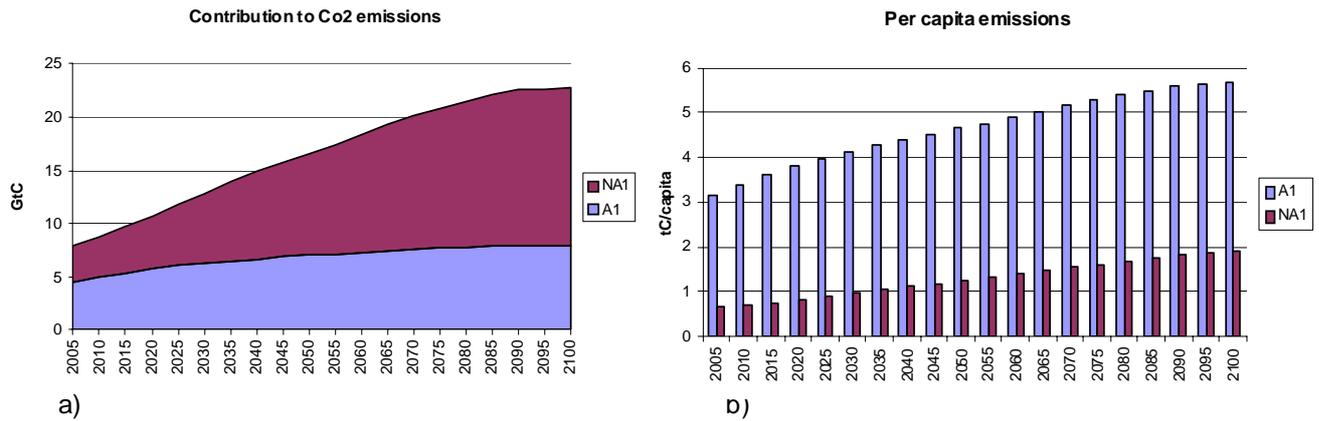
According to the latest IPCC report (2007) there is unequivocal evidence of the warming of the climate system, which is expected to affect both ecosystems and socio-economic systems to varying degrees. Changes in atmospheric concentrations of greenhouse gases (GHGs) are deemed responsible for the observed increase in average global temperature, which has risen by 0.76°C since 1850 – mostly in the last 50 years. The IPCC also points to widespread agreement over the fact that such changes in the climate system may be spurred by global GHG emissions from human activities, which have increased by 70% between 1970 and 2004. If emissions continue unabated, the average global surface temperature is likely to rise by a further 1.8-4.0°C this century (IPCC, 2007). A temperature increase between 2 and 3 °C is thought to be a threshold beyond which irreversible and possibly catastrophic changes in the system may take place.

After many decades of debate, climate change has now become a central topic in the policy agenda of all industrialised nations, and is becoming increasingly critical for developing countries as well. Policies and actions to control climate change have already been implemented around the globe – from the European commitment to cut GHG emissions by at least 20% by 2020, to international and local adaptation strategies, such as the effort led by the OECD for mainstreaming adaptation in Official Development Assistance.

It is clear however, that a global coordinated effort is needed to keep global temperature change below dangerous levels, as illustrated by Figure 1. While it is true that industrial emissions from fossil fuels have been and continue to be mostly attributable to industrialised nations, it is also true that soon Non Annex I countries will overtake Annex I in terms of their CO₂ emissions (left panel). At the same time, per capita emission levels will remain much lower in developing countries, given the differences in population growth and initial lifestyles (right panel).

The implication of such emission projections is therefore twofold: while global action is needed, such action is likely to entail differentiated targets and levels of effort. Negotiations are already underway to define a climate control agreement for the post-Kyoto world, and a number of proposals have appeared in both academic and policy literature (see, for instance, IEA, 2002; Aldy and Stavins, 2007; Stern, 2008). However, to date there has been no attempt to compare and contrast the architectures for an agreement on climate policy using a common framework. Such an exercise would enable a better understanding of the implications of different designs and a more transparent trade-off between the different criteria deemed important for international agreements.

Figure 1: Projected fossil fuel CO₂ emissions from the WITCH model in the Business as Usual scenario



Therefore, the main objective of this paper is to provide a quantitative comparison of the main architectures for agreement put forward in the literature using WITCH¹ – an energy-economy-climate model. The proposals are assessed according to four criteria: economic efficiency; environmental effectiveness; distributional implications; and political acceptability measured in terms of feasibility and enforceability. The ultimate aim is to derive useful policy implications that could provide insights for designing the next agreement on climate change.²

The paper is organised as follows. We begin in Section 2 by briefly describing the underlying model and then present, in Section 3, the features that characterise the architectures for agreement being examined. The main section of the paper (Section 4) compares and contrasts eight different architectures, according to the following criteria: their environmental effectiveness (Section 4.1); their economic efficiency (Section 4.2); their distributional implications (Section 4.3) and finally the political acceptability of the proposals (Section 4.4.4). Section 5 concludes the paper, summarising key lessons and policy implications.

2 A tool to compare architectures for agreement: the WITCH model

WITCH (Bosetti, Carraro *et al.*, 2006) is a climate-energy-economy model designed to assist in the study of the socio-economic dimension of climate change. It is structured to provide information on the optimal responses of world economies to climate damages and to identify impacts of climate

¹ www.feem-web.it/witch

² The analysis presented in this paper originates within the context of the Harvard Project on International Climate Agreements (http://belfercenter.ksg.harvard.edu/project/56/harvard_project_on_international_climate_agreements.html) which aims at identifying the key features to design scientifically sound, economically efficient and politically feasible post-2012 international policy architectures for global climate change.

policy on global and regional economic systems. A complete description of the model and a list of papers and applications are available at www.feem-web.it/witch.

WITCH is a hybrid model because it combines features of both top-down and bottom-up modelling: the top-down component consists of an inter-temporal optimal growth model in which the energy input of the aggregate production function has been expanded to yield a bottom-up description of the energy sector. The model provides a fully intertemporal allocation of investments in energy technologies and R&D that is used to evaluate optimal and second best economic and technological responses to different policy measures.

Countries are grouped in 12 regions that cover the world and whose strategic interactions are modelled through a dynamic game. The game theory set-up accounts for interdependencies and spillovers across regions of the world, and equilibrium strategies reflect inefficiencies induced by global strategic interactions. This allows us to analyze both fully cooperative equilibria (in the case in which it is assumed that all regions of the world sign a climate agreement) and partial/regional coalitional equilibria (when only a subgroup of regions sign the agreement or different groups of regions sign different agreements).

In WITCH, technological progress in the energy sector is endogenous, thus enabling us to account for the effects of different stabilisation policies on induced technical change, via both innovation and diffusion processes. Feedbacks from economic variables to climatic variables, and vice versa, are also accounted for in the model's dynamic system.³

Several features of the model allow us to investigate a number of issues in greater detail than most of the studies in the existing literature. First, though quite rich in its energy modelling and close in spirit to bottom up energy models, WITCH is based on a top-down framework that guarantees the coherent, fully intertemporal allocation of investments under the assumption of perfect foresight. Second, the model can track all actions that have an impact on the level of mitigation – R&D expenditures, investment in carbon free technologies, purchases of emission permits or expenditures for carbon taxes – and we can thus evaluate equilibrium responses stimulated by different policy tools. This leads to a transparent evaluation of abatement costs and to a clearer quantification of the uncertainties affecting them.

Diffusion and innovation processes are modelled to capture advancements in carbon mitigation technologies, through both learning by doing and research. The model also explicitly

³ The model is solved numerically in GAMS/CONOPT for 30 5-year periods, although only 20 are retained as we do not impose terminal conditions. Solution time for the Baseline scenario is approximately 30 minutes on a standard Pentium PC.

includes the effects of international technology spillovers and captures innovation market failures. The detailed representation of endogenous technical change and the explicit inclusion of spillovers in technologies and knowledge are crucial to understanding and assessing the impact of policy architectures that combine climate and R&D policies.

3 Architectures for agreements

We explore eight policy architectures, which have been discussed in the literature or have been proposed as potential successors to the Kyoto agreement. These architectures are inspired by the proposals put forward within the Harvard Project on International Climate Agreements⁴. All of them are assessed against a scenario without climate policy (business as usual, BaU). Table 1 summarises the key distinguishing features of the architectures that we compare and contrast in this paper.

In Table 1, we emphasise two main features of the policy architecture that have important implications for its cost and feasibility, namely its scope and timing. Universal agreements involve all regions, while partial agreements only require cooperation among a subset of regions. Agreements may require immediate efforts from participating countries, or they may take into account differential abilities to undertake abatement and, therefore, involve incremental participation, where some regions – usually transition economies and developing countries – are allowed to enter the agreement at a later point in time, when they satisfy some pre-defined criteria. A further distinction across architectures is the type of policy instrument involved: most schemes use a cap and trade approach, but carbon taxes and R&D policies are also considered.

Two key aspects of the architectures considered in this paper should be pointed out at this stage, in order to make the results of our analysis clear. First, all proposed architectures focus on CO₂ mitigation only, excluding other greenhouse gases. Secondly, as climate leaks and free riding incentives are likely to be substantial for less than a global agreement, all the proposed architectures envisage all countries - at least - committing to not exceeding their projected emissions under the BaU scenario. This may seem restrictive, but less so if we consider that regions do benefit from committing to the BaU, since they then have the option of participating in the market for carbon permits, undertaking cheap abatement and receiving financial resources for it.

⁴ Most architectures considered in this paper are carefully described in Aldy and Stavins (2007) and Aldy, Stavins et al. (2007).

Table 1: Architectures for agreement

Name	Key feature	Policy Instrument	Scope	Timing
CAT with redistribution	Benchmark cap and trade	Cap and Trade	Universal	Immediate
Global carbon tax	Global tax recycled domestically	Carbon Tax	Universal	Immediate
REDD	Inclusion of REDD	Cap and Trade	Universal	Immediate
Climate Clubs	Clubs of countries	Cap and Trade and R&D	Partial	Incremental
Burden Sharing	Delayed participation of DCs.	Cap and Trade	Universal	Incremental
Graduation	Bottom up targets	Cap and Trade	Partial	Incremental
Dynamic Targets	Political feasibility	Cap and Trade	Universal	Incremental
R&D Coalition	R&D cooperation	R&D	Universal	Immediate

Let us provide a short description of each climate policy proposal.

3.1 Cap and trade with redistribution

In this benchmark scenario, a standard cap and trade policy is implemented; there is a global carbon market and complete and immediate cooperation of regions towards the attainment of a climate stabilisation goal. The goal is to achieve the stabilisation of CO₂ concentrations at 450ppmv by 2100, which is roughly 550 ppmv CO₂ equivalent.

As shown above, today's average per capita emissions vary substantially across countries. In the US, for instance, emissions are around 5.5 tC/per capita, compared to 0.06 tC/capita in Sub-Saharan Africa and 1.3 tC/capita in China. It is often argued that a fair long-term agreement for tackling climate change would require a move from the current trend of allocating allowances on the basis of historical emissions towards the adoption of an equal per capita rule, based on the Rawlsian principle of equal entitlement to pollute. Thus, permits in this scheme are grandfathered according to an equal per capita rule (EPC). It should be noted that, given that a perfect global carbon market is assumed, marginal abatement costs are equalised and the allocation scheme has a

negligible effect on global variables. It does however have important distributional implications as it implies significant wealth transfers through the global carbon market.

3.2 Global tax recycled domestically

This second architecture does not envisage an explicit emission target, but exogenously sets a global carbon tax consistent with a CO₂ emission path leading to 450 ppmv stabilization. While requiring global cooperation in deciding upon the path of the carbon tax and its implementation, this architecture is autarchic in the sense that there is no global market for emission trading: rather, the revenues from the tax are recycled domestically in the national budgets.

The assumed carbon tax starts at around 3 US\$/t CO₂, but hikes rapidly to provide incentives for substantial emission reductions: in 2050, the tax reaches 500 US\$/tCO₂, and increases to over 1000 US\$/tCO₂ by the end of the century. Although in a very broad sense, this architecture is inspired by the work undertaken by McKibbin and Wilcoxon (see McKibbin and Wilcoxon, 2007), who emphasise the absence of international carbon trading as one of the key features of their policy architecture.

3.3 Reducing Emissions from Deforestation and Degradation (REDD)

The idea is to allow tropical forest countries to set aside forest land that would otherwise be cleared in exchange for payment from industrialised countries looking to reduce their carbon emissions in order to meet targets set under international agreements like the Kyoto Protocol. According to Ebeling (2006), the inclusion of REDD in a climate agreement would significantly lower the costs of meeting the environmental target. Similar proposals to include CDM mechanisms and avoid deforestation in international climate agreements have been put forward by Plantinga and Richards (see, e.g., Plantinga and Richards, 2008).

This architecture for agreement entails essentially the same instrument as the previous Cap and Trade with a redistribution proposal (see section 3.1). However, it includes avoided deforestation as a potential mitigation option, with CO₂ abatement from avoided deforestation in the Amazon forest included in the permit market. The reason why only Brazil is allowed to get credits for avoided emissions from deforestation lies in the fact that it is the only country that already has a monitoring and enforcement system in place. Obviously, results would be strengthened if the crediting system were open to other countries, such as DR Congo or Papua New

Guinea. Specific abatement costs⁵ for the avoided deforestation mitigation option were considered, with the opportunity costs of developing forested land under alternative land uses as a proxy.

3.4 Climate Clubs

This architecture for an international agreement is inspired by the proposal put forward by David Victor (Victor, 2007). Differentiated effort is expected from different regions of the world, depending on their ability to abate. A group of virtuous regions – the Climate Club⁶ – agrees to abide by their Kyoto target, reducing GHG emissions by 70% with respect to their emission levels in the 1990s by the year 2050. Their effort is to some degree compensated by joint cooperation in technology development, which increases the extent to which knowledge for energy efficiency improvements and R&D efforts to develop new carbon free technologies spills over across regions belonging to the Climate Club.

Fast-growing countries like China, India, Latin America, Transition Economies and the Middle East are also part of the global deal, but their effort is gradual. These countries face increasingly stringent targets⁷ to reduce their CO₂ emissions below what they would emit in a business as usual scenario. In the second half of the century, fast growing countries agree to increase their abatement effort to converge towards the effort of the Climate Club. The rest of the world does not have any binding target.⁸

There is a global market for carbon permits, in which all regions may participate. Regions that do not have an explicit emission reduction target must commit to not exceeding their BaU emissions level in order to participate in the carbon market: this expedient encourages abatement from non signatories, and thus reduces the incentive to free-ride.

3.5 Burden sharing

A key feature of this post-Kyoto architecture is the delayed participation of non-Annex I countries. While the group of Annex I countries commit to undertake abatement efforts immediately, with the burden shared on an equal per capita basis, non-Annex I countries are initially required to commit

⁵ Abatement costs curves for REDD were constructed using data from the Woods Hole Centre, and focus on Brazil (<http://whrc.org/BaliReports/>). Supply estimates from the tropical Asian region will be also included once available.

⁶ The members of the Climate Club are the US, Europe, Canada, Japan, New Zealand, Australia, South Korea, and South Africa.

⁷ The target is to reduce industrial CO₂ emissions by 5% wrt BAU by 2020; by 10% wrt BAU by 2030; 20% wrt BAU by 2040; and 30% wrt BAU by 2050.

⁸ Different versions of the Climate Club architecture were simulated to test sensitivity to countries' club definition (e.g. having the Middle East within the ROW group), to the global emission trading assumption, to the definition of enhanced spillovers within the Climate Club and to measure the penalty imposed by the Club structure as opposed to a full and immediate participation agreement.

to not emitting more than their projected emissions under the BaU scenario, in order to avoid free-riding incentives and carbon leakage.

In 2040 – when emissions from non-Annex I countries are higher than emissions of Annex I countries in a business as usual path (see Figure 1) – binding abatement targets are extended to the whole world except Sub-Saharan Africa, whose level of development remains well below the world average.

This architecture is inspired by the policy proposal by Keeler (see, for instance, Keeler, and Thompson, 2008) and Bosetti *et al.* (2008).

3.6 Graduation

Inspired by Michaelowa's proposal (2007), this policy architecture entails differentiated efforts among signatory countries, with differentiation based on the satisfaction of bottom-up graduation criteria and with the ultimate objective of stabilizing atmospheric CO₂ concentrations at 450 ppmv.

The idea of bottom-up target is that they can take into account the ability of regions to undertake abatement effort and their contribution to the climate change problem. Graduation to binding targets is based on the satisfaction of two criteria, based on per capita income and emissions relative to the world average⁹.

Annex I countries do not graduate, but rather enhance their abatement effort in order to compensate for the emissions of non-Annex I countries and ensure the achievement of the 450 ppmv stabilisation target.

3.7 Dynamic Targets

The key feature of the Dynamic Targets policy architecture stands in the way it is deeply rooted into the political reality and to statements made by political leaders. Inspired by the proposal described in Frankel (2007), bottom-up targets are based on progressive cut factors – with respect to emissions in 1990 for the first period, and then with respect to projected emissions in the BaU scenario, corrected by a Lieberman-Lee Latecomer Catch-up factor for countries that have not yet ratified Kyoto.

⁹ The first graduation step is reached when the average of the two criteria is satisfied, that is, emissions per capita match the average world emissions per capita, and income per capita increases to 5,000 US\$ (2005 value). When countries reach the first graduation level, their abatement target is equivalent to 5% with respect to 2005 emissions. The second graduation period is reached when emissions per capita are 1.5 of the world's average and income per capita is US\$ 10,000. It entails a reduction in emissions by 10% with respect to 2005 levels. The only exception is China, which reduces emissions gradually, starting from 2050, in order to cut the level by 50% with respect to the 2005 emissions. Sub-Saharan Africa never graduates, and therefore faces no binding targets. It commits however to the BaU, in order to be able to participate in the carbon market.

Progressive cut factors take into account historic emissions relative to the emissions of the EU in 1990, current and projected emissions in the BaU, income per capita relative to the EU average, and population. This target-setting rule therefore takes the fact that emissions from developing countries will soon overtake those of industrialised countries on an absolute basis – even though not necessarily on a per capita basis – explicitly into account.

Targets are defined for all regions, with the world divided into three broad groups: early movers (Europe, US, Canada, Japan, New Zealand, Australia, South Korea, and South Africa) take action from 2010-2015-2025; the late comers, with China and Latin America facing binding emission reduction targets from 2035, and India from 2050; and all other regions, that agree not to exceed their emissions under the BaU scenario and can thus take part in the international market for carbon permits. Sub-Saharan Africa does not face any emission target until 2030 – after which it enters the market for carbon permits by committing to not exceeding its BaU emissions.

3.8 R&D and Technology Development

This last policy architecture is very different in nature from the previous ones, since it does not entail any emission reduction target. The main concern of this architecture – which is inspired by Scott Barrett’s proposal (Barrett, 2007) – is to ensure the acceptability of the global agreement. It therefore focuses on R&D policies only; because of the different incentive structure characterising such policies (they provide a club good rather than a public good).

In this architecture for a global deal, all regions of the world agree to contribute a fixed percentage of their GDP for the establishment of an International Fund to foster climate-related technology advancement. The share of GDP devoted to technology improvements is roughly equal to double the public energy R&D expenditures in the 1980s, which is 0.2% of regional GDP (see Bosetti, Carraro *et al.* 2007a for an analysis of optimal energy R&D investment strategies).

The financial resources of the fund are redistributed to all regions on an equal per capita basis, and they are equally split to foster deployment of two key low-carbon technologies – Wind and Solar and Carbon Capture and Sequestration – and for innovation in a breakthrough zero carbon technology in the non-electric sector. Thus, the subsidy to these three technologies lowers their costs, favouring their deployment and leading to emission reductions as a by-product of the new technology mix.

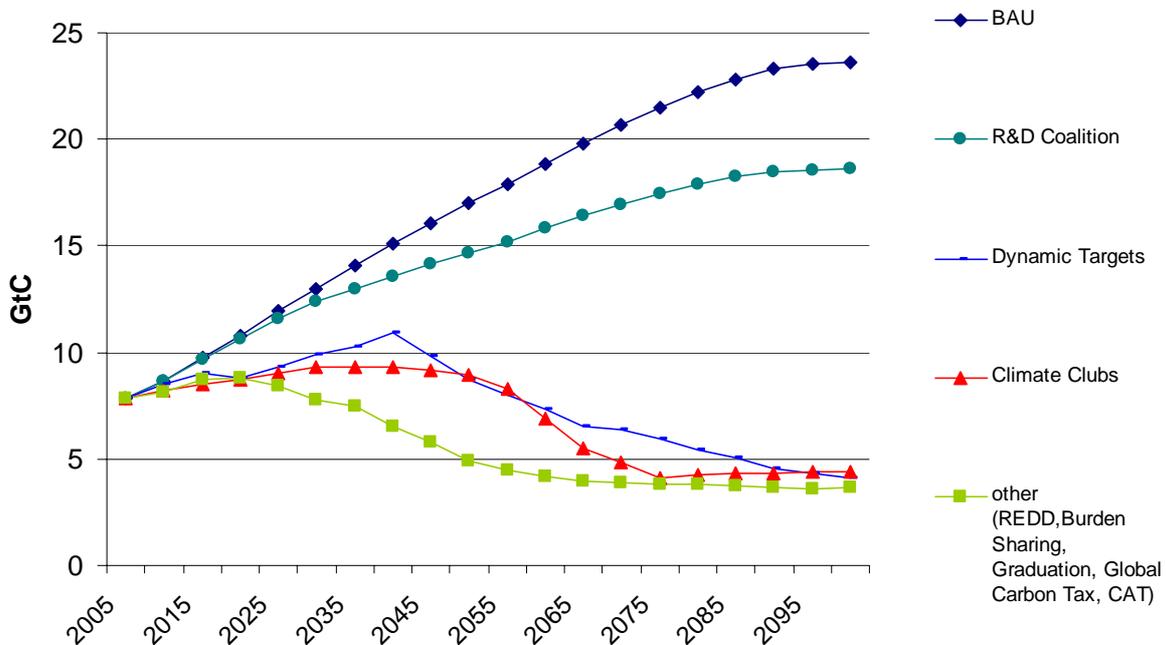
4 Assessing architectures for agreement

4.1 Climate effectiveness

The first and most important objective of a climate treaty, most would argue, is its environmental effectiveness – that is, the degree to which the problems associated with climatic change are addressed.

Figure 2 shows the path of industrial CO₂ emissions implied by the eight architectures for agreement described briefly above and by the business as usual scenario. In the BaU scenario, global atmospheric carbon emissions are projected to continue increasing from the current level of slightly less than 8 GtC to over 22 GtC by 2100. The more stringent architectures lead to a stabilisation of emissions at well below 5 GtC by the middle of the century. These are the three global coalitions with different implementation instruments – cap and trade with and without avoided deforestation, and the global carbon tax. These three architectures are characterised by an explicit target for atmospheric CO₂ concentrations, which is set at 450ppmv. Interestingly, one of the architectures based on bottom-up targets – the Graduation architecture – also leads to the stabilisation of CO₂ concentrations at 450 ppmv.

Figure 2: Global energy CO₂ emissions paths

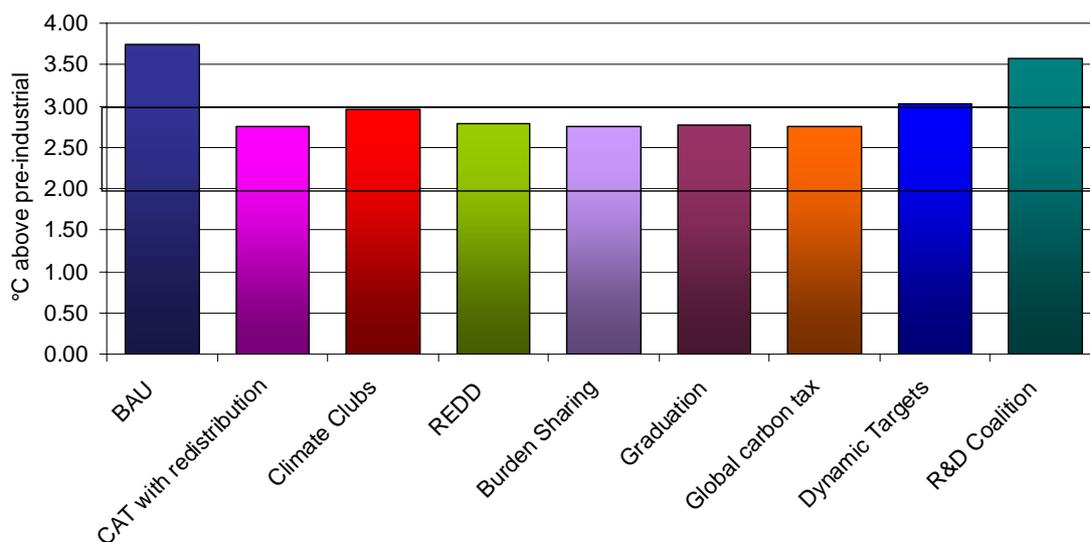


A second set of architectures which rely on either universal participation with incremental - rather than immediate - effort, or on partial participation, achieve the same amount of emissions at the end of the century, but through a different transition path. These architectures are Dynamic Targets and Climate Club with late comers. Their emissions paths are less smooth than REDD or CAT's, reflecting the different dates at which regions start to face binding constraints. Consequently, these two architectures would achieve a less stringent target for atmospheric CO2 concentrations, which stabilise at about 550ppmv.

Finally, the global coalition cooperating on energy R&D does not achieve the stabilisation of CO2 emissions – and consequently of atmospheric concentrations – even though emissions are lower than for business as usual. Over the century, cumulative emissions are only 17% lower than in the BaU, as opposed to an average of 62% lower for the other policy architectures. Let us recall, however, that the crucial feature of this policy architecture is the provision of adequate incentives to cooperation and not a given stabilisation target with high costs and limited incentives.

Figure 3 shows temperature increase above pre-industrial levels as a result of the different architectures in 2100.¹⁰ Even though the magnitude of the increase implied by each of the proposed architectures is to be taken as a rough estimate, given the many scientific uncertainties, this comparison provides a relative ranking of the proposals with respect to temperature change.

Figure 3: Temperature change above pre-industrial levels in 2100



¹⁰ We used the MAGICC model to relate emissions and concentrations to temperature changes.

In the BaU scenario, where no international policy to curb CO₂ emissions is implemented, temperature change is expected to reach 3.7 °C above pre-industrial levels in 2100. When cooperation on low carbon technologies and zero carbon breakthrough innovation is pursued in the absence of any emission reduction targets, the expected temperature increase is only slightly lower, at 3.5 °C. The more environmentally aggressive policy architectures yield a temperature change of around 2.7 °C, whereas intermediate efforts lead to a temperature increase of around 3 °C.

It is therefore clear that none of the policy architectures analysed in this paper are able to keep temperature change below the 2°C threshold, which is advocated by more proactive countries like the European Union.¹¹ On the other hand, stabilising emissions below 5 GtC keeps temperature change below 3°C, the less stringent upper limit often called for by the US (Newell and Hall, 2007).

In order to check whether different proposals entail different paths of temperature change, we also consider the rate of temperature change over the century. Even though it is difficult to know which path of temperature change is best, given our ignorance about the existence of potential threshold effects, it is reasonable to think that more gradual temperature changes will entail lower costs – if not economic, at least environmental, as more gradual changes imply more time for ecosystems to adapt. To this aim, in addition to temperature increase by the end of the century, we also count the number of 5-year periods for which temperature increase is greater than 0.1° C with respect to the previous 5-year period, as shown in Table 2. The effect of the different policy architectures on the rate of temperature change is very similar to their overall effect on temperature – that is, more stringent architectures give fewer periods with a temperature change greater than 0.1°C over the previous period, while the R&D coalition architecture, without an explicit emission target, is similar to the BaU scenario.

Table 2: Number of times that five-year temperature change is greater than 0.1°C

BAU	CAT with redistribution	Climate Clubs	REDD	Burden Sharing	Graduation	Global carbon tax	Dynamic Targets	R&D Coalition
19	12	14	12	12	12	12	14	19

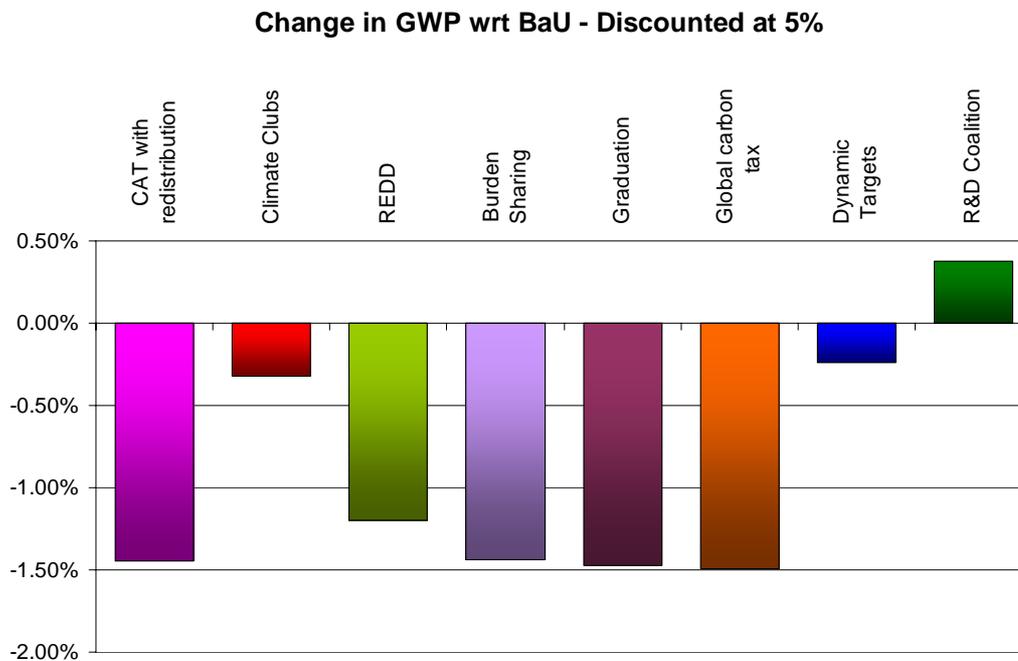
¹¹ One should keep in mind that the carbon signal that would be generated by such policies would imply significant abatement in other GHGs as well, if they were to be included in the policy agreement, thus causing an additional abatement of global temperature increase by roughly 0.2°C.

4.2 Economic efficiency

Different emissions paths resulting from the eight policy architectures imply different streams of costs and benefits. We therefore adopt a simple criterion for comparing the cost implications of the post-Kyoto proposals, and compute the difference in Gross World Product (GWP) under each one of the proposed policies with respect to the BaU scenario. This global indicator is defined as the discounted sum of GDP losses, aggregated across world regions, over the next century, and discounted at a 5% discount rate (a rate which is close to the average market interest rate).

While temperature change varies less across the eight architectures for agreement because of the inertia in the climate system, the economic costs of the different set-ups vary considerably. Figure 4 shows that more stringent policy architectures imply a higher GWP loss. Stabilising atmospheric CO₂ concentrations at 450 ppmv would cost between 1.2% and 1.49% of GWP. The most costly architecture would be the autarchic Global Tax implemented domestically, and the least costly would be the Global Cap and Trade with emission reduction from avoided deforestation as an option (REDD). The inclusion of avoided deforestation as a mitigation option reduces the costs of meeting the environmental target from 1.49% of GWP to slightly above 1.2%.

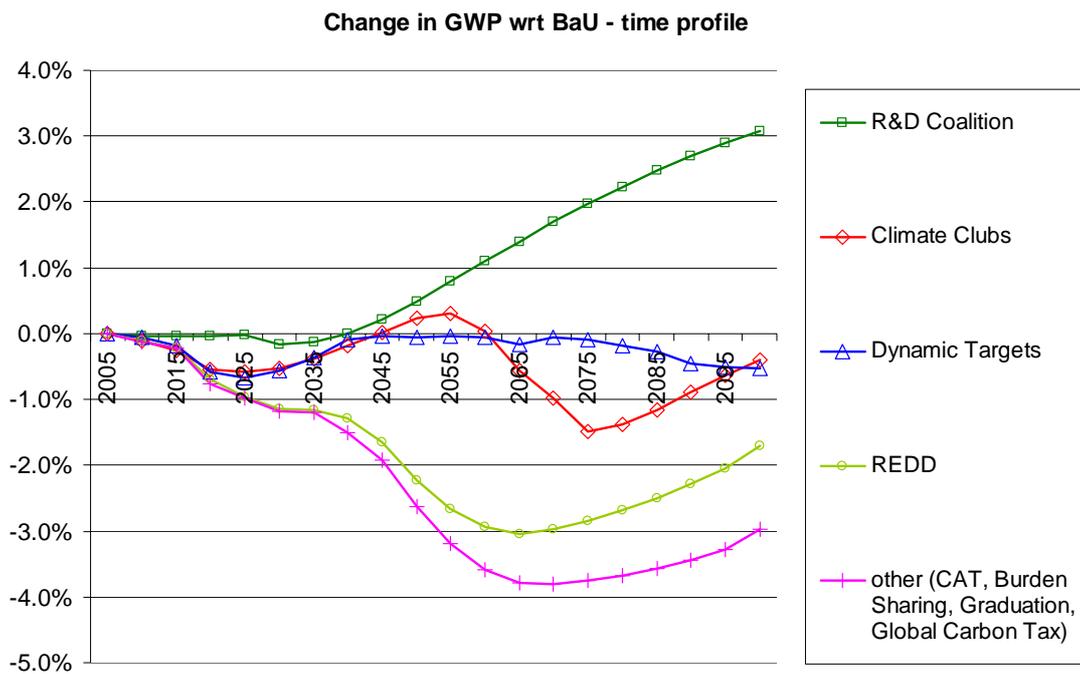
Figure 4 Implications for GWP



Climate Clubs and Dynamic Targets – which stabilise CO2 concentrations at about 490 and 500 ppmv respectively – entail moderate costs: around 0.32% and 0.24% of gross world product respectively. Finally, the R&D Coalition leads to gains at the global level, of about 0.37% of GWP. These gains are explained by the positive effects of R&D cooperation that reduces free-riding incentives on knowledge production.¹²

When we look at the temporal distributions of the costs of the different architectures (see *Figure 5*) we see that the stringent architectures requiring universal and immediate action imply an immediate loss of GWP, rising up to 4% by the middle of the century. Gradual effort implies, on the other hand, less costly intervention at the beginning of the century. Only the global coalition based on R&D Cooperation leads to gains from 2040 – while implying short-term costs due to the diversion of resources to replenish the global R&D fund.

Figure 5: Temporal distribution of the policy costs



4.3 Equity and distributional impacts

The distribution of the costs and benefits of climate change and climate change policy is of paramount importance in determining both the feasibility and desirability of a specific architecture

¹² See Bosetti, Carraro et al. (2007b) for a detailed analysis of knowledge spillovers.

for agreement. The analysis of how GDP changes over time for different world regions in the different scenarios may offer some indications as to what the distributional implications of climate change policies are, and it highlights winners and losers under each scenario. This information is likely to be important for policy makers and negotiators.

Several criteria have been proposed in the literature as ways to measure the equity and distributional implications of climate change agreements (see, e.g., Goulder, 2000), such as the criteria of responsibility, ability to pay, or distribution of the benefits from controlling climate change. While the first two criteria would seem to indicate that industrialised countries should bear most of the burden of controlling climate change, the last criterion would imply that developing countries – who would be the largest beneficiaries from controlling climate change – should bear a relatively higher share of the burden (Aldy, Barrett *et al.*, 2003).

For the purpose of our assessment, we abstract from the current debate, and use a compact measure of distributional equity to characterise the eight policy architectures and the BAU. We compute the Gini Index for GDP in 2100, which represents the concentration of income between regions of the world, and shows inequality in income distribution (the lower the value of the indicator, the more equal the distribution of income).

Table 3: Gini Index in 2100

BAU	CAT with redistribution	Climate Clubs	REDD	Burden Sharing	Graduation	Global carbon tax	Dynamic Targets	R&D Coalition
0.200	0.198	0.158	0.197	0.196	0.158	0.178	0.156	0.181

In all scenarios, there is an improvement in the distribution of income among world’s regions with respect to the current situation. However, there are some differences that can be seen from Table 3: three policy architectures emerge as being more egalitarian, since they distribute the effort in a fair way according to income per capita and average per capita emissions. These are Dynamic Targets – which takes historical emissions and projected emissions under the BaU scenario into account to determine regional efforts – Climate Clubs and Graduation.

By comparing the two global architectures with a stabilisation target, immediate participation and the implementation through a cap and trade system (CAT with redistribution and REDD), we can observe that the inclusion of avoided deforestation among the mitigation options leads to an improvement in the distribution of income across regions– and this reflects the fact that avoided deforestation is mostly an option in developing and tropical countries. Finally, notice that the

carbon tax policy is an intermediate one in terms of distributional effects.

4.4 Enforceability and feasibility

In the context of international agreements, enforceability and compliance become a critical issue: the national sovereignty of individual states may lead to strategic behaviour, free-riding incentives, and to countries not complying with the agreement they have signed. Ideally, a global deal for climate change would sustain full participation and compliance, while ensuring an efficient level of emission reduction. Yet, because of the lack of a supranational institution able to enforce a climate policy, achieving a global agreement on GHG emission control may be very difficult if not impossible (Barrett, 2003).

When analyzing the feasibility and enforceability of the proposed architectures for agreement, one should therefore assess whether the set-ups limit incentives to free-ride, and whether they would be enforceable. The discourse on feasibility and enforceability of post-Kyoto architectures so far has been limited to qualitative analysis, without an attempt to quantify the degree to which each architecture deters free-riding behaviour. In this paper, we borrow from game theoretic concepts to derive quantitative measures of enforceability and political acceptability for all policies at global and regional levels respectively.

We use the concept of potential internal stability (PIS, see Carraro, Eyckmans and Finus, 2006) as a proxy for the theoretical enforceability of the agreement. This is a weak stability concept in the sense that an agreement is said to be potentially internally stable if the aggregate payoffs are at least as large as the sum of the regional payoffs in the BaU. If this condition is satisfied, all coalition members could be at least as well off as under the business as usual scenario through suitably designed transfer schemes. Global welfare is computed as the sum of welfare for each region.

The second column of Table 4 summarises the results in terms of potential enforceability of the architectures at the global level. It is clear that all but one architecture imply an *improvement* in global welfare over the status quo – if one could design appropriate transfer schemes, then all regions could be made at least as well off as under the business as usual scenario. The only exception is the autarkic coalition, where all countries, including developing countries, are required to undertake emission reductions domestically by imposing a carbon tax.

Notice however that most of the welfare gains are experienced in developing countries. Hence, the stabilisation of the agreements would require the transfer of resources from developing to developed countries – which is unlikely to be politically acceptable and feasible.

Table 4: Potential enforceability and political acceptability

	Potential stability World welfare	Feasibility
	% change wrt BAU	No. Of countries with +ve variation in welfare
CAT with redistribution	0.681%	3
Climate Clubs	0.183%	6
REDD	0.456%	4
Burden Sharing	0.243%	3
Graduation	0.085%	3
Global carbon tax	-0.168%	0
Dynamic Targets	0.202%	5
R&D Coalition	0.103%	12

While at the global level almost all architectures for agreement seem to be potentially enforceable, the picture is very different when we move down to the regional level, to explore the feasibility of the proposals. The last column of Table 4 shows the likely political feasibility of each policy architecture – approximated by the number of regions whose welfare under the specific climate policy architecture is higher than in the business as usual scenario. Thus, the higher the number of countries that find a specific coalition profitable from an individual perspective, the more likely it is that the architecture is politically acceptable. Notice that individual profitability is only a necessary condition for stability if the latter is defined in the usual manner (i.e. using the concept of cartel stability proposed in industrial organization; see Carraro and Siniscalco, 1993). However, individual profitability may become a sufficient condition for stability if a concept of farsighted stability is adopted (Chew, 1994) or if a minimum participation constraint is imposed (Carraro, Marchiori, Orefice, 2003).

It is clear that in the R&D Coalition and Climate Clubs architectures – both involving some form of cooperation on R&D – a large share of countries find the agreement profitable (*all* and *half* of the countries are better off, respectively). The result on the climate club architecture is particularly interesting, as it seems to support the role of issue linkage in generating scope for gains from cooperation. The universal but incremental coalition based on Dynamic Targets is also likely

to be politically feasible, as 5 out of 12 regions find it profitable: it is quite likely that a careful revision of the criteria for setting binding emission reduction targets could lead to a redistribution of welfare so that all countries would be better off.

The above analysis of political acceptability and potential enforceability of the proposed post-2012 climate policy architecture is clearly a simplification, and can be criticised on various accounts – such as the choice of the welfare indicator, or the fact that other important factors that are likely to ultimately determine whether an international agreement can be accepted at the national level are overlooked. Our results do nonetheless provide a good starting point for the assessment of the enforceability dimension of the proposed architectures for agreement.

4.5 Comparison recap

A summary of the performance of the Post-Kyoto architectures presented in the previous sections is provided in Table 5. Significant differences across schemes are reported, which makes an univocal ranking impossible. Some clear indications emerge nonetheless. The architectures have been ordered by increasing environmental performance. Notice however that this is the same as ordering by decreasing economic efficiency (the second column), i.e. increasing costs. It also corresponds to decreasing enforceability of the agreement.

Table 5: Assessment criteria for the different policy architectures

	Environmental Effectiveness (T°C above pre-industrial)	Economic Efficiency (GDP change wrt BAU, 5% d.r.)	Distributional impact (Gini 2100)	Enforceability Countries with positive welfare change, out of 12)
BAU	3.75	-	0.200	-
R&D Coalition	3.58	0.37%	0.181	12
Dynamic Targets	3.02	-0.24%	0.156	5
Climate Clubs	2.95	-0.32%	0.158	6
REDD	2.76	-1.20%	0.197	4
Burden Sharing	2.76	-1.44%	0.196	3
CAT with redistribution	2.76	-1.45%	0.198	3
Graduation	2.76	-1.47%	0.158	3
Global carbon tax	2.76	-1.49%	0.178	0

There is therefore evidence of a perfect trade-off between environmental effectiveness and economic efficiency and enforceability.

Among the environmentally more efficient architectures – CAT, REDD, Burden Sharing, Graduation and Global Carbon Tax – REDD shows that the inclusion of deforestation in a climate agreement can significantly improve the economic efficiency of the policy, and also its enforceability, since it provides additional incentives for participation to some developing countries. Note however that for all these architectures GWP losses are above 1%. Graduation reports the fairer distribution of income within this group.

Dynamic Targets and Climate Club are policies that come at a very low economic cost, though obviously at the expense of foregone climate effectiveness. They both perform well in terms of distribution and feasibility. Finally, the R&D Coalition actually improves the world economic performance, and can thus count on all regions willingness to participate, but achieves very little in terms of climate protection.

Multi criteria techniques could be used to provide a more precise ranking of the climate policy architectures analysed in this paper. As an example, one can apply the minimax criterion to identify the architecture that minimises the maximum possible loss across all dimensions considered. According to this criterion, the R&D Coalition policy architecture is to be preferred to all other architectures. Given the uncertain nature of the issues at stake, though, a deterministic approach could lead to misleading conclusions. Further investigation based on stochastic Data Envelopment Analysis and other probabilistic multi criteria approaches, could help identifying the set of most robust climate policy architectures.

5 Conclusions and policy implications

In this paper, we have evaluated eight policy architectures, focusing on:

- Their relative environmental effectiveness – measured as temperature change above pre-industrial levels in 2100;
- Their economic efficiency – measured as changes in gross world product with respect to the status quo;
- Their distributional implications – assessed by the Gini index at the end of the century, and
- Their potential enforceability, measured by changes in global and regional welfare with respect to the status quo.

These indicators are meant to provide policymakers with a clearer picture of the various implications of some of the policy options currently on climate negotiators' tables.

The comparative analysis presented in the previous sections allowed us to draw a series of general recommendations.

First, the 2°C temperature target as envisaged by the IPCC and the European Commission requires more drastic measures than those indicated in all the policy architectures considered in this paper.

Second, non-CO₂ gases should also be included among the mitigation options: not only would their inclusion lead to lower temperature increases for similar concentration of CO₂ in the atmosphere, but it would also lower the costs of meeting the stabilisation target.

Third, a trade-off between environmental effectiveness and economic efficiency clearly emerges from our analysis, as does another between environmental effectiveness and political enforceability.

Fourth, the inclusion of avoided deforestation alleviates the policy cost and improves enforceability.

Fifth, a fairer distribution of income can also be achieved, but the global economic loss is small only for policies which aim at intermediate stabilisation objectives, in the range of 650 ppmv CO₂ equivalent (550 ppmv CO₂ only). This stabilisation target is shown to have little impact on economic activity, but may not attain sufficient climate protection.

Finally, policies aiming at R&D cooperation that do not involve any carbon constraints or taxes, are shown to have a marginal effect on climate, though a positive one on economic activity. Thus, they are likely to be the only ones leading to a global, self-enforcing agreement.

Far from providing a final and unique answer, this analysis is intended as a starting point for other critical comparisons of proposals for climate policy agreements. Further research may adopt more sophisticated analytical tools to account for the public perception of climate change and for different priorities among the different dimensions considered.

References

- Aldy, J., Barrett, S., and Stavins, R. N. (2003), Thirteen plus one: a comparison of global climate policy architectures, FEEM Working Paper Series, 64.2004, Milan, Italy and RFF Discussion Paper 03-26.
- Aldy, J., and Stavins, R. N. (Eds.) (2007), *Architectures for Agreement: Addressing Global Climate Change in the Post-Kyoto World*, Cambridge University Press, Cambridge, UK.
- Aldy, J., and Stavins, R. N. (2008), Climate Policy Architectures for the Post-Kyoto World, *Environment*, 50, 6-17.
- Aldy, J. E., Stavins, R. N., Carraro, C., and Pizer, W. A. (2007), Architectures for Agreement: Issues and Options for Post-2012 International Climate Change Policy, paper presented at Conference of the Parties, Cambridge, Mass.: Harvard Project on International Climate Agreements, Bali, Indonesia.
- Barrett, S. (2003), *Environment and Statecraft*, Oxford University Press, Oxford.
- Barrett, S. (2007), A multitrack climate treaty system, in *Architectures for Agreement: Addressing Global Climate Change in the Post-Kyoto World*, edited by Aldy, J. and Stavins, R. N., pp. 237-259, Cambridge University Press, Cambridge, UK.
- Bosetti, V., Carraro, C., Galeotti, M., Massetti, E., and Tavoni, M. (2006), WITCH: A World Induced Technical Change Hybrid Model, *The Energy Journal*, Special Issue on Hybrid Modeling of Energy-Environment Policies: Reconciling Bottom-up and Top-down, 13-38.
- Bosetti, V., Carraro, C., Massetti, E., Sgobbi, A., and Tavoni, M. (2007a), Optimal Energy Investment and R&D Strategies to Stabilise Atmospheric Greenhouse Gas Concentrations, FEEM Working Paper Series 95.07, CEPR Discussion Paper 6549 and CESifo Working Paper N. 2133;
- Bosetti, V., Carraro, C., Massetti, E., and Tavoni, M. (2007b), International Energy R&D Spillovers and the Economics of Greenhouse Gas Atmospheric Stabilization”, FEEM Nota di Lavoro 82.07, CEPR Discussion Paper 6426 and CESifo Working Paper N. 2151; Forthcoming in *Energy Economics*.
- Bosetti, V., Carraro, C., and Tavoni, M. (2008), Delayed Participation of Developing Countries to Climate Agreements: Should Action in the EU and US be Postponed?, FEEM, CEPR and CESifo working paper.
- Carraro, C., Eyckmans, J. and M. Finus (2006), Optimal Transfers and Participation Decisions in International Environmental Agreements, *Review of International Organizations*, Vol. 1, No. 4, 379-396.
- Carraro, C., Marchiori, M. and S. Orefice (2003), Endogenous Minimum Participation in International Environmental Treaties, FEEM Nota di Lavoro 113.03 and CEPR DP 4281.
- Carraro, C. and D. Siniscalco (1993), Strategies for the International Protection of the Environment, *Journal of Public Economics*, 4, 1993.

Chwe, M. S.-Y. (1994), Farsighted Coalitional Stability. "Journal of Economic Theory", vol. 63, pp. 299-325.

Ebeling, J. (2006), Tropical deforestation and climate change. Towards an international mitigation strategy, University of Oxford, Oxford.

Frenkel, J. (2007), Formulas for quantitative emission targets, in *Architectures for Agreement: Addressing Global Climate Change in the Post-Kyoto World*, edited by Aldy, J. and Stavins, R. N., pp. 31-56, Cambridge University Press, Cambridge, UK.

Goulder, L. H. (2000), Central Themes and Research Results in Global Climate Change Policy, Paper prepared for the Intergovernmental Panel on Climate Change, Working Group III, Third Assessment Report, Stanford, California.

IEA (2002) *Beyond Kyoto: energy dynamics and climate stabilisation*. Vol. International Energy Agency, Paris.

IPCC (2007), *Climate Change 2007: Synthesis Report*, IPCC.

Keeler, A., and Thompson, A. (2008), Rich country mitigation policy and resource transfers to poor countries, paper presented at the Harvard Project on International Climate Agreements First Workshop, Cambridge, Mass., 15-16 March 2008.

McKibbin, W. J., and Wilcoxon, P. J. (2007), A credible foundation for long-term international cooperation on climate change, in *Architectures for Agreement: Addressing Global Climate Change in the Post-Kyoto World*, edited by Aldy, J. and Stavins, R. N., pp. 185-208, Cambridge University Press, Cambridge, UK.

Michaelowa, A. (2007), Graduation and deepening, in *Architectures for Agreement: Addressing Global Climate Change in the Post-Kyoto World*, edited by Aldy, J. and Stavins, R. N., pp. 81-104, Cambridge University Press, Cambridge, UK.

Newell, R., and Hall, D. (2007), U.S. Climate Mitigation in the Context of Global Stabilization, Resources for the Future, Washington D.C.

Plantinga, A. J., and Richards, K. R. (2008), The role of terrestrial carbon sequestration in a post-Kyoto international climate change treaty, paper presented at the Harvard Project on International Climate Agreements First Workshop, Cambridge, Mass., 15-16 March 2008.

Stern, N. (2008), Key elements of a global deal on climate change, The London School of Economics and Political Science, London.

Victor, D. (2007), Fragmented carbon markets and reluctant nations: implications for the design of effective architectures, in *Architectures for Agreement: Addressing Global Climate Change in the Post-Kyoto World*, edited by Aldy, J. and Stavins, R. N., pp. 133-160, Cambridge University Press, Cambridge, UK.

Wigley, T. M. L., Richels, R., and Edmonds, J. A. (1996), Economic and Environmental Choices in the Stabilization of Atmospheric CO₂ Concentrations, *Nature*, 379, 240-243.