



Politically Feasible Emission Target Formulas to Attain 460 ppm CO₂ Concentrations

Citation

Bosetti, Valentina, and Jeffrey A. Frankel. 2011. Politically Feasible Emission Target Formulas to Attain 460 ppm CO₂ Concentrations. HKS Faculty Research Working Paper Series RWP11-016, John F. Kennedy School of Government, Harvard University

Published Version

<http://web.hks.harvard.edu/publications/workingpapers/citation.aspx?PubId=7658>

Permanent link

<http://nrs.harvard.edu/urn-3:HUL.InstRepos:4735391>

Terms of Use

This article was downloaded from Harvard University's DASH repository, and is made available under the terms and conditions applicable to Other Posted Material, as set forth at <http://nrs.harvard.edu/urn-3:HUL.InstRepos:dash.current.terms-of-use#LAA>

Share Your Story

The Harvard community has made this article openly available. Please share how this access benefits you. [Submit a story](#).

[Accessibility](#)



HARVARD Kennedy School
JOHN F. KENNEDY SCHOOL OF GOVERNMENT

Politically Feasible Emission Target Formulas to Attain 460 ppm CO₂ Concentrations

Faculty Research Working Paper Series

Valentina Bosetti

Fondazione Eni Enrico Mattei (FEEM)

Jeffrey Frankel

Harvard Kennedy School

February 2011
RWP11-016

The views expressed in the **HKS Faculty Research Working Paper Series** are those of the author(s) and do not necessarily reflect those of the John F. Kennedy School of Government or of Harvard University. Faculty Research Working Papers have not undergone formal review and approval. Such papers are included in this series to elicit feedback and to encourage debate on important public policy challenges. Copyright belongs to the author(s). Papers may be downloaded for personal use only.

Revised February 15, 2011

Politically Feasible Emission Target Formulas to Attain 460 ppm CO₂ Concentrations

Valentina Bosetti, FEEM, Milan

and

Jeffrey Frankel, Harvard University

The authors would like to thank for support the Sustainability Science Program, funded by Italy's Ministry for Environment, Land and Sea, at the Center for International Development at Harvard University and the Climate Impacts and Policy Division of the EuroMediterranean Center on Climate Change (CMCC). The paper was written while Valentina Bosetti was visiting at the Princeton Environmental Institute (PEI) in the framework of cooperation between CMCC and PEI. This version is condensed in anticipation of publication in a Post-Kyoto Symposium of the Review of Environmental Economics and Policy. The full November 2009 versions of the paper, with appendix tables, are available under the title, "Global Climate Policy Architecture and Political Feasibility: Specific Formulas and Emission Targets to Attain 460 ppm CO₂ Concentrations," as FEEM Working Paper 92.2009 and NBER Working Paper 15516.

Abstract

A new climate change treaty must plug three gaps: the absence of emission targets extending far into the future, the absence of participation by the United States, China, and other developing countries, and the absence of reason to expect compliance. To be politically acceptable, it must obey certain constraints regarding country-by-country economic costs. We offer a framework to assign quantitative emission allocations, across countries, one budget period at a time. The two-part plan: (i) China and other developing countries accept targets *at BAU* in the coming budget period, the same period in which the US first agrees to cuts *below BAU*; (ii) all countries are asked in the future to make further cuts in accordance with a formula which sums a Progressive Reductions Factor, Latecomer Catch-up Factor, and Gradual Equalization Factor. An earlier proposal for specific parameter values in the formulas achieved the environmental goal that CO₂ concentrations plateau at 500 ppm by 2100. It obeyed our political constraints: keeping the economic cost for every country below thresholds of $Y=1\%$ of income in Present Discounted Value, and $X=5\%$ of income in the worst period. In this paper we attain a concentration goal of 460 ppm CO₂, but only by loosening political constraints.

JEL classification number: Q54

key words: China, concentrations, Copenhagen, costs, developing countries, emissions, equity, global climate, global warming, greenhouse gas, international, Kyoto, political, targets, treaty

Introduction

Negotiators under the UN Framework Convention on Climate Change had hoped to achieve a successor agreement to the Kyoto Protocol, to set emission targets after 2012. Although they achieved progress on some fronts at Copenhagen in 2010 and Cancun in 2011, the road to a new treaty has been blocked by a seeming insurmountable obstacle. The United States, which until recently was the world's largest emitter of Greenhouse Gases (GHGs), is at loggerheads with China, the world's new largest emitter, and with India and other developing countries. Fortunately, there just might be a way to break through the roadblock.

On the one hand, the US Congress is clear: it will not impose quantitative limits on US GHG emissions if it fears that emissions from China, India, and other developing countries will continue to grow unabated. Indeed, that is why the Senate was unwilling to ratify the Kyoto Protocol from the beginning. Why, it asks, should US firms bear the economic cost of cutting emissions if energy-intensive activities such as aluminum smelters and steel mills would just migrate to countries that have no caps and therefore have cheaper energy – the problem known as leakage -- and global emissions would continue their rapid rise?

On the other hand, the leaders of India and China are just as clear: they are unalterably opposed to cutting emissions until after the United States and other rich countries have gone first. After all, the industrialized countries created the problem of global climate change, while poor countries are responsible for only about 20 percent of the CO₂ that has accumulated in the atmosphere from industrial activity over the past 150

years. The poor countries should not be denied their turn at economic development. As India points out, Americans emit more than ten times as much carbon dioxide per person as they do.

What is needed is a specific framework for setting the actual numbers that future signers of a Kyoto-successor treaty might realistically be expected to adopt as their emission targets. There may be a practical solution to the apparently irreconcilable differences between the US and the developing countries regarding binding quantitative targets. The United States would indeed agree to join Europe in adopting serious emission targets. *Simultaneously*, in the same agreement, China, India, and other developing countries would agree to a path that immediately imposes on them binding emission targets as well—but targets that in the first period simply follow the so-called Business-as-Usual (BAU) path. BAU is defined as the path of increasing emissions that these countries would experience in the absence of an international agreement, preferably as determined by experts' projections.

Of course an environmental solution also requires that China and the other developing countries subsequently make cuts below their Business as Usual path in future years, and eventually make cuts in absolute terms as well. The sequence of negotiation can become easier over time, as everyone gains confidence in the framework. But *the developing countries can and should be asked to make cuts in the future that do not differ in nature from those made by Europe, the United States, and others who have gone before them, taking due account of differences in income.* Emission targets can be determined by formulas

- (i) that give lower-income countries more time before they start to cut emissions, and
- (ii) that lead to gradual convergence across countries of emissions per capita over the course of the century, while
- (iii) taking care not to reward any country for joining the system late.

Speaking realistically, no country – rich or poor – will abide by targets in any given period that entail extremely large economic sacrifice, relative to the alternative of simply not participating in the system. It is time to stop making sweeping proposals that assume otherwise, and to pursue instead the narrow thread of the politically possible.

There are by now many proposals for a post-Kyoto climate change regime, even if one considers only proposals that accept the basic Kyoto approach of quantitative, national-level limits on GHG emissions accompanied by international trade in emissions permits. The Kyoto targets applied only to the budget period 2008–2012, and only to a minority of countries (in theory, the industrialized countries). The big task is to extend quantitative emissions targets through the remainder of the century and to other countries—especially the United States, China, and other developing countries.

Virtually all the existing proposals for a post-Kyoto agreement are based on scientific environmental objectives (e.g., stabilizing atmospheric CO₂ concentrations at 380 ppm in 2100), or ethical/philosophical considerations (e.g., the principle that every individual on earth has equal emission rights), or economic cost-benefit analyses (weighing the economic costs of abatement against the long-term environmental benefits). Important examples of the science-based approach, the cost-benefit-based approach, and the rights-based approach, respectively, are Wigley, Richels and Edmonds (2007), Nordhaus (1994, 2006), and Baer *et al.* (2008). This paper proposes a way to

allocate emission targets for all countries and for the remainder of the century that is intended to be more practical in that it is also based on political considerations, rather than on science or ethics or economics alone.¹

The paper is organized as follows. In the next session we explain the motivation behind our framework for setting emissions targets, beginning by reviewing the tremendous political obstacles and then offering our proposed approach for “squaring the circle,” that is, for reconciling apparently irreconcilable constraints. We then present the rules to guide the setting of emission targets. We go through the specific quantitative targets, after the 2008-12 budget period covered by Kyoto, with which the leaders of the EU and some other countries have already associated themselves recently. These will provide some guidance for formulating what targets it would be reasonable to expect of others in subsequent periods. The section on determining targets for developing countries that are “fair,” that is, analogous to those who have gone before, explains the estimation of parameters for three components of the formula: the *Progressive Reductions Factor*, the *Latecomer Catch-up Factor*, and the *Gradual Equalization Factor*. The subsequent section shows the specific numerical emission target: paths that follow from the formulas for all countries and in all budget periods of the century. Next we report the economic and environmental effects of the proposed targets, according to the WITCH model. Conclusions conclude.

¹ Aldy, Barrett, and Stavins (2003) and Victor (2004) review a number of existing proposals. Numerous others have offered their own thoughts on post-Kyoto plans, at varying levels of detail, including Aldy, Orszag, and Stiglitz (2001); Barrett (2006); Nordhaus (2006); and Olmstead and Stavins (2006).

Addressing the Constraints

The industrialized countries did, in 1997, agree to quantitative emissions targets for the Kyoto Protocol's first budget period. So we know that it can be done in some sense. At multilateral venues such as the United Nations Framework Convention on Climate Change (UNFCCC) meeting in Bali (2007) and the Group of Eight (G8) meeting in Hokkaido (July 2008), world leaders agreed on a broad long-term goal of cutting total global emissions in half by 2050. At a meeting in L'Aquila, Italy, in July 2009, the G8 leaders agreed to an environmental goal of limiting the temperature increase 2°C, which corresponds roughly to a GHG concentration level of 450 ppm (or approximately 380 ppm CO₂ only).

But these meetings did not come close to producing agreement on who will cut how much, nor agreement on multilateral targets within a near-enough time horizon that the same national leaders are likely to still be alive when the abatement commitment comes due. To quote Al Gore (1993, p.353), "politicians are often tempted to make a promise that is not binding and hope for some unexpectedly easy way to keep the promise." For this reason, the aggregate targets endorsed so far cannot be viewed as more than aspirational.

Moreover, nobody has ever come up with an enforcement mechanism that simultaneously has sufficient teeth and is acceptable to member countries. Given the importance countries place on national sovereignty it is unlikely that this will change. Hopes must instead rest on weak enforcement mechanisms such as the power of moral suasion and international opprobrium, and possibly trade measures. It is safe to say that

in the event of a clash between such weak enforcement mechanisms and the prospect of a large economic loss to a particular country, aversion to the latter would win out.

A workable successor to Kyoto

Unlike the Kyoto Protocol, our proposal seeks to bring all countries into an international policy regime on a realistic basis and to look far into the future. But we cannot pretend to see with as fine a degree of resolution at a century-long horizon as we can at a five- or ten-year horizon. Fixing precise numerical targets a century ahead is impractical. Rather, we need a century-long sequence of negotiations, fitting within a common institutional framework that builds confidence as it goes along. The framework must have enough continuity so that success in the early phases builds members' confidence in each other's compliance commitments and in the fairness, viability, and credibility of the process. Yet the framework must be flexible enough that it can accommodate the unpredictable fluctuations in economic growth, technology development, climate, and political sentiment that will inevitably occur. Only by striking the right balance between continuity and flexibility can we hope that a framework for addressing climate change would last a century or more.

Political constraints

We take five political constraints as axiomatic:

1. The United States will not commit to quantitative targets if China and other major developing countries do not commit to quantitative targets at the same time. (This leaves completely open the initial level and future path of the targets.) Any plan will

be found unacceptable if it leaves the less developed countries free to exploit their lack of GHG regulation for “competitive advantage” at the expense of the participating countries’ economies and leads to emissions leakage at the expense of the environmental goal.

2. China, India, and other developing countries will not make sacrifices they view as
 - a. fully contemporaneous with rich countries,
 - b. different in character from those made by richer countries who have gone before them,
 - c. preventing them from industrializing,
 - d. failing to recognize that richer countries should be prepared to make greater economic sacrifices than poor countries to address the problem, or
 - e. failing to recognize that the rich countries have benefited from an unfair advantage in being allowed to achieve levels of per capita emissions that are far above those of the poor countries.

3. In the short run, emission targets for developing countries must be computed relative to current levels or BAU paths; otherwise the economic costs will be too great for the countries in question to accept. But in the longer run, no country should be rewarded for having “ramped up” emissions far above levels in an agreed base year. The reference year agreed to at Rio and Kyoto was 1990. Fairness considerations aside, if post-1990 increases are permanently “grandfathered,” then countries that have not yet agreed to cuts will have an incentive to ramp up emissions in the interval before they join. Of course there was nothing magic about 1990 but, for better or worse, it is the year on which Annex I countries have until Copenhagen based their planning. (If the

international consensus base year shifts from 1990 to 2005, our proposal will do the same.)

4. No country will accept a path of targets that is expected to cost it more than Y percent of income throughout the 21st century (in present discounted value). Frankel (2009) set Y at 1 percent.
5. No country will accept targets in any period that are expected to cost more than X percent of income to achieve during that period; alternatively, even if targets were already in place, no country would in the future actually abide by them if it found the cost to doing so would exceed X percent of income. Income losses are here defined relative to what would happen if the country in question had never joined. Frankel (2009) set X at 5 percent.

Squaring the circle

Of the above propositions, even just the first and second alone seem to add up to a hopeless stalemate: Nothing much can happen without the United States, the United States will not proceed unless China and other developing countries start at the same time, and China will not start until after the rich countries have gone first. There is a possible solution, one knife-edge position that satisfies the constraints. At the same time that the United States agrees to binding emission cuts, China and other developing countries agree to a path that immediately imposes on them binding emission targets—but these targets in their early years simply follow the BAU path.

In later decades, the formulas we propose do ask substantially more of the developing countries. But these formulas also obey basic notions of fairness, by asking

only for cuts that are analogous in magnitude to the cuts made by others who began abatement earlier and that make due allowance for developing countries' low per capita income and emissions and for their baseline of rapid growth. These ideas were developed in earlier papers (Frankel 1999, 2005, 2007; and Aldy and Frankel, 2004), which suggested that the formulas used to develop emissions targets incorporate four or five variables: 1990 emissions, emissions in the year of the negotiation, population, and income. One might also include a few other special variables such as whether the country in question has coal or hydroelectric power -- though the 1990 level of emissions conditional on per capita income can largely capture these special variables -- and perhaps a dummy variable for the transition economies.

We narrow down the broad family of formulas to a more manageable set, by the development of the three factors: a short-term Progressive Reductions Factor, a medium-term Latecomer Catch-up Factor, and a long-run Gradual Equalization Factor. We then put them into operation to produce specific numerical targets for all countries, for all remaining five-year budget periods of the 21st century. These are then fed into the WITCH model to see the economic and environmental consequences. International trading plays an important role. The framework is flexible enough that one can adjust a parameter here or there—for example if the economic cost borne by a particular country is deemed too high or the environmental progress deemed too low—without having to abandon the entire formulas framework.

Parameters chosen in Frankel (2009) showed that an environmental goal of 500 ppm in CO₂ concentrations could be achieved while satisfying the constraints. Far more aggressive cuts in emissions would be needed if the environmental goals of interest to

policy makers were to be attained. For this reason, we attempt in this paper to achieve a more aggressive goal of 460 ppm. We take no position ourselves on the desirable stringency of the goal.

Rules to guide the formulas that set emission targets

As noted, all developing countries that have any ability to measure emissions would be asked to agree immediately to emission targets that do not exceed their projected BAU baseline trajectory going forward. (Most countries in Africa would probably be exempted for some years from any kind of commitment, even to BAU targets, until they had better capacity to monitor emissions.)

The idea of committing to only BAU targets in the early decades will provoke strong objections from environmentalists and business interests in advanced countries. But they might come to realize that this commitment is more important than it sounds: It precludes the carbon leakage that, absent such an agreement, would undermine the environmental goal and it ameliorates the competitiveness concerns of carbon-intensive industries in the rich countries. The developing countries can not exploit the opportunity to go above their BAU paths as they would in the absence of this commitment.

This approach recognizes that it would be irrational for China to agree to substantial actual cuts in the short term. Indeed China might well register strong objections to being asked to take on binding targets of any kind at the same time as the United States. But the Chinese may also come to realize that they would actually gain from such an agreement, by acquiring the ability to sell emission permits at the same

world market price as developed countries. (China currently receives lower prices for lower-quality project credits under the Kyoto Protocol's Clean Development Mechanism.)

How do we know they would come out ahead? China is currently building roughly 100 power plants per year, to accommodate its rapidly growing demand. The cost of shutting down an already-functioning coal-fired power plant in the United States is far higher than the cost of building a new clean low-carbon plant in China in place of what otherwise might be a new dirty coal-fired plant. For this reason, when an American firm pays China to cut its emissions voluntarily, thereby obtaining a permit that the American firm can use to meet its emission obligations, both parties benefit, even in strictly economic terms. The environmental benefit is that China's emissions would (voluntarily) fall below its BAU commitment from the beginning. From a dynamic perspective, the incentive to shift towards a less carbon intensive capital stock will provide substantial additional benefits in ten or twenty years time, when China will face a constraining target, given the long-lived nature of these plants.

One must acknowledge that BAU paths are neither easily ascertained nor immutable. Countries may "high-ball" their BAU estimates in order to get more generous targets (though this may be difficult for those who have hitherto "low-balled" their claimed emissions path). Even assuming that estimates are unbiased, important unforeseen economic and technological developments could occur between 2010 and 2020 that will shift the BAU trajectory for the 2020s, for example. Any number of unpredictable events have already occurred in the years since 1990; they include German reunification, the 1997–1998 East Asia crisis, the boom in the BRIC countries (Brazil,

Russia, India, and China), the big rise in world oil prices, and the global financial crisis of 2007–2009.

A first measure to deal with the practical difficulty of setting the BAU path is to specify in the Kyoto-successor treaty that estimates would best be generated by an independent international expert body, not by national authorities. A second measure is to provide for updates of the BAU paths every budget period. Allowing for periodic adjustments to the BAU baseline does risk undermining the incentive for carbon-saving investments, on the logic that such investments would reduce future BAU paths and thus reduce future target allocations. This risk is the same as the risk of encouraging countries to ramp up their emissions, which we specified above to be axiomatically ruled out by any viable proposal. That is why we introduce a Latecomer Catch-up Factor into the formula, which rapidly diminishes the weight assigned to BAU after a few budget periods and instead tethers countries to their 1990 emission levels in the medium run.

Countries are expected to agree to the second step, quantitative targets that entail specific cuts below BAU, at a time determined by their circumstances. In our initial simulations, the choice of year for introducing an obligation actually to cut emissions was generally guided by two thresholds: when a country's average per capita income exceeds \$3000 per year and/or when its per capita annual emissions approach 1 ton or more. But we found that starting dates had to be further modified in order to satisfy our constraints regarding the distribution of economic losses.

Our formulas approach assigns emission targets in a way that is more sensitive to political realities than is typical of other proposed target paths, which are constructed either on the basis of a cost-benefit optimization or to deliver a particular environmental

and/or ethical goal. Specifically, numerical targets are based (a) on commitments that political leaders in various key countries had already proposed or adopted, as of 2009, and (b) on formulas designed to assure latecomer countries that the emission cuts they are asked to make represent no more than their fair share, in that they correspond to the sacrifices that other countries before them have already made.

Finally comes the other important concession to practical political realities: If the simulation in any period turns out to impose on any country an economic cost of more than $X\%$ of income, we assume that this country drops out. Dropping out could involve either explicit renunciation of the treaty or massive failure to meet the quantitative targets. For now, our assumption is that in any such scenario, the whole scheme would eventually unravel. This unraveling would occur much earlier if private actors rationally perceived that at some point in the future major players will face such high economic costs that compliance will break down. In this case, the future carbon prices that are built into most models' compliance trajectories will lack credibility, private actors today will not make investment decisions that reflect those projected future prices, and the effort will fail in the first period. Therefore, our approach to any scenario in which any major player suffers economic losses greater than $X\%$ has been to go back and adjust some of the starting dates or other parameters of the emission formulas, so that costs are lower and this is no longer the case.

We hope by these mechanisms to achieve political viability: non-negative economic gains in the early years for developing countries, average costs over the course of the century below Y percent of income per annum, and protection for every country against losses in any period as large, or larger than, X percent of income. Only if they

achieve political viability are announcements of future cuts credible. And only credible announcements of future cuts will send firms the long-term price signals and incentives needed to guide investment decisions today.

Goals already announced by national leaders

The starting point for our emission targets are the near-term goals that were already announced by national leaders in anticipation of the Copenhagen meeting. Our accounting is in term of country-specific or region-specific numeric emission targets for every fifth year: 2015, 2020, etc. For each five-year budget period, computations are based on the midpoint. For example the Kyoto period 2008–2012 is represented as 2010.

The European Union

The EU emissions target for 2008–2012 was agreed at Kyoto: 8 percent below 1990 levels.² Regarding the second budget period, 2015–2020, Brussels in 2008 committed to a target of 20 percent below 1990 levels.³ The European Union also said it would cut emissions 30 percent below 1990 levels, however, if other countries joined in. For the year 2020, given assumptions on other countries' commitments, we now set a target of 30% below 1990 levels. (This is the first respect in which we are being more

² Americans who claim on this basis that the European Union has not yet taken any serious steps go too far. Ellerman and Buchner (2008) show that the difference between allocations and emissions in 2005 and 2006 was probably in part attributable to abatement measures implemented in response to the positive price of carbon.

³ Documentation of legislation or announcements by leaders in the EU and other national governments is given in the footnotes to the 2009 working paper version of this study.

aggressive than the numbers in Frankel, 2009, which used the 20% cut for the EU.) For the third period, 2020–2025, and thereafter up to the eighth period, 2045–2050, the EU targets progress in equal increments to a 50 percent cut below 1990 levels: In other words, targets relative to 1990 emissions start at 35 percent below, and then progress to 50 percent below.

Japan, Canada, and New Zealand

These three Pacific countries are assigned the goal for the Kyoto budget period of a 6 percent reduction below 1990 levels. Of all ratifiers, Canada is probably the farthest from achieving its Kyoto goal by 2012. But Japan dominates this country grouping in size. In a concession to realism, we assume that these three countries do not hit the numerical target until 2012 (versus hitting it on average over the 2008–2012 budget period).

What about future budget periods? Japan's then-Prime Minister, Yasuo Fukuda, in 2008, announced a decision to cut Japanese emissions 60–80 percent by mid-century and successor Taro Aso in 2009, announced a plan to cut 15 per cent by 2020. In September, the incoming Prime Minister, Yukio Hatoyama, declared a goal of cutting emissions to 25 per cent below 1990 levels over the next 10 years, provided other countries were similarly ambitious. We interpret Japan's targets as cuts of 10 percent every five years between 2010 and 2050, computed logarithmically. The cumulative cuts are 80 percent in logarithmic terms, or 51 percent in absolute terms (i.e., to 49 percent of the year–2010 emissions level).

The United States

The Lieberman–Warner bill of 2007 would have begun by reducing emissions in 2012 to below 2005 levels and would have tightened the emissions cap gradually each year thereafter, such that by the year 2050 total emissions would be held to 30 percent of 2012 levels (i.e., a 70 percent reduction from emissions levels at the start date of the policy, measured non-logarithmically). During the 2008 US presidential election campaign, the Republican candidate, John McCain advocated a 2050 emissions target of 60 percent below 1990 levels (or 66 percent below 2005 levels) while Barack Obama endorsed a more aggressive target of reducing 2050 emissions 80 percent below 1990 levels.

The earlier paper (Frankel, 2009) assumed U.S. targets that cut the average annual emissions growth rate in half during the period 2008–2012, to 0.7 percent per year.⁴ At that point, we assumed that emissions plateau (growth is held to zero) for the period 2012–2017. *Then* we implemented the rest of the Lieberman–Warner formula, such that emissions in 2050 reach a level 67 percent below 1990 levels.⁵ Spread over 38 years, this implied sustained reductions of 2.6 percent per year on average, or 13 percent every five years.

The Waxman-Markey bill that was passed by the House of Representatives in June 2009 (but not the Senate) – formally known as the American Clean-Energy and Security Act, or ACES Act -- was less aggressive with respect to the near-term targets. It specified that US emission allowances would continue to grow at 3 per cent per year

⁴ Or 3.5 percent cumulatively, so that emissions in 2012 are 31.5 percent above 1990 levels. That is, 27 percent logarithmically.

⁵ Using our postponed base this is 98.5 percent below 2012 levels, logarithmically.

from 2012 to 2017. On the other hand, it was aggressive with respect to the subsequent 33 years: Waxman-Markey assumed a US rate of reduction of about 5 per cent per year from 2017 to 2050 -- unless the price ceiling specified by an escape clause were to kick in.

Australia

Canberra has been reluctant to take strong actions because the country is so dependent on coal. In 2008, however, then-Prime-Minister Kevin Rudd announced plans to cut Australia's emissions to 60 percent below 2000 levels by 2050. In 2009 the government went on to set a target 5 per cent below 2000 levels by 2020. In the regional groupings of our model, Australia is classified together with South Korea and South Africa, which are also coal-dependent.

Korea and South Africa

Until relatively recently it looked unlikely that any “non-Annex I” countries would consider taking on serious cuts below a BAU growth path within the next decade. But in 2008 the new president of South Korea, Myung-bak Lee, “tabled a plan to cap emissions at current levels over the first Kyoto period.” This was a ambitious target in light of Korea's economic growth rate. He also “vowed his country would slash emissions in half by 2050,” like the industrialized countries—of which Korea is now one. Emissions had risen 90 percent since 1990 and it is hard to imagine any country applying the brakes so sharply as to switch instantly from 5 percent annual growth in emissions to zero. We choose to interpret the Korean plan to flatten emissions as covering a period

that stretches out over the next eleven years, so that in 2020 the level of emissions is the same as in 2005.

Meanwhile, South Africa evidently proposed in 2008 that its emissions would peak by 2025 and begin declining by 2030.

Mexico

President Felipe Calderon's environment minister, Juan Rafael Elvira, announced in mid-2009 that Mexico was committing itself to reduce its greenhouse gas emissions by 50 million metric tons a year between then and 2012, and by 50 percent below 2002 levels by 2050.

China

Getting China to agree to binding commitments is the *sine qua non* of any successful post-Kyoto plan. In August 2009, a Chinese top climate change policy-maker set a target for emissions to peak by 2050. In the earlier paper we assumed that China starts cutting relative to BAU in 2030. But since we are now assuming more aggressive cuts by the industrialized countries during this period, and the year-2100 goal of CO₂ concentrations at 450 ppm cannot be met without substantial effort by China as well, we now move up to 2025 the date at which it begins to cut.

This leaves three questions: (1) how to determine the magnitude of China's cuts in this first budget period—that is, for the first period in which it is asked to make cuts below BAU; (2) how to determine Korea's cuts in its second budget period; and (3) how to set targets for everyone else. The other regions are Latin America—which like Korea

should logically act before China and India, in light of its stage of development—Russia, Middle East/North Africa, Southeast Asia, India/South Asia, and Africa. Table 1 shows the starting dates for each, which are placed earlier than in the preceding paper in order to hit the more aggressive environmental goal.

Table 1: Years when signers are to commit to targets at BAU and then below BAU

	year when they are assumed to commit to TARGET or BAU	year when they are assumed to commit to TARGET (PCF & LCF) never above BAU	year when GEF kicks in
USA	2010	2010	2050
EU	2010	2010	2050
KOSAU	2010	2020	2050
CAJAZ	2010	2015	2050
TE	2010	2025	2055
MENA	2010	2025	2055
SSA	2025	2050	2080
SASIA	2010	2025	2055
CHINA	2010	2025	2055
EASIA	2010	2025	2055
LAM	2010	2020	2050

EU = West Europe and East Europe
 CAJAZ = Canada, Japan + New Zealand
 MENA = Middle East + North Africa
 SASIA = India and the rest of South Asia
 EASIA = Smaller countries of East Asia

KOSAU = Korea, South Africa + Australia (all coal-users)
 TE = Russia and other Transition Economies
 SSA = Sub-Saharan Africa
 CHINA = PRC
 LAM = Latin America + the Caribbean

Our general guiding principle for the emission targets, once they start cutting below BAU, is to ask countries only to do what is analogous to what has been done by others who have gone before them. This general principle is put into practice by means of three factors.

Formulas to determine “fair” targets for developing countries

This section discusses the three factors in the formulas for determining “fair” emissions targets for countries in later years, particularly developing countries. “Fair” is here defined as analogous to targets of countries who have gone before. The three factors are additive (logarithmically).

Progressive Reductions Factor

We call the first the Progressive Reductions Factor. It is based on the pattern of emission reductions (relative to BAU) assigned to countries under the Kyoto Protocol, as a function of income per capita. This pattern is illustrated in Figure 1, which comes from the data as they were reported at that time. Other things equal, richer countries are asked to make more severe cuts relative to BAU, the status quo from which they are departing in the first period. Specifically, each 1 percent difference in income per capita, measured relative to EU income in 1997, increases the abatement obligation by 0.14 percent, where the abatement obligation is measured in terms of reductions from BAU relative to the EU cuts agreed at Kyoto. Normally, at least in their early budget periods, most countries’ incomes will be below what the Europeans had in 1997, so that this factor dictates milder cuts relative to BAU than Europe made at Kyoto. In fact the resulting targets are likely to reflect a “growth path”—that is, they will allow for actual emission increases relative to the preceding periods. The formula is:

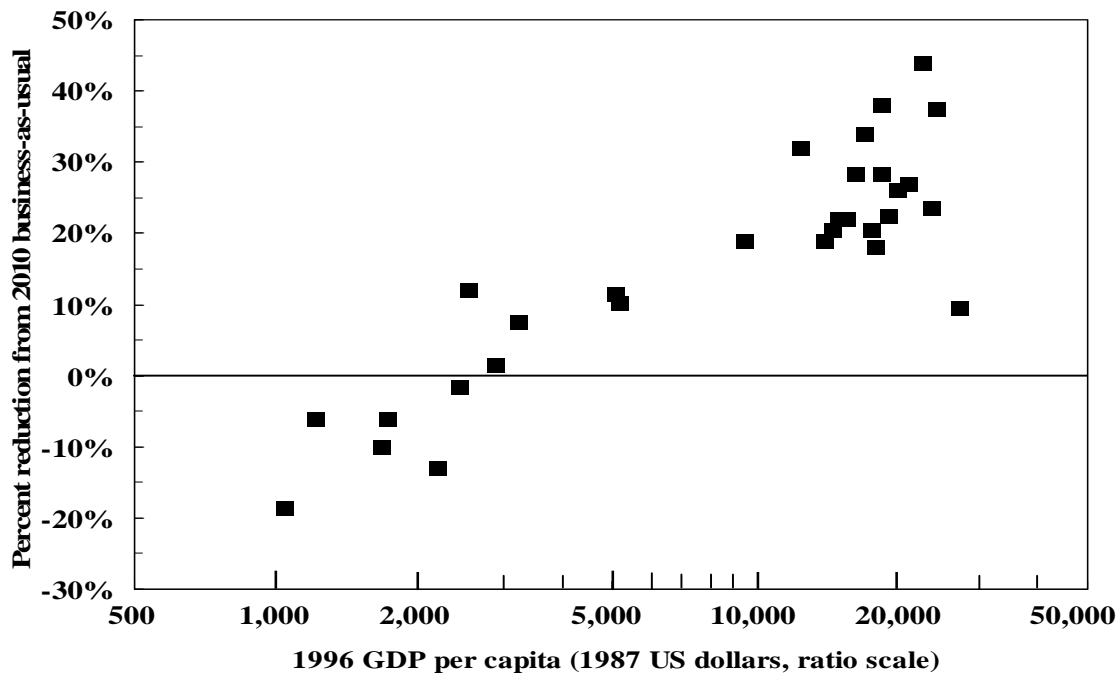
PRF (expressed as country cuts vs. BAU)

$$= \text{EU's Kyoto commitment for 2008 relative to its BAU}$$

$$+ .14 * (\text{gap between the country's current income per capita and the EU's in 2007}).$$

The parameter (0.14) was suggested by ordinary least squares (OLS) regression estimates using the data shown in Figure 1. Other parameters could be chosen instead, if the parties to a new agreement wanted to increase or decrease the degree of progressivity.

Figure 1: The Emissions Cuts Agreed at Kyoto Were Progressive with Respect to Income, when Expressed Relative to BAU



Sources: The World Bank, the U.S. Energy Information Administration, and national communications to the UNFCCC

Latecomer Catch-up Factor

The Latecomer Catch-up Factor is the second element in the formula. Latecomers are defined as those countries that have not ratified Kyoto or for which Kyoto did not set quantitative targets. These countries should not be rewarded by permanently readjusting

their targets to a higher baseline. Aside from notions of fairness, such re-basing would give all latecomers an incentive to ramp up their emissions before signing on to binding targets, or at a minimum would undercut any socially-conscious incentives they might otherwise introduce to reduce emissions unilaterally in the time period before they join the system. Thus the Latecomer Catch-up factor is designed to close gradually the gap between the starting point of the latecomers and their 1990 emission levels. It is parameterized according to the numbers implicit in the Waxman-Markey bill to bring US emissions to 70 percent below 1990 levels by 2050 and the Lee proposal to flatten South Korea's emissions over a period beginning in 2008. In other words, countries are asked to move gradually in the direction of 1990 emissions in the same way that the United States and Korea under current proposals would have done before them.

The formula for a country's Latecomer Catch-up Factor (LCF) is as follows. Further percentage cuts (relative to BAU plus a Progressive Reductions Factor) are proportional to how far emissions have been allowed to rise above 1990 levels by the time the country joins in. The important parameter represents the firmness with which latecomers are pulled back toward their 1990 emission levels. The parameter for Europe at the time the Kyoto Protocol was negotiated was sufficient to pull the EU-average below its 1990 level. But to calibrate this formula, the most relevant countries are not European (since the Europeans are not latecomers), but rather the United States and Korea, since these are the only countries among those that did not commit themselves to Kyoto targets whose political leaders had by 2009 indicated explicitly what targets they were willing to accept in the second budget period. The parameters α and λ were chosen

to fit the US target in the 2009 Waxman-Markey bill and the Korean target (a flattening of emissions). The Latecomer Catch-up Factor then works out to:

$$LCF = 0.54 - 0.773 \log(\text{country's current emissions} / \text{country's 1990 emissions}).$$
⁶

In order to come close to our environmental target (460 ppmCO₂ is as close as we get) without an unacceptable allocation of economic costs across countries, we had to sacrifice a little of the simplicity of the LCF equation, by adding a dummy variable for both TE and China. Transition Economies experienced emissions in 1990 that were higher than the subsequent trend; whereas China would be experiencing extremely high costs due to the projected baseline. Hence, we insert here special adjustment terms: -0.13 for China and 0.38 for the Transition Economies.⁷

Gradual Equalization Factor

The third element is the Gradual Equalization Factor (GEF). Even though developing countries under the proposal benefit from not being asked for abatement efforts until after the rich countries have begun to act, and face milder reduction requirements, they will still complain that it is the rich countries that originally created an environmental problem for which the poor will disproportionately bear the costs, rather than the other way around. Such complaints are not unreasonable. If we stopped with

⁶ This catch-up parameter is much stronger than that used in Frankel (2009). If Korea were to back away from its president's commitment, but some other important middle-income country were to step up to the plate with explicit and specific numerical targets, then the calculation could be redone.

⁷ This is a departure from our preferred principle of applying the same formula for all countries, a simplicity that is appealing aesthetically and, more important, politically. (As in Frankel, 2009.) But it is one of the concessions we have to make to attain the more aggressive environmental goal.

the first two factors, the richer countries would be left with the permanent right to emit more GHGs, every year in perpetuity. This seems unfair.

In the short run, pointing out the gap in per capita targets is simply not going to alter the outcome. India and other poor countries will have to live with it. Calls for the rich countries to cut per capita emissions rapidly, in the direction of poor-country levels, ignore the fact that the economic costs of such a requirement would be so astronomical that no rich country would ever agree to it. When one is talking about a lead time of 50 to 100 years, however, the situation changes. With time to adjust, the economic costs are not impossibly high, and it is reasonable to ask rich countries to bear their full share of the burden. Furthermore, over a time horizon this long some of the poor countries will in any case become rich (and possibly vice versa).

Accordingly, during each decade of the second half of the century, the formula includes an equity factor that moves per capita emissions in each country a small step in the direction of the global average. This means downward in the case of the rich countries and upward in the case of the poor countries. Asymptotically, the repeated application of this factor would eventually leave all countries with equal emissions per capita, although corresponding national targets need not necessarily converge fully by 2100.⁸

The parameter for the speed of adjustment in the direction of the world average was initially chosen to match the rate at which the EU's already-announced goals for 2045–2050 converge to the world average. This number is 0.1 per five-year budget

⁸ Zhang (2008) and others, motivated by a rights-based approach, propose that countries “contract and converge” to targets that reflect equal emissions per capita. The Greenhouse Development Rights approach of Baer *et al.* (2008), as extended by Cao (2009), emphasizes, from a philosophical standpoint, the allocation of equal emission rights at the individual level, though these authors apparently recognize that, in practice, individual targets would have to be aggregated and implemented at the national level.

period, which is also very similar to the rate of convergence implicit in the goals set by the Lieberman bills for the United States during 2045–2050. Thus:

GEF = -0.1 (percentage gap between country's lagged emissions per capita and world's).

In order to attain lower stabilization levels one could adjust the equalization parameter, but the effect would be that costs increase dramatically, especially for some countries such as China and Transition Economies.

The numerical emission target paths for all countries in all decades

Table 1 summarizes the dates at which all countries are asked to take on BAU targets and then reductions below BAU as governed by the three different formula elements (PRF, LCF, and then GEF). Table 2 in the Working Paper reports the emissions targets produced by the formulas for each of eleven geographical regions, for every period between now and the end of the century.

The eleven regions are:

EU = Western Europe and Eastern Europe

US = United States

KOSAU = Korea, South Africa, and Australia

CAJAZ = Canada, Japan, and New Zealand TE = Russia and other Transition Economies

MENA = Middle East and North Africa

SSA = Sub-Saharan Africa

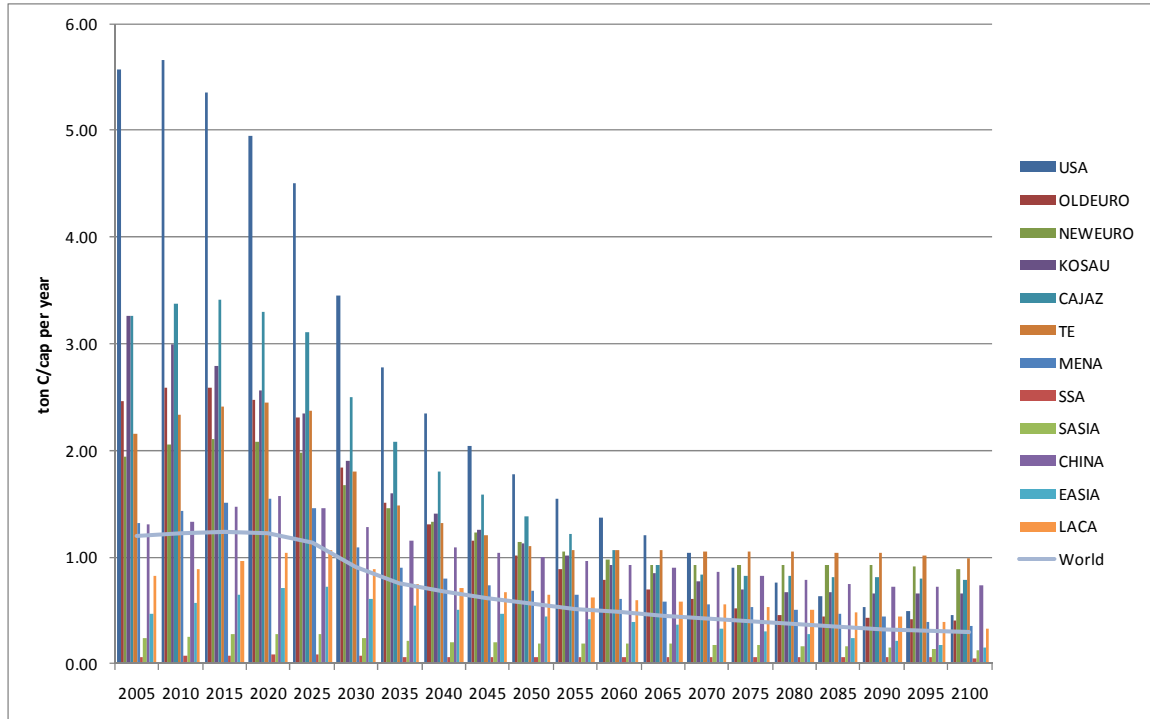
SASIA = India and the rest of South Asia

CHINA = PRC

EASIA = Smaller countries of East Asia

LAM = Latin America and the Caribbean

Figure 2: Actual Emission per capita throughout the century, for 11 regions



The bar chart in Figure 2 shows projected emissions, expressed in per capita terms, for every region in every budget period. The United States, even more than other rich countries, is currently conspicuous by virtue of its high per capita emissions. But its target path begins to come down after 2010. Emissions in all the rich regions decline rapidly between 2020 and 2050. Emissions in developing countries continue to rise for a bit longer, and then come down more gradually. But their emissions per capita numbers of course start from a much lower base. China peaks at about 1 ½ ton C per capita in 2020. None of the other developing countries ever gets above 1 ton C per capita. The industrialized countries, in contrast, emit between 2 and 5 ½ tons C per capita before they start to cut. In the second half of the century, everyone converges to levels below one ton per capita.

Figure 3:
Assigned targets and actual emissions for industrialized countries in the aggregate
 (Note: Predicted actual emissions exceed caps by amount of permit purchases)

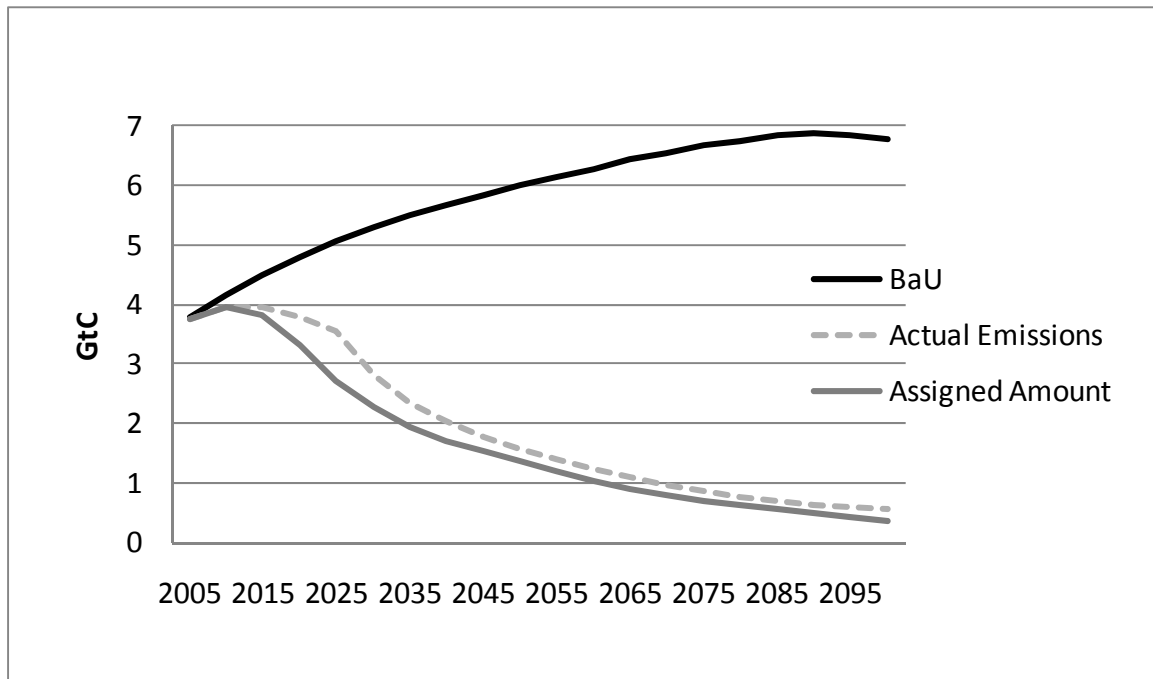
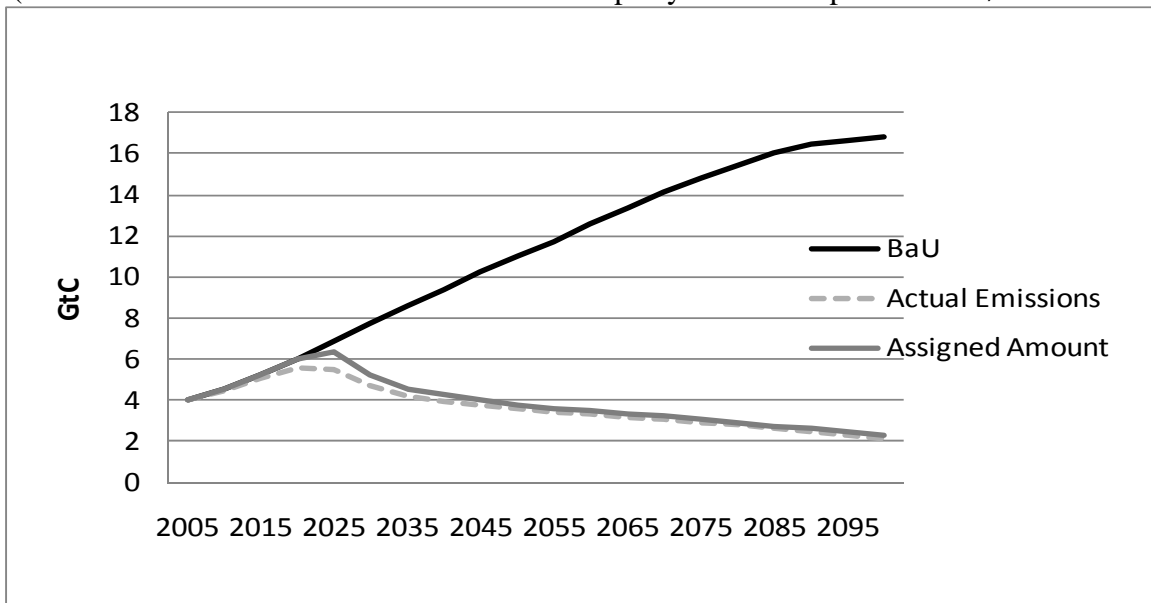


Figure 3 reports aggregate targets (caps) for member countries of the Organization for Economic Co-operation and Development (OECD). They decline from about 4 gigaton or Gt C in 2020 to 1 Gt C in 2060. The graph also shows the simulated value for actual emissions of the rich countries, which decline more gradually than the targets through 2070 because carbon permits are purchased on the world market, as is economically efficient. The total value of the permit purchases runs about $\frac{1}{2}$ Gt C in the middle decades of the century. The quantity of permits purchased by the OECD countries is generally less than one fifth of their total reductions. The US is the larger buyer. This is a far smaller trading share than was the case in the earlier paper, a

consequence of the tougher targets that are here imposed on the developing countries. It is fortunate in the respect that legislation in both Brussels and Washington places limits on how much emission reductions can be achieved through permit purchases. The trading share falls off sharply in the second half of the century.

Figure 4: Assigned targets and actual emissions for poor countries in the aggregate
 (Note: Predicted actual emissions fall below caps by amount of permit sales)



Emissions peak in 2020 in the TE group (transition economies), MENA, China, and Latin America. Emissions in sub-Saharan Africa remain at very low levels throughout the century. Figure 4 shows that among non-OECD countries overall, both emissions targets and actual emissions peak in 2020. The simulated path of actual emissions lies a little above the target caps. The difference, again, is the value of permits sold by the poor countries to the rich countries. The total falls to 2 Gt C at the beginning of the 22nd century.

Total world emissions peak in 2020 below 10 Gt C. (The path of the global aggregate is shown in Figure 5 of the working paper, omitted here to save space.)

Economic and environmental consequences of the proposed targets, according to the WITCH model

Estimating the economic and environmental implications of any set of targets is a complex task.⁹ WITCH (www.feem-web.it/witch) is an energy-economy-climate model developed by the climate change modeling group at FEEM. The model has been used extensively in the past five years to analyze the economic impacts of climate change policies. WITCH is a hybrid top-down economic model with energy sector disaggregation. Those who might be skeptical of economists' models on the grounds that "technology is the answer" should rest assured that technology is central to this model. The model features endogenous technological change via both experience and innovation processes. Countries are grouped in twelve regions, where Western Europe and Eastern Europe are counted separately, that cover the world and that strategically interact following a game theoretic set-up. The WITCH model and detailed structure are described in Bosetti *et al.* (2006) and Bosetti, Massetti, and Tavoni (2007).

Original baselines in many models have been disrupted in recent years by such developments as stronger-than-expected growth in Chinese energy demand and the 2008

⁹ Researchers have applied a number of different models to estimate the economic and environmental effects of various specific proposed emission paths; see, for example, Edmonds, Pitcher, Barns, Baron, and Wise (1992); Edmonds, Kim, McCracken, Sands, and Wise (1997); Hammett (1999); Manne, Mendelsohn, and Richels (1995); Manne and Richels (1997); McKibbin and Wilcoxon (2007); and Nordhaus (1994, 2008). Weyant (2001) provides an explanation and comparison of different models.

spike in world oil prices. WITCH has been updated with more recent data and revised projections for key drivers such as population, GDP, fuel prices, and energy technology characteristics. The base calibration year has been set at 2005, for which data on socio-economic, energy, and environmental variables are now available (Bosetti, De Cian, Sgobbi, and Tavoni, 2009b).

Economic effects

Although economists trained in cost-benefit analysis tend to focus on economic costs expressed in terms of income, the politically attuned tend to focus also on the predicted carbon price, which in turn has a direct impact on the prices of gasoline, home heating oil, and electric power. The price of carbon dioxide under these targets rises very substantially, reaching \$1800 per ton in 2100.¹⁰ This is a high number, approximately twice what the CO₂ price was with an environmental goal of 500 ppm. But at least the rise is smooth, which is a desirable property. The right margin of the graph translates the cost from dollars per ton of carbon to terms that the American consumer can relate to: the increment to the cost of gasoline. It rises to European levels by 2040, and to \$16 per gallon in 2100.

Economic losses measured in terms of national income are illustrated in Figure 5a and 5b, for the first and second halves of the century, respectively. They too rise gradually. Given a positive rate of time discount, this is a good outcome. As late as 2055, all regions sustain economic losses that are no greater than 3.5 per cent of income. (As of mid-century, the US is running the largest cost among OECD countries, relative to BAU, and MENA and China are running the largest costs among non-OECD countries.)

¹⁰ Illustrated in Figure 6 of the working paper.

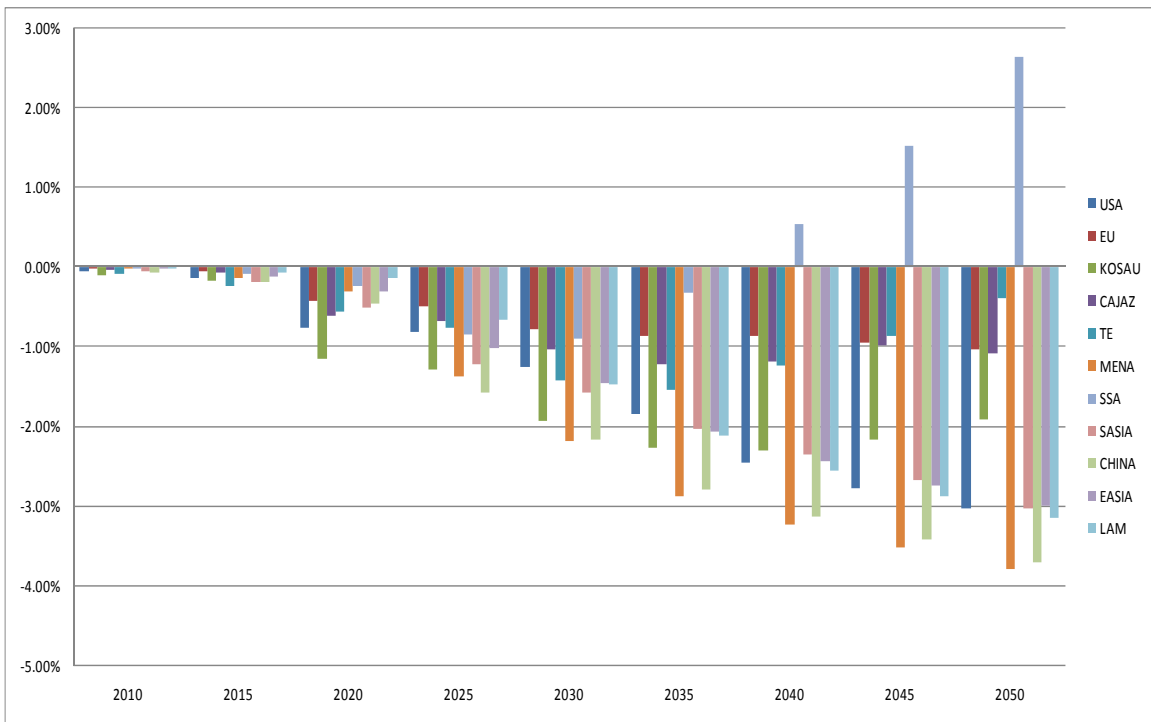
Later in the century, the costs go much higher, above 11 percent of income in the case of TE and China. The costs estimated by the WITCH model are broadly in line with those estimated by a range of other leading models, as summarized in Clarke, et al (2009).

These costs of participation are overestimated in one sense, and increasingly so in the later decades, if the alternative to staying in the treaty one more decade is dropping out after seven or eight decades of participation. The reason is that countries will have already substantially altered their capital stock and economic structure in a carbon-friendly direction. The economic costs reported in the simulations and graphs treat the alternative to participation as never having joined the treaty in the first place. In another sense, however, the costs are underestimated: any country that drops out can in fact exploit leakage opportunities to the hilt. Its firms can buy fossil fuels at far lower prices than their competitors in countries that continue to participate.

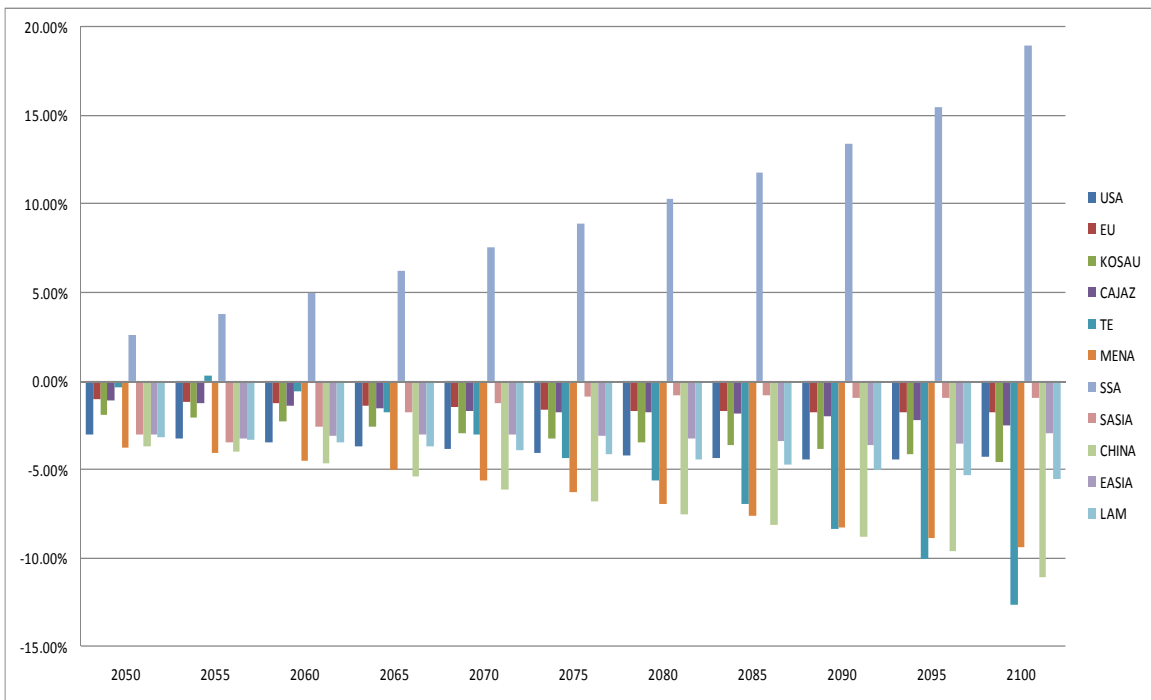
The combination of parameters adopted yield costs that rise above our self-imposed threshold of 5 percent of national income, after 2065, a consequence of the more aggressive environmental goal. All economic effects are deliberately gross of environmental benefits—that is, no attempt is made to estimate environmental benefits or net them out.

Figure 5: Income Losses by Region and Period Over the Century

a) 2010-2045



b) 2050- 2100



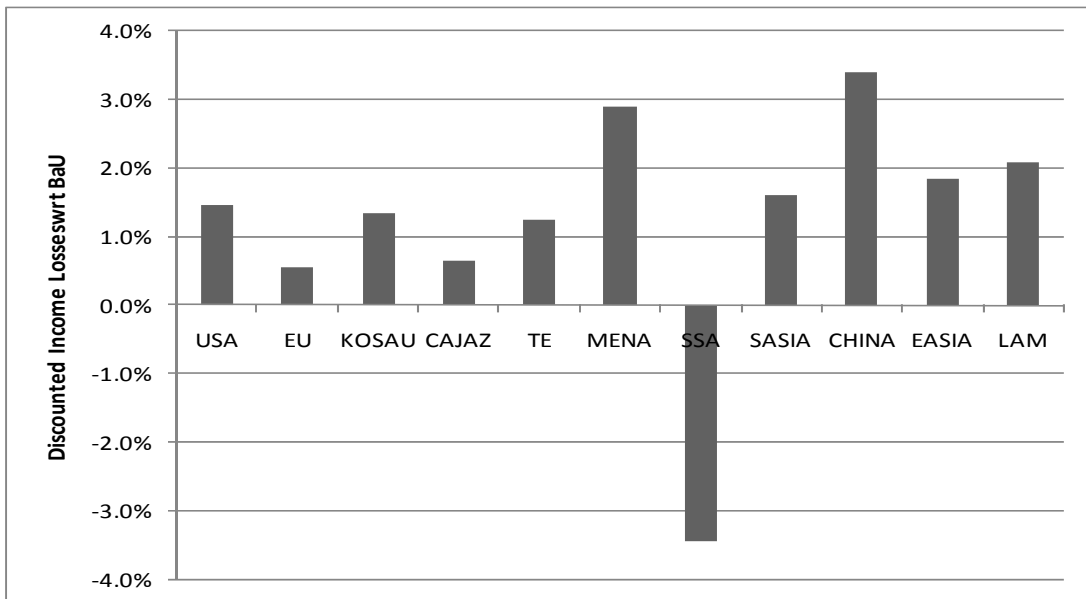
We measure the present discounted value of costs with a discount rate of 5 percent.¹¹ Total economic costs come to 1.39 percent of annual gross world product. Table 2 and Figure 6 provide the regional detail for these figures.

We have tried the more conventional alternative of choosing country targets to minimize the threshold for PDV country costs. The gain in reduced PDV of losses is small, on the order of 1/10 of one percent of GDP. What is lost is the simplicity of a common formula approach across countries and across time, the constraint that no country should endure an unusually high cost in any single period, and the correspondingly enhanced credibility.

Table 2: Implied Economic Cost of Emission Targets for each of 11 regions
Present Discounted Value at discount rate = 5%, expressed as per cent of income

<i>USA</i>	<i>EU</i>	<i>KOSAU</i>	<i>CAJAZ</i>	<i>TE</i>	<i>MENA</i>	<i>SSA</i>	<i>SASIA</i>	<i>CHINA</i>	<i>EASIA</i>	<i>LAM</i>
1.5%	0.6%	1.3%	0.6%	1.3%	2.9%	-3.4%	1.6%	3.4%	1.9%	2.1%

Figure 6: Economic Costs by Region, 2010-2100,
discounted to 2005 at 5% discount rate



¹¹ Figure 8 of the working paper shows the path of Gross World Product loss aggregated across regions.

Environmental effects

Under the emission numbers produced by this proposal, the concentration of CO₂ in the atmosphere is projected to reach 460 ppm in the latter half of the century. Figure 7 shows the path of concentrations. Figure 8 shows the path of temperature. Based on the modeled concentration trajectory, global average temperature is projected to stay below 2.8 degrees Celsius (°C) above pre-industrial levels at the end of the century, as opposed to almost 4°C under the BAU trajectory. The result is less ambitious than the goal set by the G-8 leaders at their 2009 summit of stabilizing the temperature increase below 2°C. One might be disappointed by the very modest reduction in temperature in which increasingly stringent climate policies result. The reason for this is nonlinearity: 1% in concentrations translates to less than 1% in global warming. Policies aiming at reducing emissions from land use and other greenhouse gasses could lead to a larger effect on concentrations and final temperature.

Figure 7: CO₂ concentrations achieve year-2100 concentration goal of 460 ppm

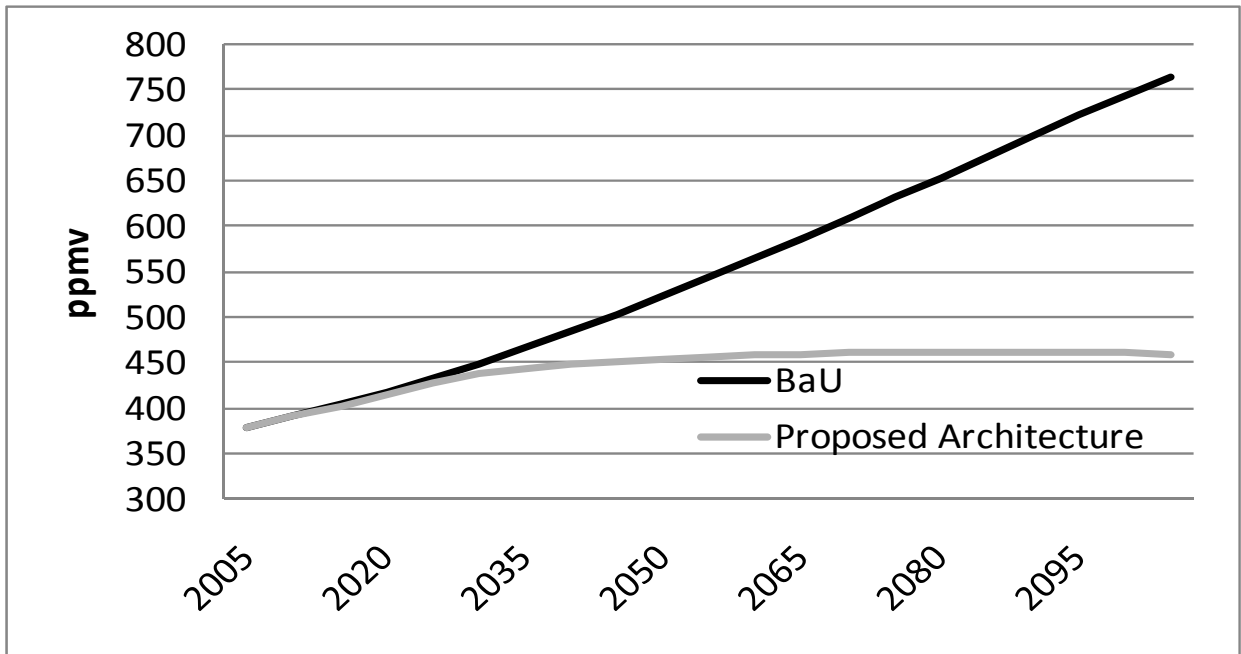
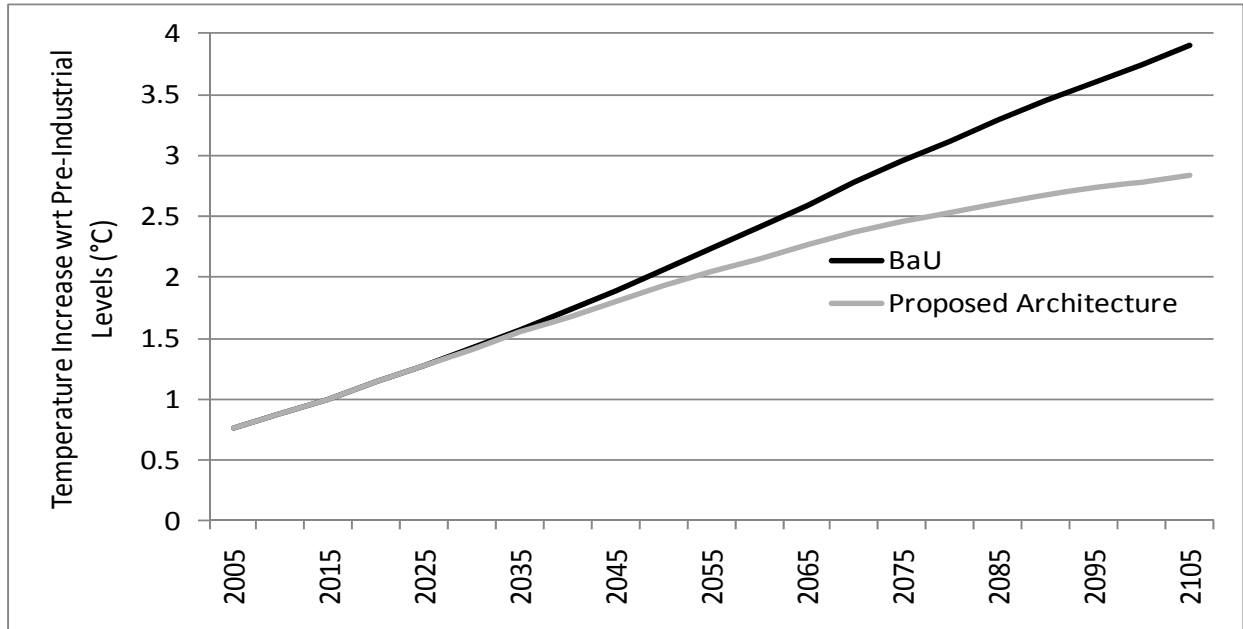


Figure 8: Rise in temperature under proposed targets vs. BAU



Conclusion

A politically credible framework

Some may wish to conclude from the results in this paper that the environmental goals of 380 or 450 ppm in CO₂ concentrations are not attainable in practice, and that our earlier proposal for how to attain 500 ppm is the better plan (Frankel, 2009). We take no position on which environmental goal is best overall. Rather, we submit that, whatever the environmental goal, our approach will give targets that are more practical economically and politically than various approaches that have been proposed by others.

Our framework specifies the allocation of emission targets across countries in such a way that every country is given reason to feel that it is only doing its fair share and in such a way as to build trust as the decades pass. Without such a framework,

announcements of distant future goals are not credible and so will not have the desired effects. Furthermore, this framework—in providing for a decade-by-decade sequence of emission targets, each determined on the basis of a few principles and formulas—is flexible enough that it can accommodate, by small changes in the formula parameters, major changes in circumstances during the course of the century.

Directions for future research

Several particular extensions are possible for future research.

First, we could compare our proposed set of emissions paths to other proposals under discussion in the climate change policy community or being analyzed using other integrated assessment models.¹² Our conjecture is that we could identify countries and periods in alternative pathways where an agreement would be unlikely to hold up because its targets were not designed to limit economic costs for each country.

Second, we could take into account GHGs other than CO₂ and could allow for other mitigation measures such as forestation, updating to correspond to the outcome of ongoing negotiations.

Third, we could implement constraints on international trading. Such constraints can arise either from a philosophical worldview that considers it unethical to pay others to take one's medicine, or from a more cynical worldview that assumes international transfers via permit sales will only line the pockets of corrupt leaders. Constraints on

¹² For example, the CLEAR path offered by Wagner *et al.* (2008) proposes that by 2050 Russia has cut its emissions 30 percent below 1990 levels, China 46 percent below 2012 levels, India 8 percent above 2012 levels, and the other non-Annex I countries 23 percent below 2012. The Global Development Rights approach of Baer *et al.* (2008) apparently proposes a US emissions target for 2025 that is 99 percent below its BAU path.

trading could take the form of quantity restrictions—for example, that a country cannot satisfy more than Z percent of its emissions obligation by international permit purchases.

The fourth possible extension of this research represents the most important step intellectually: to introduce uncertainty, we want to allow for rates of economic growth or technological progress that turn out to be higher or lower than was forecast in the BAU path. We would adduce the consequences of our rule that if any country makes an *ex post* determination in any period that by staying in the treaty it loses more than X percent of income, even though this had not been the expectation *ex ante*, that country will drop out.

One benefit of this exercise would be to assure those who believe that the costs are likely eventually to turn out lower (or higher) than implied by the WITCH model that the target formulas could be adjusted accordingly, as the truth is revealed, while staying within the framework.

The ultimate objective in making the model stochastic is to show that the general policy framework is relatively robust with respect to unexpected developments and to seek modifications of the formulas to produce a version that is still more robust. Formulas should be set so as to protect against inadvertent stringency on the one hand—that is, a situation where the cost burden imposed on a particular country is much higher than expected—or inadvertent “hot air” on the other hand. “Hot air” refers to the possibility that targets are based on obsolete emission levels with the result that countries are credited for cutting tons that wouldn’t have been emitted anyway.

Three possible modifications to deal with uncertainty are promising. First, we should allow for renegotiation in the future of parameters determining emission targets,

based on unexpected developments. Second, when the target for each decade is set, it should be indexed to GDP within that budget period. Perhaps the constant of proportionality in the indexation formula would simply equal 1, in which case it becomes an efficiency target, expressed in carbon emissions per unit of GDP. This approach would be much less vulnerable to within-decade uncertainty (Lutter, 2000). A third possible feature that would make the policy more robust and that is favored by many economists is an escape clause or safety valve that would limit costs in the event that mitigation proves more expensive than expected, perhaps with a symmetric floor on the price of carbon in addition to the usual ceiling.

References

- Aldy, Joseph, Scott Barrett, and Robert Stavins, 2003, "Thirteen Plus One: A Comparison of Global Climate Architectures," *Climate Policy*, 3, no. 4, 373-97.
- and Jeffrey Frankel, 2004, "Designing a Regime of Emission Commitments for Developing Countries that is Cost-Effective and Equitable," *G20 Leaders and Climate Change*, Council on Foreign Relations.
- , Peter Orszag, and Joseph Stiglitz, 2001, "Climate Change: An Agenda for Global Collective Action." *The Pew Center Workshop on the Timing of Climate Change Policies*. October.
- Baer, Paul, Tom Athanasiou, Sivan Kartha and Eric Kemp-Benedict, 2008, *The Greenhouse Development Rights Framework: The Right to Development in a Climate Constrained World* (Hendrich Boll Stiftung, Stockholm, 2nd edition).
- Barrett, Scott, 2006, "Climate Treaties and 'Breakthrough' Technologies," *American Economic Review*, vol. 96, no. 2, May, 22-25.
- Bosetti, V., C. Carraro, M. Galeotti, E. Massetti and M. Tavoni, 2006, "WITCH: A World Induced Technical Change Hybrid Model." *The Energy Journal*, pp. 13-38.
- , C. Carraro, A. Sgobbi, and M. Tavoni, 2009, "Modelling Economic Impacts of Alternative International Climate Policy Architectures: A Quantitative and Comparative Assessment of Architectures for Agreement," in Joseph Aldy and Robert Stavins, eds., *Post-Kyoto International Climate Policy*. (Cambridge, UK: Cambridge University Press).
- E. De Cian, A. Sgobbi, M. Tavoni, 2009b, "The 2008 WITCH Model: New Model Features and Baseline," Working paper no. 85 (Fondazione Eni Enrico Mattei: Milan).
- , E. Massetti and M. Tavoni, 2007, "The WITCH Model. Structure, Baseline, Solutions". FEEM Working Paper no. 10.
- Cao, Jing, 2009, "Reconciling Human Development and Climate Protection: Perspectives from Developing Countries on Post-2012 International Climate Change Policy," in *Post-Kyoto International Climate Policy*, edited by Joe Aldy and Rob Stavins (Cambridge University Press: Cambridge, UK).
- Clarke, Leon, Jae Edmonds, Volker Krey, Richard Richels, Steven Rose, Massimo Tavoni, 2009, "International climate policy architectures: Overview of the EMF 22 International Scenarios," *Energy Economics* 31, S64-S81.
- Edmonds, J.A., H.M. Pitcher, D. Barns, R. Baron, and M.A. Wise, 1992, "Modeling Future Greenhouse Gas Emissions: The Second Generation Model," in *Modeling Global Climate Change*, Lawrence Klein and Fu-chen Lo, editors (United Nations University Press: Tokyo), pp. 295-340.
- S.H. Kim, C.N. McCracken, R.D. Sands, and M.A. Wise, 1997, "Return to 1990: The Cost of Mitigating United States Carbon Emission in the Post-2000 Period," October, Pacific Northwest National Laboratory.

Ellerman, Denny, and Barbara Buchner, 2008, "Over-Allocation or Abatement? A Preliminary Analysis of the EU ETS Based on the 2005-06 Emissions Data," *Environmental and Resource Economics* 41, no. 2, October, pp. 267-287.

Frankel, Jeffrey, 1999, "Greenhouse Gas Emissions," *Policy Brief* no.52, Brookings Institution, Washington, DC.

--- 2005, "You're Getting Warmer: The Most Feasible Path for Addressing Global Climate Change Does Run Through Kyoto," in *Trade and Environment: Theory and Policy in the Context of EU Enlargement and Transition Economies*, edited J.Maxwell and R.Reuveny (Edward Elgar Publishers, UK).

--- 2007, "Formulas for Quantitative Emission Targets," in *Architectures for Agreement: Addressing Global Climate Change in the Post Kyoto World*, J.Aldy and R. Stavins, eds. (Cambridge University Press).

--- , 2009, "An Elaborated Proposal For Global Climate Policy Architecture: Specific Formulas and Emission Targets for All Countries in All Decades," in *Post-Kyoto International Climate Policy*, edited by Joe Aldy and Rob Stavins (Cambridge University Press). NBER WP 18476.

Gore, Al, 1993, *Earth in the Balance* (Penguin Books, New York).

Hammett, James, 1999, "Evaluation Endpoints and Climate Policy: Atmospheric Stabilization, Benefit-Cost Analysis, and Near-Term Greenhouse Gas Emissions," *Climatic Change* 41: 447-468.

Lutter, Randy, 2000, "Developing Countries' Greenhouse Emissions: Uncertainty and Implications for Participation in the Kyoto Protocol," *Energy Journal* 21(4): 93-120.

Manne, Alan, Robert Mendelsohn, Richard Richels, 1995, "MERGE: A Model for Evaluating Regional and Global Effects of GHG Reduction Policies," *Energy Policy* 23:17.

--- and Richard Richels, 1997, "On Stabilizing CO2 Concentrations – Cost-Effective Emission Reduction Strategies," Stanford University and Electric Power Research Institute, April.

McKibbin, Warwick, and Peter Wilcoxon, 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 Joseph Aldy and Robert Stavins, Cambridge University Press.

Nordhaus, William, 1994, *Managing the Global Commons: The Economics of Climate Change*, MIT Press: Cambridge.

--- 2006, "Life After Kyoto: Alternative Approaches Global Warming Policies," *American Economic Review, Papers and Proceedings*, vol. 96, no. 2, May: 31-34.

--- 2008, *A Question of Balance: Weighing the Options on Global Warming Policies* (Yale University Press).

Olmstead, Sheila, and Robert Stavins, 2006, "An International Policy Architecture for the Post-Kyoto Era," *American Economic Review, Papers and Proceedings*, vol. 96, no. 2, May: 35-38.

Pizer, William, 2006, "The Evolution of a Global Climate Change Agreement," *American Economic Review, Papers and Proceedings*, vol.96, no.2, May, 26-30.

Stewart, Richard, and Jonathan Weiner, 2003, *Reconstructing Climate Policy: Beyond Kyoto* (American Enterprise Institute Press, Washington DC).

Victor, David, 2004, *Climate Change: Debating America's Policy Options* (Council on Foreign Relations, New York).

Wagner, Gernot, James Wang, Stanislas de Margerie and Daniel Dudek, 2008, "The CLEAR Path: How to Ensure that if Developing Nations Adopt Carbon Limits, Their Early Actions Will be Rewarded," Environmental Defense Fund Working Paper, October 30.

Weyant, John, 2001, "Economic Models: How They Work & Why Their Results Differ." In *Climate Change: Science, Strategies, & Solutions*. Eileen Claussen, Vicki Arroyo Cochran, and Debra Davis, editors (Brill Academic Press, Leiden), pp. 193-208.

Wigley, Tom M.L., Rich G. Richels and Jae A. Edmonds, 2007, "Overshoot Pathways to CO2 Stabilization in Multi-GasContext," in *Human-induced climate change: An interdisciplinary assessment* (Cambridge University Press), edited by RG Richels, AS Manne, and TML Wigley, Chapter 32, pp. 387-401.

Zhang, Yongsheng, 2008, "An Analytical Framework and Proposal to Succeed Kyoto Protocol: A Chinese Perspective," Development Research Center of the State Council, China, Dec.