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SUSTAINABLE COOPERATION IN GLOBAL CLIMATE POLICY: SPECIFIC FORMULAS AND EMISSION TARGETS

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We propose a framework that, building on the pledges made by governments after the Copenhagen Accord of 2009, could be used to assign allocations of emissions of greenhouse gases (GHGs), across all countries, one budget period at a time, as envisioned at the 2011 negotiations in Durban. Under this two-part plan: (i) China, India, and other developing countries accept targets at Business as Usual (BAU) in the coming budget period, the same period in which the U.S. first agrees to cuts below BAU; and (ii) all countries are asked in the future to make further cuts in accordance with a common numerical formula that each country is likely to view as fair. We use a state of the art integrated assessment model to project economic and environmental effects of the computed emission targets.

Keywords: Allocations; assigned amounts; climate change; Copenhagen Accord; Durban; developing countries; emission targets; equity; greenhouse gases; integrated assessment model; international environmental agreements; kyoto protocol; UNFCCC.

JEL Codes: Q54, F53

1. Introduction

Of all the obstacles that have impeded a global cooperative agreement to address the problem of Global Climate Change, perhaps the greatest has been the gulf between the advanced countries on the one hand, especially the United States, and the developing countries on the other hand, especially China and India. As long ago as the "differentiated responsibilities" language of the Berlin Mandate of 1995 under the United Nations Framework Convention on Climate Change (UNFCCC), it was understood that developing countries would not be asked to commit legally to emissions reductions in the same time span that industrialized countries did. But as long ago as the Byrd–Hagel Resolution of 1997, it was understood that the U.S. Senate would not ratify any treaty that did not ask developing countries to take on meaningful commitments at the same time as the industrialized countries. Sure enough, the U.S. did not ratify the Kyoto Protocol that was negotiated later the same year.[1]

Each side has a valid point to make. On the one hand, the U.S. reasoning is clear: It will not impose quantitative limits on its own greenhouse gas (GHG) emissions if it fears that emissions from China, India, and other developing countries will continue to grow unabated. Why, it asks, should American 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 U.S. and other rich countries have gone first. After all, the industrialized countries created the problem of global climate change, while developing countries are responsible for only about 20% of the CO_2 that has accumulated in the atmosphere from industrial activity over the past 150 years. Limiting emissions, they argue, would hinder the efforts of poor countries at economic development. As India points out, Americans emit more than 10 times as much carbon dioxide per person that its citizens do.

In December 2011, the UNFCCC Conference of Parties in Durban, South Africa, produced a new ray of hope for an agreement. It chose 2015 as the deadline for negotiating a successor to the Kyoto Protocol to come into force by 2010. Crucially, major developing countries agreed for the first time to the principle of legally binding emission limits.

What is needed is a specific framework for setting the actual emission targets that signers of a Kyoto-successor treaty can realistically be expected to adopt.[2] There is one practical solution to the apparently irreconcilable differences between the U.S. and the developing countries regarding binding quantitative targets. The U.S. 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 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 other developing countries subsequently make cuts below their BAU path in future years, and eventually

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[1]Canada ratified, but eventually dropped out, faced with the extremely high economic cost it would have taken to achieve its emissions target. The EU is thought to have met its target by 2012.

[2]Technically the Copenhagen Accord and Cancun Agreements did not build toward a successor regime to the Kyoto Protocol, because they included quantitative commitments from developing countries whereas the Kyoto Protocol continues to exist and continues to apply only to so-called Annex I countries. The sooner the two separate tracks are integrated, the better. In this study, when we speak of a workable successor to Kyoto, we are talking about a regime that includes developing countries.

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 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 remain practical and yet satisfy equity concerns if they are determined by formulas that:

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

We build on previous exploratory work — Frankel (2009) and Bosetti and Frankel (2012) — to focus our attention on the political constraints that define a credible commitment for all parties, rather than just on the resulting environmental effectiveness of the agreement.

In the present paper, we build on the quantitative pledges expressed in the Copenhagen Accord and Cancun Agreements. These encompass undertakings from more than 80 countries, including numerical goals not just for the E.U. 27 but also for 13 other Annex I countries (advanced countries plus a few former members of the Soviet Bloc) and — most importantly — for seven big emerging markets: Brazil, China, India, Indonesia, Mexico, South Africa, and South Korea. Thus, we have a firm numerical basis on which to extrapolate what sorts of emission targets are politically reasonable.

In order to project our targets into the future, we use the World Induced Technical Change Hybrid (WITCH) model (Bosetti *et al.*, 2006), an energy–economy–climate model that has been used extensively for economic analysis of climate change policies. The model divides the world into 13 regions. Each region's economy is described by a Ramsey-type optimal growth model. Through a tâtonnement process, regions can trade emissions allocations in the carbon market. The integrated assessment modeling effort allows us to capture a full range of mitigation technologies, including negative emissions options such as sequestration through forest management and biomass power production coupled with capture and storage of CO_2. These are crucial options when evaluating the cost of carbon reduction commitments to each region. In addition, the model allows accounting for lost income to oil producers, which plays a crucial role in defining the cost of carbon policies by region.

The paper is structured as follows. Section 2 describes the underlying set of axioms that define the formulas. In Sec. 3, we discuss the targets submitted within the Copenhagen framework. We use the model to project them and assess their degree of progressivity. We then use the projected figures to calibrate the formulas and project future targets for all regions throughout the century. Section 4 discusses the resulting targets and Sec. 5 what they imply in terms of economic and environmental consequences. Finally, Sec. 6 concludes.

2. A Framework to Set Emissions Targets for all Countries and all Decades

Virtually all the many existing proposals for a post-Kyoto agreement are based on scientific environmental objectives (e.g., stabilizing atmospheric CO_2 concentrations at 380 ppm in 2100), ethical/philosophical considerations (e.g., the principle that every individual on earth has equal emission rights), economic cost–benefit analyses (weighing the economic costs of abatement against the long-term environmental benefits), or some combination of these considerations.[3] This paper studies a way to allocate emission targets for all countries, 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, ethics, or economics alone.[4]

2.1. *Before Copenhagen*

At the 2007 UNFCCC Conference of Parties in Bali, governments agreed on a broad long-term goal of cutting total global emissions in half by 2050. At a 2009 meeting in L'Aquila, Italy, the G8 leaders agreed to an environmental goal of limiting the temperature increase to 2°C, which is thought to correspond roughly to a GHG concentration level of 450 ppm (or approximately 380 ppm CO_2 only).

These meetings did not come close to producing agreement on who would cut how much in order to achieve the lofty stated goals. Further, the same national leaders are unlikely still to be alive or in office when realistic multilateral targets to reach these goals would come due. For this reason, the aggregate goals set out in these contexts cannot be viewed as anything more than aspirational.

Industrialized countries did, in 1997, agree to national quantitative emissions targets for the Kyoto Protocol's first budget period (2008–2012), so in some sense we know that agreements on specific emissions restrictions are possible. But nobody has ever come up with an enforcement mechanism that simultaneously imposes serious penalties for non-compliance 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 relatively weak enforcement mechanisms such as the power of moral suasion and international opprobrium or possibly trade penalties against imports of carbon-intensive products from non-participants. It is safe to say that, in the event of a clash between weak enforcement mechanisms and the prospect of a large economic loss in a particular country, aversion to the economic loss would likely win out.

[3] Important examples of the science-based approach, the cost–benefit-based approach, and the rights-based approach, respectively, are Wigley *et al.* (2007), Nordhaus (1994, 2008), Baer *et al.* (2008) or Cao (2009).

[4] Chakravarty *et al.* (2009) and German Advisory Council on Global Change (2009) propose gradual convergence of per capita targets. Llavador *et al.* (2011) propose convergence in welfare per capita. Numerous others have offered their own thoughts on post-Kyoto plans, at varying levels of detail, including Aldy *et al.* (2001), Aldy and Stavins (2008), Barrett (2006), Barrett and Stavins (2003), Bierman *et al.* (2010), Birdsall *et al.* (2009), Carraro and Egenhofer (2003), Kolstad (2005), Nordhaus (2006), Olmstead and Stavins (2006), Seidman and Lewis (2009) and Stern (2007, 2011). Aldy *et al.* (2003) and Victor (2004) review a number of existing proposals. Aldy *et al.* (2010) offers a more comprehensive survey.

2.2. *A framework to last a century*

Unlike the Kyoto Protocol, the plan studied here 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 5- or 10-year horizon. Fixing precise numerical targets a century ahead is impractical. Rather, there will have to be 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 a framework for addressing climate change hope to last a century or more.

2.3. *Political constraints*

We take five political constraints as axiomatic:

(1) The U.S. 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 as a "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, 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 if post-1990 increases were *permanently* "grandfathered", then countries that have not yet agreed to cuts would have a strong incentive to ramp up emissions in the interval before they

joined. Countries cannot be rewarded for having ramped up emissions far above 1990 levels, the reference year agreed to at Rio and Kyoto. Of course there is nothing magical about 1990 but, for better or worse, it is the year on which Annex I countries have until now based their planning.[5]

(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). For now, we set *Y* at 1%. We return to this point in the concluding section, to discuss the trade-off between economic losses and the environmental objective.

(5) No country will accept targets in any period that re 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. For now, we set *X* at 5%. Again, we return to this point below.

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 U.S., the U.S. 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 only one possible solution, only one knife-edge position satisfies the constraints. At the same time the U.S. agrees to binding emission cuts in the manner of Kyoto, 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 consider 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 by making 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[6] 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.

It is important to stress again that environmental damages do not play any explicit role in our set of axions. We start from the assumption that emissions need to be curbed, but we do not presume to be able to make the choice of how ambitious the

[5]If the international consensus were to shift the base year from 1990 to 2005, our proposal would do the same. 10 countries that accepted targets at Kyoto continued at Cancun to define their targets relative to 1990, including the E.U. (counted as one country). Australia shifted to 2000 as its point of reference, Canada and the U.S. to 2005. The latter three countries were reflecting the reality of current emission levels that by then had risen very far above their 1990 levels. But our Latecomer Catchup Factor fulfills the same function.

[6]Frankel (1999, 2005, 2007) and Aldy and Frankel (2004). Some other authors have made similar proposals.

overall environmental goal should be. Our approach is rather to consider what method of allocating across countries any given global emissions total is likely best to satisfy the principles of economic and political feasibility.

We narrow down the broad family of possible formulas to a manageable set, by the development of three factors: A short-term Progressive Reductions Factor, a medium-term Latecomer Catch-up Factor, and a long-run Gradual Equalization Factor (GEF). 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. Next, these targets are fed into the WITCH model to see the economic and environmental consequences. 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 framework. Such adjustments would be made by negotiators along the way, as future environmental, technological, and economic developments turn out to depart from forecasts in current models.

Assigned emissions targets are only a starting point. International trading in emission permits plays an important role, allowing emissions to be reduced in the geographical pattern that is most efficient economically, which differs from the pattern of emission permits across countries. International trading is necessary to reduce the cost to the world economy of reducing total emissions by a given amount, in that it is far cheaper to pay China not to build a new coal-fired power plant than to shut down a perfectly operational coal-fired plant in the U.S. In addition, the ability to sell permits gives developing countries like China and India an important financial incentive to join the system, in that it would leave them with net economic gains in the early years.

Each country would be given a quantity of permits equal to its assigned target. As we see it, the government in many countries would choose to be the agent that trades with other countries. A country like the United States, however, might choose to implement its national target by a comprehensive domestic system of allocating permits (whether by auctions, direct distribution, or a combination of the two) to domestic residents (in particular to corporations with nationality determined by country of legal residence) and then giving domestic residents the ability to trade permits directly with other countries.[7] In any case, the price of permits would be determined in a relatively integrated global market, thus working to equalize the marginal cost of abatement geographically.

[7]In a country like the U.S., a proposal that the federal government transfers large sums of money to foreign governments, including some suspected of corruption, would meet strong opposition. Passing to domestic corporations the right to buy permits abroad would help defuse the political opposition, because it would be recognized that the corporations would only exercise this right voluntarily, to reduce economic costs. Another fundamental way to address widespread concerns about international trading is to design a system where targets are achieved more by domestic changes in emissions than by international trade. Our proposal turns out to have this property, as a side-effect of the principle that the target formula assigns heavy weight to BAU numbers.

3. The Post-Copenhagen Submissions as Quantitative Starting Points

Countries are expected to agree to the second step, quantitative targets that entail specific cuts below BAU, at a time determined by their circumstances. The starting dates are chosen so that lower-income countries are not asked to go before higher-income countries. In some cases, we adjusted the starting dates to help particular countries or regions satisfy political constraints 4 or 5. As already noted, this approach assigns emission targets in a way that is more sensitive to political realities than other proposed target paths. Specifically, numerical targets are based (a) on commitments that political leaders in various key countries have already proposed or adopted, as of December 2010, and (b) on formulas designed to assure latecomer countries that the emission cuts they are being 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.

3.1. *The Cancun targets*

Table 1 summarizes the quantitative targets submitted under the Copenhagen Accord and recognized in Cancun in December 2010. Most countries defined their targets relative to their 1990 emission levels (as was done in the Kyoto Protocol), some relative to a more recent base year (usually 2005) and some relative to BAU (a baseline that is more subject to interpretation). When evaluating the Latecomer Catch-up Factor, we will want to express targets relative to 1990. When evaluating the Progressive Reduction Factor, we express the targets relative to BAU as estimated by the WITCH model (not by the country itself), shown in the last two columns of the table. For all non-OECD countries, we assume that caps imposed before 2025 are no more stringent than BAU levels. Even though a few individual countries expressed readiness for caps that bind more sharply at Copenhagen and Cancun (e.g., Brazil's 2020 pledges), we do not feel that it would be appropriate to extend such commitments to the entire region in which such countries are located (e.g., Latin America).

A detailed description of each target is provided in Appendix A.

3.2. *"Fair" emission targets*

Economists usually try to avoid the word "fair", since it means very different things to different people. In the context of climate change policy, "fair" to industrialized countries implies that they should not have to cut carbon emissions if the emission-producing industries are just going to relocate to developing countries that are not covered by the targets. Our plan addresses this concern by assigning targets to all countries, rich and poor, thus precluding leakage, even if in some cases they are only BAU targets.

"Fair" to developing countries means that they should not have to pay economic costs that are different in nature than those paid by industrialized countries before them, taking into account differences in income. Our plan addresses this concern by

Table 1. Quantitative emission targets for 2020 submitted at Cancun under the Copenhagen Accord.

Country	Pledge at COP15	Greenhouse Gases Emissions (GT CO2-eq)									Copenhagen Pledges							
		Excluding LULUCF			LULUCF			Total			Target		wrt 1990 (%)		wrt 2005 (%)		wrt BaU (%)	
		1990	2005	2020	1990	2005	2020	1990	2005	2020	LC	HC	LC	HC	LC	HC	LC	HC
Australia	−5%, −15% to −25% wrt 2000	0.42	0.53	0.62	0.02	0.02	0.01	0.44	0.54	0.63	0.48	0.37	11	−15	−11	−32	−23	−41
Belarus	−5/−10 wrt 1990	0.14	0.08	0.10	0.00	0.00	0.00	0.14	0.09	0.10	0.13	0.13	−6	−11	56	48	29	22
Canada	−17 wrt 2005	0.59	0.73	0.83	0.02	0.04	0.04	0.62	0.77	0.88	0.65	0.65	6	6	−16	−16	−26	−26
Croatia	−5 wrt 1990	0.03	0.03	0.04	0.00	0.00	0.00	0.03	0.03	0.04	0.03	0.03	−5	−5	−2	−2	−20	−20
Euro 27	−20/−30 wrt 1990	5.57	5.12	6.13	0.02	0.01	0.02	5.59	5.13	6.15	4.47	3.91	−20	−30	−13	−24	−27	−36
Iceland	−30 wrt 1990	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	−30	−30	−36	−36	−44	−44
Japan	−25 wrt 1990	1.27	1.35	1.54	0.02	0.02	0.02	1.29	1.38	1.57	0.98	0.98	−24	−24	−29	−29	−38	−38
Kazakhstan	−15 wrt 1992	0.36	0.24	0.26	0.00	0.00	0.00	0.36	0.24	0.26	0.31	0.31	−16	−16	29	29	18	18
New Zealand	−10 to −20 wrt 1990	0.06	0.08	0.09	0.00	0.00	0.00	0.06	0.08	0.09	0.06	0.05	−9	−19	−28	−36	−37	−44
Norway	−30/−40 wrt 1990	0.05	0.05	0.06	0.00	0.00	0.00	0.05	0.05	0.06	0.03	0.03	−32	−42	−36	−46	−44	−52
Russian Federation	−15/−25 wrt 1990	3.32	2.12	2.31	0.06	0.04	0.01	3.38	2.16	2.32	2.83	2.50	−16	−26	31	16	22	8
Switzerland	−20/−30 wrt 1990	0.05	0.05	0.06	0.00	0.00	0.00	0.05	0.05	0.06	0.04	0.04	−23	−32	−22	−31	−32	−40
Turkey	BaU	0.19	0.33	0.40	0.00	0.00	0.00	0.19	0.33	0.40	0.40	0.40	115	115	22	22	—	—
Ukraine	−20 wrt 1990	0.93	0.42	0.52	0.00	0.00	0.00	0.93	0.42	0.52	0.74	0.74	−20	−20	75	75	44	44

Table 1. (*Continued*)

Country	Pledge at COP15	Greenhouse Gases Emissions (GT CO2-eq)									Copenhagen Pledges							
		Excluding LULUCF			LULUCF			Total			Target		wrt 1990 (%)		wrt 2005 (%)		wrt BaU (%)	
		1990	2005	2020	1990	2005	2020	1990	2005	2020	LC	HC	LC	HC	LC	HC	LC	HC
United States	−17 wrt 2005	6.11	7.10	8.23	0.07	0.03	0.00	6.18	7.13	8.23	5.90	5.90	−5	−5	−17	−17	−28	−28
Brazil	−0.97/−1.05 GtCO2-eq wrt BaU	0.72	1.11	1.53	0.89	1.45	1.13	1.61	2.56	2.66	1.68	1.61	4	0	−34	−37	−37	−40
China	carbon intensity of output by 40–45	3.72	7.61	10.75	0.04	0.03	−0.28	3.76	7.64	10.47	10.47	10.47	179	179	37	37	—	—
India	carbon intensity of output by 20–25	1.33	2.05	2.59	0.05	0.04	0.01	1.38	2.09	2.60	2.60	2.60	89	89	24	24	—	—
Indonesia	−26/−41 wrt BaU	0.45	0.73	1.13	0.41	0.84	0.49	0.86	1.57	1.62	1.20	0.96	40	12	−24	−39	−26	−41
Mexico	−51 Mt CO2-eq/ −30 wrt BaU	0.45	0.61	0.84	0.03	0.04	0.03	0.48	0.65	0.87	0.82	0.61	71	27	26	−6	−6	−30
South Africa	−34 wrt BaU	0.34	0.44	0.51	0.00	0.00	0.00	0.35	0.44	0.51	0.34	0.34	−2	−2	−23	−23	−34	−34
South Korea	−30 wrt BaU	0.30	0.67	0.79	0.00	0.00	0.00	0.30	0.67	0.79	0.55	0.55	84	84	−18	−18	−30	−30

Source: Calculations based on Business as Usual (BaU) scenarios of the WITCH model prepared for The Emission Gap Report, United Nations Environment Program; adjustments were made when countries are not individually represented in the WITCH model.

including in the formula the Progressive Reductions Factor, β, which in the early years assigns to richer countries targets that cut more aggressively relative to BAU, as well as the GEF, ϕ which dictates that in the long run all countries converge in the direction of equal emission rights per capita.

Moreover, countries that are not restraining emissions in the short run should not be rewarded for emitting while others are making mitigation efforts. This is accounted for by means of a Latecomer Catch-up Factor, λ.

3.3. *Choice of parameters*

We perform our analysis with values for parameters based on econometric estimation of the equation parameters from the actual Copenhagen–Cancun submissions. (results are provided in the Appendix). This allows us to test whether the political process actually worked along the lines of our formulas, which would suggest that we have correctly distilled what is implicitly considered "fair" in international negotiations. It also allows us to use the numbers in order to project the same reasoning into the future.

We regress emission cuts in 2020 derived from countries' actual statements, including all the Cancun targets, but expressed with respect to baseline emissions (BAU), against current income per capita. The degree of progressivity is seen to be highly significant statistically (the full set of results is reported in Appendix B). We also use the Copenhagen–Cancun submissions to estimate the parameters for latecomer catch-up together with the progressivity parameter (these results are presented in Appendix B as well). The idea is that countries that are not restraining emissions should not be rewarded for emitting while others are making mitigation efforts. Based on numbers estimated from the 2020 targets, any country in its first commitment period, t, should obey the following formula:

$$(\text{LnTarget}_t - \text{lnBAU}_t) = c - \gamma(\ln \text{IPC}_\tau) + \beta(\ln \text{emissions}_\tau - \text{lnBAU}_t) - \beta\lambda(\ln \text{emissions}_\tau - \ln \text{emission}_{1990}) \quad (1)$$

where the progressivity parameter γ is 1.4 (IPC stand for income per capita), the latecomer catch-up λ is 0.9, τ is the period the agreement is signed (with $\tau < t$), and the parameter β is 0.4.

We have all along intended that the latecomer catch-up process would be complete within a few decades, in other words that the partial accommodation accorded to countries that have ramped up their emissions between 1997 and 2012 would not be long-lasting. Thus, where we extend the analysis to modify parameter values in light of the Copenhagen–Cancun submissions, we set $\lambda = 1.0$ in the second period of cuts (call it year $t + 1$), so that the equation in that case becomes:

$$(\text{LnTarget}_{t+1} - \text{lnBAU}_{t+1}) = c - \gamma(\text{IPC}_t) - \beta(\text{lnBAU}_{t+1} - \ln \text{emissions}_{1990}). \quad (2)$$

In words, the level of emissions during this the period when the agreement is signed drops out of the equation as early as the second period of cuts for any given country.

Starting in that period, the formula for the target becomes a weighted average of BAU and 1990 emission levels (minus the usual Progressive Reduction Factor) and β is now the weight placed on 1990 emissions, versus BAU.

The third component of the formula is the GEF. Beginning in 2050, we switch to a formula that in each period sets assigned amounts in per capita terms, as follows: A weighted average of the country's most recent assigned amount and the global average, with a weight of δ on the latter. We set the constant term $c = 0.8$[8] and $\delta = 0.11$.

To explore more stringent environmental goals, one could adjust the constant term down in order to force a more rapid decarbonization. In the exercise that is the central focus of this paper, the choice of parameters corresponds to an environmental objective of 500 ppm CO_2 concentrations in 2100.

3.4. *Constraints on economic costs*

We assume that countries determine whether or not to join the climate change regime and abide by any agreement by balancing the costs and benefits, broadly interpreted. The benefits to a given country from participating are not modeled in the analysis. That is, the damage function is switched-off. But they would include the country's contribution to mitigating global climate change itself (which is less important for small countries), auxiliary benefits such as the environmental and health effects of reducing local air pollution, the avoidance of international moral opprobrium, and perhaps the avoidance of trade penalties against non-participants. The benefits that some countries get from the right to sell emission permits are explicitly counted within (net) economic costs.

We capture the cost–benefit calculation by interpreting political constraints as precluding that a country agrees to participate if the targets would impose an economic cost greater than $Y\%$ of income in terms of present discounted value. In other words, Y can be interpreted as the sum of the benefits of participation. If costs exceed benefits, the country will defect. We further assume that political constraints preclude that a country will continue to comply with an agreement if the targets would impose a cost in any one period greater than $X\%$ of income. In Frankel (2009), X was set at 5% of income, and Y at 1%. Bosetti and Frankel (2012) allowed looser constraints.

What is the benchmark to which each country compares participation when evaluating its economic costs? In our previous work, we assumed that the alternative to participation is BAU: what the world would look like if there had never been a serious climate change agreement in the first place. This may indeed be the relevant benchmark, especially when the X threshold for the present discounted value of cost is interpreted as determining whether countries agree to the treaty ex ante, each

[8]We make an exception to our general practice of applying a uniform formula to all: We give the transition economics (TE) group a constant term of 0.5 rather than 0.8 (to allow for the special circumstances of their obsoletely high emissions in 1990).

conditional on the others agreeing. Treaties like the Kyoto Protocol do not go into effect unless a particular high percentage of parties ratify the treaty. There was room for no more than one large holdout.

In this study, we contrast this widely adopted criterion for measuring each country's economic costs with one that better suits the fundamental Nash theory of the sustainability of cooperative agreements. In the classic prisoner's dilemma, the two players are doomed to the Nash non-cooperative equilibrium if each calculates that he will be better off defecting from the cooperative equilibrium *even if the other does not defect*. But the cooperative equilibrium is sustainable if every participant figures that the benefits of continuing to cooperate outweigh the costs, taking the strategies of the others as given. We will use the phrase "Nash criterion" to describe the way of measuring economic costs to each country participating in the agreement relative to an alternative strategy of dropping out while others stay in.

Therefore, we introduce here a new interpretation of the political constraint. Each country calculates the economic benefit of dropping out of an agreement *under the assumption that the rest continue to participate*, which we call the Nash criterion for evaluating the economic cost of participating. If that economic benefit exceeds X% of GDP in any given year, the country will drop out. In that case — perhaps — the entire agreement will unravel, as other countries make similar calculations. If this weakness is perceived from the beginning, then the agreement will never achieve credibility in the first place.[9]

The Nash criterion may sound like a more difficult test to meet than the earlier one. If one adds the gains from free-riding to the costs of compliance with an agreement, then it sounds less likely that we will find 500 ppm or any other given environmental target to satisfy the constraint that economic costs remain under the threshold for sustainable cooperation. But that would be to view the question solely from the viewpoint of the many countries for whom a viable international climate regime is a good thing. From the viewpoint of most oil producers, any international climate regime reduces the demand for fossil fuels and so probably leaves them worse off. Free riding on others' efforts is not a meaningful concept in their case. For the oil producers, therefore, defining the benchmark as the case where they drop out alone but the rest of the world stays in produces lower estimated costs to abiding by the agreement. The global oil price is going to go down regardless. This could make the cost–benefit test easier to meet than under the earlier criterion.[10]

Middle East and North Africa (MENA) shows up with far higher costs than was true in our earlier research. The reason is that many countries in the MENA are oil

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[9]Among those emphasizing the "time inconsistency" of leaders' promises to cut emissions in the future are Helm *et al.* (2003).

[10]The test of sustainability becomes easier to satisfy if the oil exporters are the ones who are otherwise in most danger of violating the *X* and *Y* thresholds. This in fact turns out to be the case in our estimates. (The test would become *harder* to satisfy if the other countries, those that want a climate change regime to work, are the ones who are most in danger of violating the *X* and *Y* thresholds.)

exporters, and the current version of the WITCH model pays more attention to the economic costs imposed on oil producers from a decline in world demand for fossil fuels. We presume these cost estimates to be well-founded. Therefore, to reduce them we now grant MENA a later starting date. The same is true to an extent of costs estimated for the TE and Canada. When pursuing the more ambitious environmental goal, in Sec. 7, we let the TE countries keep the hot air that is implicit in their Cancun submissions, in order to bring down their costs. Among the countries not considered as oil producers, the category that includes Korea, South Africa, and Australia generally shows the highest costs, especially toward the end of the century. This turns out to be attributable to an assumption of the model that these countries include deposits of "unconventional oil" such as tar sands that could become profitable later in the century, but that are penalized by a climate change regime along with the conventional oil producers. We are not convinced that the potential for these "oil grades 7 and 8" is necessarily well-founded and so we have chosen to emphasize in our simulations a version of the model that omits them, with the result that costs are not so high for Korea, South Africa, and Australia.

4. The Numerical Emission Target Paths that Follow from the Formulas

Table 2 reports the starting points of binding emissions targets for each of 12 geographical regions. The 12 regions are:

E.U. = Western Europe and Eastern Europe
U.S. = United States
CAJAZ = Canada, Japan, and New Zealand
MENA = Middle East and North Africa
INDIA = India

Table 2. Target starting points for the 12 modeled regions (the case of 500 ppm goal).

	2020	2050
E.U.	30% below 1990 emissions	50% below 1990
USA	17% below 2005	83% below 2005
Australia, S.Africa and S.Korea	34% below baseline	50% below baseline
Japan, Canada and NZ	30% below 2005	65% below 2005
TE	BAU	Cap based on formula in 2055
LAM	BAU	Cap based on formula in 2040
India	BAU	BAU (cap based on formula, from 2060)
EASIA	BAU	BAU (cap based on formula, from 2060)
SASIA	BAU	BAU
CHINA	BAU	Cap based on formula in 2050
SSA	BAU	BAU
MENA	BAU	Cap based on formula in 2065

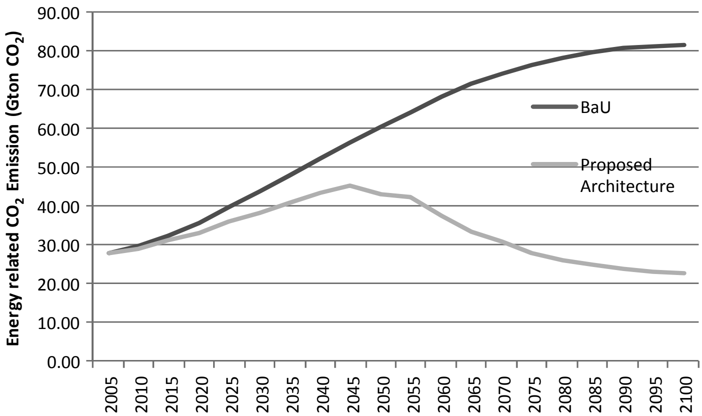

Figure 1. Global emission targets resulting from the formula, 500 ppm goal

CHINA = PRC
EASIA = Smaller countries of East Asia
KOSAU = Korea, South Africa, and Australia
TE = Russia and other Transition Economies
SSA = Sub-Saharan Africa
SASIA = rest of South Asia
LAM = Latin America and the Caribbean

Starting at the most highly aggregated level, Fig. 1 shows global emissions resulting from the projected targets. The path is a bit more aggressive than in previous work, as a reflection of the pledges made at Cancun. The emissions peak comes in 2045.[11] Cuts steepen after 2050, with the result that energy-related emissions worldwide fall from a level over 40 Gigatons (Gt) of CO_2 in 2040, to 20 Gt in 2100, one quarter of their BAU level.

How important is it that all countries/regions participate? If one country drops out and others respond by doing the same, so that the result is to unravel the entire agreement, then obviously the effect is very large. But what if just one country or region drops out, or fails to sign up in the first place? Fig. 2 examines this question. The bottom path represents full cooperation, the same as in Fig. 1: All countries sign up and continue to participate throughout the century. If South Asia alone refuses to play, the result is the next-lowest emissions path; it hardly makes any difference for global emissions as these economies are small. If Canada, Japan, and New Zealand are the only ones to drop out, the effect is just a bit more, and so on. The uppermost path shows what happens if China alone drops out. It represents a big jump in emissions over the second highest path (the case where India alone drops out), or the third highest

[11]Remarkably, this happens to correspond to the cost-efficient path found by Manne and Richels (1996, 1997), wherein global emissions peak in 2040–2050.

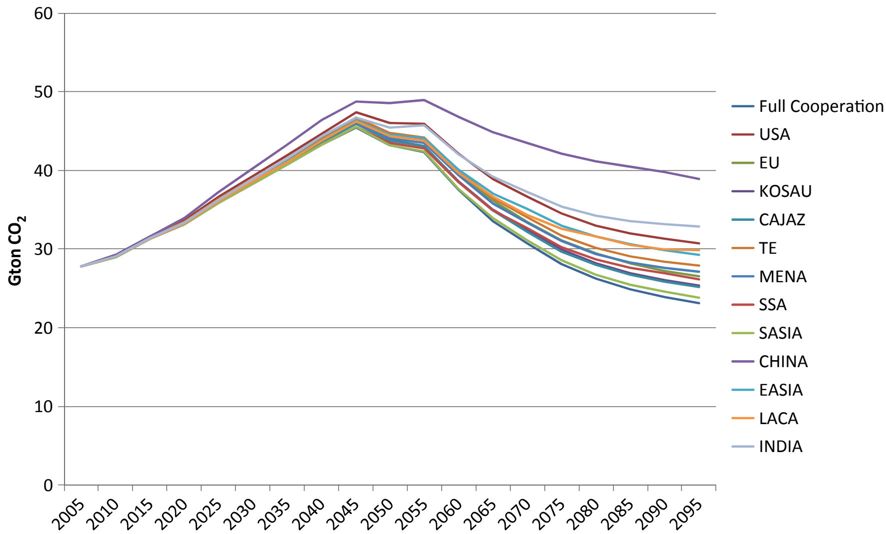

Figure 2. Global emission if one drops out, but cooperation otherwise continues

(where the U.S. alone drops out). This illustrates that Chinese participation is the sine qua non of a successful global effort to address climate change, followed in importance by the participation of India and the U.S. It is more than noteworthy that these three big countries did not accept targets under the Kyoto Protocol.[12]

Next we disaggregate between industrialized countries and developing countries. Figure 3(a) shows the former, defined now as members of the Organization for Economic Cooperation and Development (Annex I countries excluding TE). Emissions begin to decline as early as 2010, reflecting a real-world peaking of targets around 2007 and recalibration of baselines caused in large part by the global recession that reduced industrial country activity sharply in 2009[13] (Targets go on to decline from about 13 Gt of CO_2 in 2010 to less than 3 Gt of CO_2 in 2100).

The graph also shows the simulated value for actual emissions of the rich countries, which decline more gradually than the targets through mid-century because carbon permits are purchased on the world market, as is economically efficient. The total value of the permit purchases runs about 6 Gt of CO_2 in the middle decades of the century and then declines.

[12]In each of the "Nash" simulations, where one country drops out at a time, it turns out that the free riding country emits less than it would in the BAU baseline. According to the WITCH model, they take the opportunity from the cost improvements in the carbon-free technologies among those countries that continue to participate and this outweighs the conventional leakage effects (according to which they consume more fossil fuels because the world price is reduced and they expand production in energy-intensive sectors because they gain a competitive advantage).

[13]That the peaking of rich-country emissions is attributable to the 2009 recession is consistent with the failure of most models to predict the peak (absent strong climate change policy). In Frankel (2009), emissions did not begin to fall until 2025. Even in the more aggressive policy scenario of Bosetti and Frankel (2012), they only peaked in 2010 and began to fall in 2015.

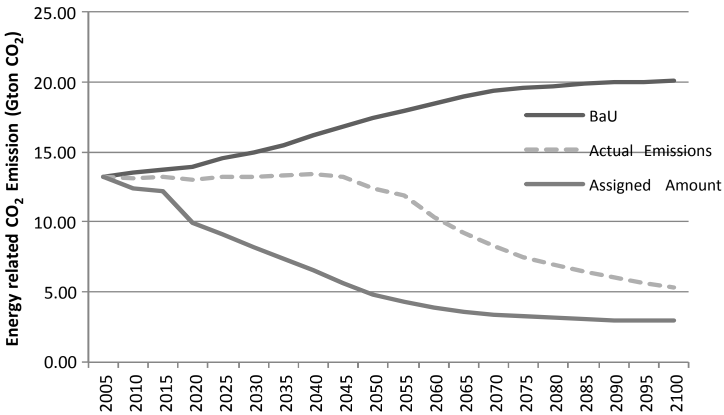

Figure 3(a). Targets and emission by OECD countries under the 500 ppm goal

Figure 3(b) shows that among non-OECD countries overall, both emissions targets and actual emissions peak in 2045. 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. Thanks to emission permit sales, actual emissions fall below the BAU path, though still rising before developing countries are forced to cut by more aggressive targets after 2045. The total falls from the peak of about 38 Gt of energy-related CO_2 emissions in 2045 to less than half that in 2100. The year-2100 emissions are about one third of the BAU level for that year.

Other things being equal, it is desirable that the rich countries does not achieve too large a share of emission reductions in the form of permit purchases. This outcome holds as a side-effect of formulas that give weight to BAU numbers when allocating emission targets across countries.

The bar chart in Fig. 4 expresses emissions in per capita terms, for every region in every budget period. The U.S., even more than other rich countries, is conspicuous by

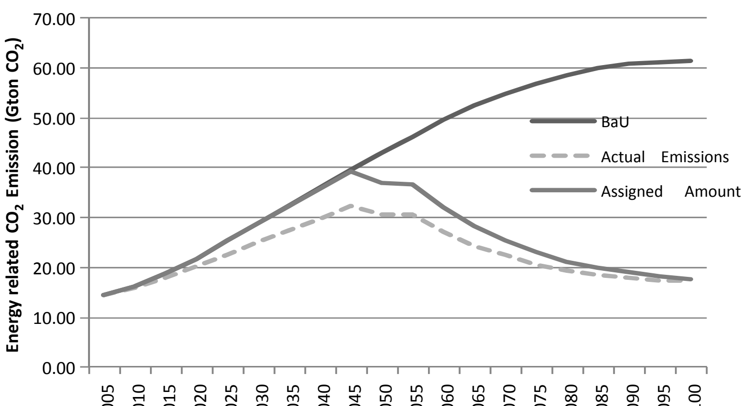

Figure 3(b). Targets and emission by developing countries under the 500 ppm goal

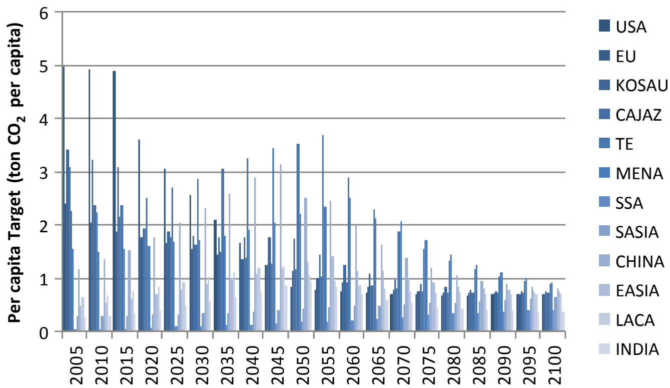

Figure 4. Per capita emission targets under the 500 ppm goal

virtue of its high per capita emissions: close to 5 tons CO_2 per capita. But they start to come down after 2015, like the other rich regions. 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 almost 3 tons CO_2 per capita in 2040. Other developing countries rarely get above 1 ton CO_2 per capita; India climbs just over 1 ton per capita briefly at the peak in 2060. In the second half of the century, everyone converges toward levels below one ton per capita, thanks to the gradual equalization formula.

5. Consequences of the Targets, According to the WITCH Model

We run these emission levels through the WITCH model to see the effects. Before we turn to the costs in terms of lost income, which is the measure of economic welfare that is most relevant to economists, we look first at the effect on the price of energy, which is politically salient and also a good indicator of the magnitude of the intervention.

5.1. *Economic effects*

Figure 5 reports that the price of carbon remains quite reasonable through 2045, but then begins to climb steeply. By 2100 it surpasses \$250 per ton of CO_2. Many in the business world would consider this as a very high price. The effect translates into an increase in the price for U.S. gasoline around \$2.5 per gallon. Needless to say, this idea would be extremely unpopular, although the increment is on the same order of magnitude as petrol taxes today in Europe and Japan.[14]

[14]The prices for carbon and gasoline here are substantially less than the prices estimated in Frankel (2009), let alone Bosetti and Frankel (2012). The explanation is partly the greater attention paid to wind and to gas plus CCS, but mainly because of bio energy with CCS. The lower the number of carbon-free alternatives, the larger the role for energy saving. The implication was a higher price of carbon but also lower amounts of carbon in the economy.

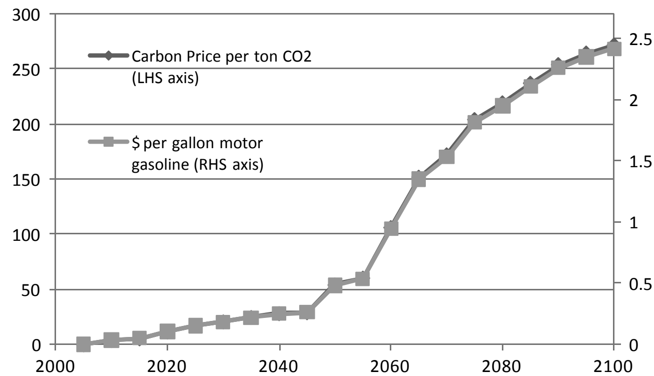

Figure 5. Effect on energy prices, under 500 ppm goal.

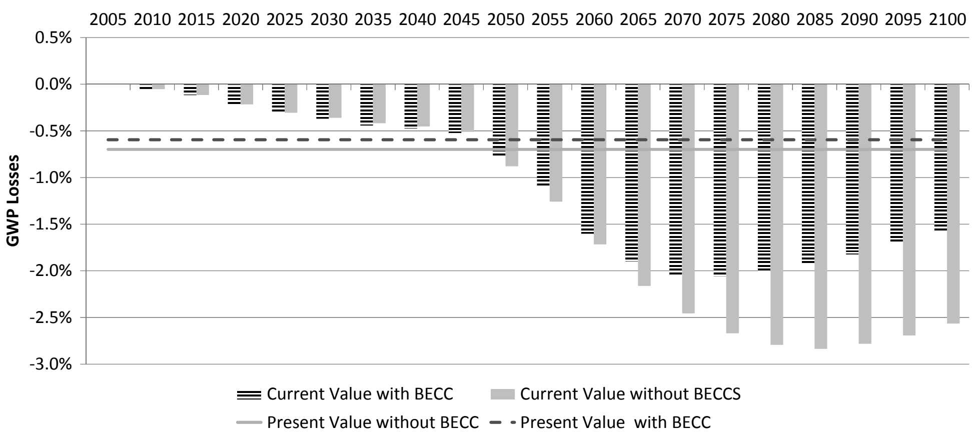

Figure 6. Global economic costs (% of income) of 500 ppm goal (*with* and *without* BE & CCS)

Global economic losses measured in terms of present and current values of national income losses are illustrated in Fig. 6. For the case where bio energy with CCS is excluded, lighter markers and columns are used, and the one that allows for bio energy and CCS, darker colors are used.[15] In the former case, cost rises gradually over time up to 2085. Given a positive rate of time discount, this is a good outcome.[16] As late as 2050, they remain below 1% of income. In the latter part of the century losses rise but never exceed 3% of income. If we look at the case with bio energy and CCS, now

[15]Other measures of cost could be considered, for example, welfare losses or total losses including the avoided climate damage. In this paper, we decided to concentrate on pure mitigation costs. We adopt the most common metrics, in order to increase comparability with other studies.
[16]Tol (1998).

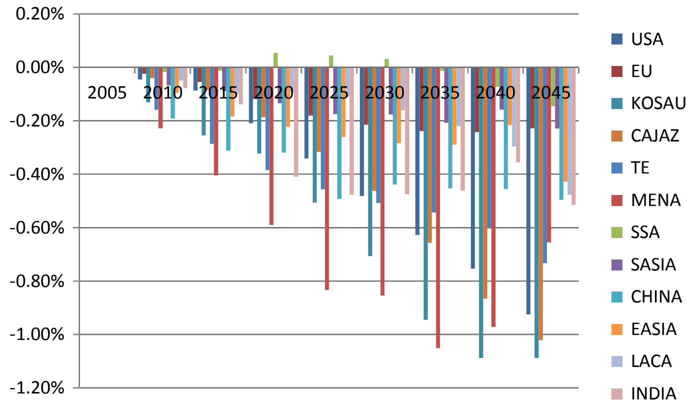

Figure 7(a). Economic losses (% of income) of each region, under 500 ppm goal, 2010–2045

global costs stay below 2.1% of income even late in the century. Either way, the present discounted value of global costs is less than 0.7% of income, using a discount rate of 5%.

Figures 7(a) and 7(b) report the economic costs country by country, for the first and second halves of the century, respectively.

Until 2050, costs remain below 1.2% of income for every country or region. In the second half of the century they rise, for the Annex I countries of Kyoto in particular. But for every country and in every budget period, the cost remains under 5% of income. This is good news: it is the (admittedly arbitrary) threshold that we have used from the beginning, under the logic that no government could afford politically to continue to abide by an agreement that was costing the country more than 5% of income. It would make no difference if such a country had benefited from permit sales in the early years or even suffered no loss at all in present discounted value; large

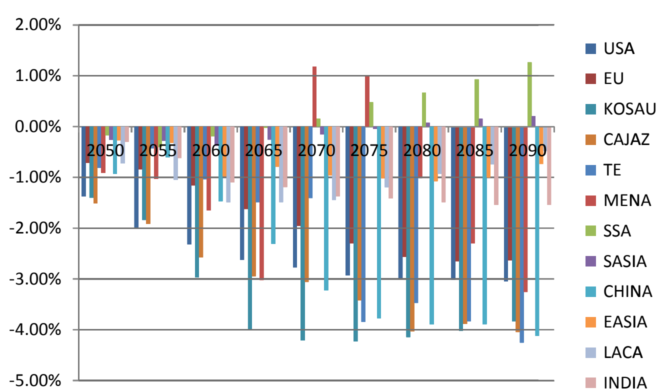

Figure 7(b). Economic losses, 2050–2090

Table 3. Present discounted value of cost, region by region (as percent of income) (a) Measured relative to alternative baseline of no international policy (i.e., BAU criterion), (b) Measured relative to the alternative of unilateral dropping out while others continue to cooperate (i.e., Nash criterion).

	USA	E.U.	KoSAu	CaJaZ	TE	MENA	SSA	SAsia	China	EAsia	LAm	India
(a)	0.6%	0.2%	0.7%	0.7%	1.2%	2.2%	−0.1%	−0.2%	1.1%	0.1%	0.5%	0.4%
(b)	0.7%	0.3%	0.8%	0.6%	0.8%	0.8%	−0.1%	0.1%	1.0%	0.4%	0.4%	0.7%

potential losses in later years would render any earlier commitments dynamically inconsistent.

Our other political constraint is that no government will sign its country up for an agreement that in ex ante terms is expected to cost more than a particular threshold, which Frankel (2009) — again arbitrarily — set at 1% of income. Table 3 reports the present discounted value of economic losses for each country or region, using a discount rate of 5%. In Table 3(a), the question is how much it costs the country in question to participate if the alternative is the case where there never was an operational international climate policy in the first place, in other words BAU. The range of economic burdens across countries is wide. It is close to zero for India and other poor countries.[17] But it is as high as 2.2% of income for the Middle East and North Africa, well above our desired threshold as discussed in axiom 4, and 1.2% for the Transition Economies.[18] It lies in between for the United States, at 0.6% of income.

One could argue that the relevant criterion in deciding whether cooperation is sustainable is not whether individual countries find the economic cost to be too high relative to an alternative where there was never any international policy action in the first place, but rather whether individual countries find the cost to be too high relative to a strategy where they drop out but others continue to cooperate (i.e., a game theoretic viewpoint).

We are not claiming to prove any theorems regarding sub-game perfect cooperative equilibria. But the spirit is that the international regime imposes moderate penalties for a country that does not participate, such as international opprobrium or trade penalties against imports of carbon-intensive products, and that these penalties are in the range of the thresholds X and Y (which we have been taking as 5% and 1% of income, respectively). Under these assumptions, if the economic gain from dropping out measured by the Nash criterion is below the threshold, then cooperation would seem to be sustainable. Only if cooperation in future periods is seen to be sustainable

[17] Pakistan and other non-India countries in South Asia actually gain, from the ability to sell permits, as does Sub-Saharan Africa.

[18] Again, the cost estimates for the two regions are higher than in past research, because the WITCH model has been revised to capture the losses to oil producing countries from a reduced global demand for fossil fuels.

ex ante will the agreement be credible from the beginning. Only if the agreement is credible will firms, in turn, begin early to phase in new and existing low-carbon technologies, in anticipation of higher carbon costs in the future. Only if firms begin to phase in these technologies from the beginning will an emissions target path that begins slowly succeed in its motivation of reducing costs by allowing sufficient time for the capital stock to turn over.

Table 3(b) estimates costs by the Nash criterion. The question is how much does it cost the country in question — considering each country one at a time — to participate if the alternative is the case where it drops out of the international agreement but the other countries continue to abide by it. One might expect that the prospect of free riding would entail substantial gains for the country dropping out, i.e., that continued participation would entail substantial costs. This is the essence of leakage. Indeed the costs are higher in Table 3(b) than Table 3(a) for most of the countries, including most of the industrialized countries. But for the former members of the Soviet Bloc (TE) and especially for the MENA countries, the economic cost is much lower in Table 3(b) than in Table 3(a). The explanation is that, regardless what they themselves do, oil producers bear substantial losses when participating countries reduce their demand for fossil fuels.

The effect of switching to the Nash criterion is to narrow the range of costs across regions, so that it runs only from 0.7% of income for India to 0.8% for MENA and 1% for China. This is very important. The importance does not stem primarily from equity considerations. If equity were the driving criterion, then the benchmark would be not just a world in which no climate change policy is undertaken, but a world in which none is needed because there have not been any greenhouse gas emissions in the first place.[19] The importance stems, rather, from the game theory considerations: any country that bears especially high costs for continuing to participate is likely to drop out. But the high-cost countries are the same as those that lose rather than gain from free riding on the coalition. In Table 3(b), the costs borne by the three highest country/regions — MENA, TE, and China — are in each case below 1% of GDP, the $Y = 1\%$ threshold for every region.

The economic losses in Figs. 7(a) and 7(b) were measured according to the Nash criterion as well. That is, the bar charts show the costs to each country, considered one at a time, to staying in the agreement, relative to a strategy of dropping out under the assumption that others continue to abide by the agreement. As already noted, every country in every period shows an economic cost from participating that is less than 5%. Thus, we have succeeded in meeting the $X = 5\%$ threshold.

Figure 8 summarizes the economic costs of participation for each country or region, under the Nash criterion. For each, the first bar shows the present discounted

[19] Viewed from this perspective, places such as India and Africa could sue countries such Saudi Arabia and the United States for the damage that their cumulative past emissions are inflicting on climate-sensitive tropical regions.

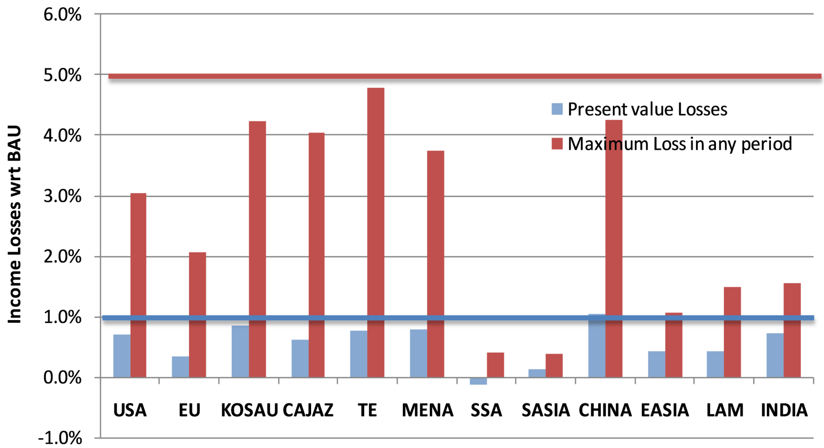

Figure 8. Economic losses for each country, by the Nash criterion, compared to X and Y thresholds

value. For all 12 regions, the cost is below 1%. To recall a lesson of Fig. 2, the regime could probably survive the defection of MENA (and also TE), but it is much less likely that it could survive the defection of China. For each region, the second bar shows the economic loss in whatever period that loss is highest. TE is the highest, almost reaching the threshold value of 5% of income. Next come China and Korea–South Africa–Australia. The finding that costs are able to stay under the thresholds is gratifying.

5.2. *Environmental effects*

Under the emission numbers considered here, the concentration of CO_2 in the atmosphere is projected to reach 500 ppm in the late years of the century. This is the implication of the choice of the parameters leading to the set of emissions targets.

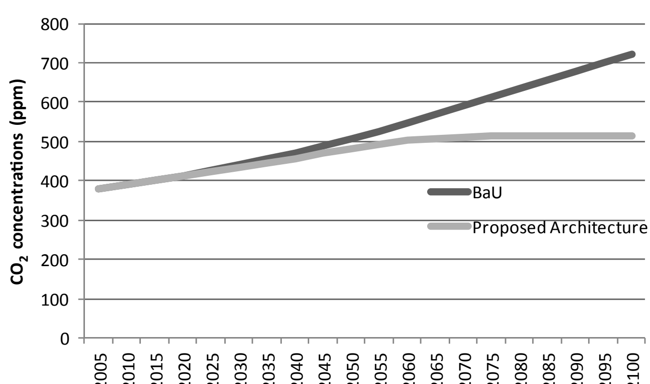

Figure 9. Path of concentrations under the 500 ppm CO_2 goal

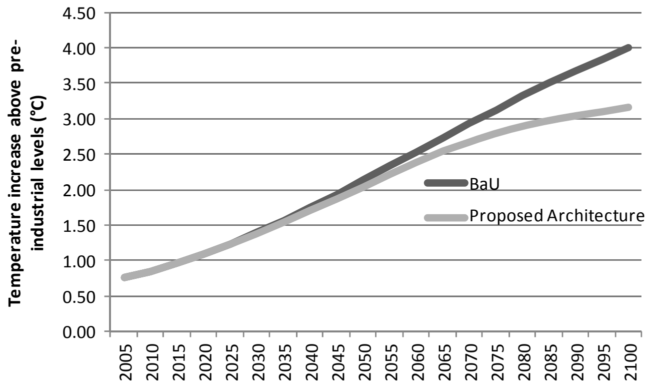

Figure 10. Rise in temperature under the 500 ppm CO_2 concentrations goal

Figure 9 shows the path of concentrations. Figure 10 shows the path of temperature, which in 2100 attains a level that is 3°C above pre-industrial levels, as compared to 4°C under BAU.

6. Concluding Perspective

The formulas (and in particular the starting periods for cuts below BAU and the GEFs) can be tuned to produce more ambitious environmental effect. With the model used here, this would lead to violations of the two cost constraints that were designed to deliver political feasibility of the target approach. One might wonder whether these higher estimated costs of mitigation are justified by estimates of the avoided costs of environmental damage.

Some economists attempt full cost–benefit analysis, to weigh economic costs of climate change mitigation against estimates of the monetized benefits of climate change mitigation, by means of integrated assessment models. Typical estimates of the monetized costs of a concentrations path corresponding to a 4° increase in year-2100 temperature (the BAU estimate), as compared to limiting the warming to 2°, are between 1% and 4% of aggregate global income.[20] This range, wide as it is, by no means spans the range of estimates by reputable economists.[21] Furthermore, many impacts that might be associated with climate change have not yet been estimated. The

[20]At the lower end of this range, the 1% of income estimate comes from Tol (2002a,b). He estimates the costs (monetized damages) of 4° of global warming at approximately 1% of income if national costs are aggregated directly and $1\frac{1}{2}$% if they are aggregated by population under an equity argument, as compared to costs of 2° warming equal to 0 or $\frac{1}{2}$% of income, respectively (see also Tol, 2005). At the higher end of this range, Nordhaus and Boyer (2000) estimate the costs of 4° of global warming at approximately 4% of income if national damages are aggregated directly and 5% if they are aggregated by population, as compared to costs of 2° at about 1% of income aggregated by either method (see also Nordhaus, 1994, 2008).

[21]Mendelsohn *et al.* (1998) estimate much lower damages from global warming, as they concentrate on agricultural impacts where adaptation would play a key role. Stern (2007, 2011) estimates much *higher* damages, attributable, in particular, to the assumption of a low discount rate, thus giving more weight to estimated damages very far into the future.

debate on how to evaluate the impact of extreme events is wide open. Thus, the mitigation scenarios studied here could be either far too mild or far too aggressive.

The wide range of the damage estimates is one reason why we prefer to leave it to society to make the tradeoff between economic cost and environmental damage and do not attempt to do so ourselves. Our focus is, rather, on how to design a framework under which cooperation is as sustainable as possible, for any given level of environmental ambition.

Some readers, especially those not familiar with the economic models of climate change policy, may be surprised at the high estimated economic costs for hitting what seem like moderate environmental goals. They can rest assure that the cost estimates of the WITCH model allow for dynamic technology effects (hence "Induced Technical Change" in the name) and tend to lie in the middle of the pack of leading economic models (for example the 11 models compared in Clarke *et al.*, 2009).[22]

But of course nobody can be sure that the estimates in these models are correct. Uncertainty regarding economic costs of mitigation is probably not as large as uncertainty regarding the avoided costs of environmental damages. Nevertheless, economic costs may turn out to be either higher or lower than estimated in our model. In future research, we plan to explore the implications of uncertainty in technology, economic growth, and the environment. A central attraction of putting the formulas approach into effect would be that the parameters could readily be adjusted in future budget periods, as more information becomes available. If technological innovations occur that reduce the cost of hitting any given environmental goal, parameters and targets can then be changed accordingly. The success of the international climate regime is much less sensitive to the designer's initial guess as to the appropriate endpoint than it is to whether the designer takes care not to impose unreasonable costs on any critical country, so that a comprehensive and credible agreement can go into effect.

Acknowledgments

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[22] Tavoni and Tol (2010) warn against the potential underestimation of projected economic costs of stringent climate targets: Only the most optimistic model results are reported, as unfeasible results are not accounted for in the aggregation.

Appendix A

Targets for E.U.

Brussels in 2008 committed unilaterally to reduce European Union (EU) emissions 20% below 1990 levels by 2020.[23] But the EU also said that it would cut emissions 30% below 1990 levels by 2020, conditional on other countries joining in. Thus, given assumptions on other countries' commitments, we now set an EU target of 30% below 1990 levels. EU targets continue their downward trajectory in the third period, 2020–2025, to 35% below 1990 levels and then progress in equal increments to a level 50% below in the eighth period, 2045–2050.

Target for Japan

Japan's Copenhagen pledge for 2020 is 25% below 1990 levels, which is 29% below 2005 levels. This is the same as what we had assumed previously, based on prime ministers' statements.

Target for U.S.

The American submission under the Copenhagen Accord is 2020 emissions at 17% below 2005 levels (which would represent the achievement of the Kyoto goal of 5% below 1990 levels, but delayed by an entire decade). We had previously taken our cue from bills in the U.S. Congress in assuming that emissions were targeted roughly to flatten between 2012 and 2020. This is more aggressive than that with respect to the near term, which is consistent with the evidence in the meantime that American emissions peaked in 2007, as a result of the ensuing recession. The Congressional bills had been aggressive in the longer term, and we follow them in assuming a year-2050 target that is 83% below the 2005 level.

Targets for Korea, South Africa and Australia

These three coal-dependent countries are grouped together. We had previously assumed that the Korean target would show flat emissions from 2005 to 2020. But Korea has persisted with more aggressive targets: its Cancun submission for 2020, though defined as 30% below BAU, translates to 18% below 2005 emissions. Similarly, with South Africa phrased as 34% below BAU, it translates to 23% below 2005. Australia is having great difficulty making up its mind. Its targets could lie anywhere from 11% to 32% below 2005. We take the South African target, 34% below BAU, to represent the threesome.

[23]Documentation of pre-Copenhagen legislation or announcements by leaders in the EU and other national governments is given in the footnotes to the 2009 working paper version of Bosetti and Frankel (2012).

Targets for Latin America

Mexico, preparing for the Cancun meeting in December 2010, felt the usual host's obligation to make a significant offer. Mexico and Brazil both suggested 2020 targets phrased relative to BAU. Brazil is the more aggressive, translating to 34% to 37% below 2005 levels. We assume that, although pledges for Brazil are stricter, Latin America overall is not yet prepared to undertake any cuts below BAU. We assume that the region is prepared to start cutting below BAU in 2040, or in 2025 when we turn to a more aggressive scenario.

Targets for East Asia

East Asia is a category here that excludes Japan, China and Korea; thus it is really Southeast Asia. Its largest member is Indonesia. Indonesia's Copenhagen target, translated from BAU terms, is in the range 24–39% below 2005 levels by 2020. But, again, we assume that the larger region is not yet prepared to be this aggressive. We continue to give BAU targets to the Southeast Asians until 2060, or until 2025 in the more ambitious case.

Targets for China and India

In important breakthroughs, China and India announced targets after Copenhagen. They expressed the targets in terms of intensity (carbon emissions divided by GDP). We, as others, estimate that these targets translate approximately into these countries' respective BAU paths. Environmentalists and American business interests may complain that these important countries do not propose to cut emissions below what they would be in the absence of an international agreement. But this has been our plan all along for China and India in the near term. The important thing is to cap their emissions and get them in the trading system. Targets below BAU come later.

Environmentalists and businessmen may come to realize that the commitment, even though only a commitment to BAU targets, is more important than it sounds. It precludes the carbon leakage which, in the absence of such an agreement, would undermine the environmental goal, and it ameliorates the competitiveness concerns of carbon-intensive industries in rich countries. A commitment to BAU targets would provide assurance that developing countries will not exploit the opportunity to go above their BAU paths, as they might in the absence of this commitment.

Our approach recognizes that it would be politically difficult to get China to agree to substantial actual cuts in the short term. Indeed China might well continue to register strong objections to being asked to take on legally binding targets of any kind at the same time as the United States. But the Chinese may be coming 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. In the absence of environmental policy, most would continue to run on cheap coal. 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. Because of this gap in costs, 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 in strictly economic terms.

Targets for former Soviet republics

Four countries report emission targets that actually work out to constitute increases above their BAU paths. These are not developing countries, but rather countries that were once part of the Soviet Union: Russia, Ukraine, Belarus and Kazakhstan. Their proposed cuts appear as the four points below the zero axis in Fig. B.1. In the case of Ukraine, the proposed target is a full 44% above its current BAU. This is because the targets keyed to 1990 for these countries were rendered obsolete, based on the judgment that their economies had collapsed following the collapse of the Soviet Union. These countries are seeking a continuation of the "hot air" that they received under the Kyoto Protocol.

One sometimes hears claims that the hot air for these countries agreed at Kyoto was inadvertent. After all, it created the potential for them to sell permits and thus get paid for emission reductions that had already occurred for reasons unrelated to the environment. This concession was in fact not inadvertent, but was judged by other delegations to be necessary to induce the former Soviet countries to agree to the Kyoto Protocol. (An additional factor in this calculation was that Russia arguably has much less of a stake in avoiding global warming than do most other countries.) The fact that other delegations judged this concession warranted in 1997 does not necessarily mean that an extension of it is warranted again today.

We will consider two cases, one where the targets for the four former Soviet countries are set equal to BAU (as estimated by us, not the countries themselves), similar to the lower-income countries, and another where they are given the extra benefits implicit in their Cancun submissions.

Appendix B

Estimating the degree of progressivity

Our first statistical exercise is to run a regression of the cuts implied by the Copenhagen–Cancun targets against the countries' current income per capita. We expect to find a positive statistical relationship between income per capita and the emission cuts, under the hypothesis that it is reasonable from a political economy viewpoint for countries to make deeper percentage cuts relative to BAU the richer they are. This is the progressive relationship that was uncovered in the Kyoto targets (Frankel, 1999, 2009): The targets agreed among Annex I countries at Kyoto in 1997, including among members of the EU considered separately, implied an estimated progressivity parameter of 0.14. Running the regression on the Copenhagen–Cancun numbers could be viewed either as an exercise in hypothesis-testing or as an exercise in parameter estimation. If our hypothesis — that it is reasonable as a matter of political economy to expect countries in their first year of emission cuts to accept larger cuts relative to BAU the higher their income — is correct, then this progressive pattern should again show up in the numbers recorded under the Cancun agreements. Alternatively, we could use the regression to obtain a new estimate of the progressivity parameter.

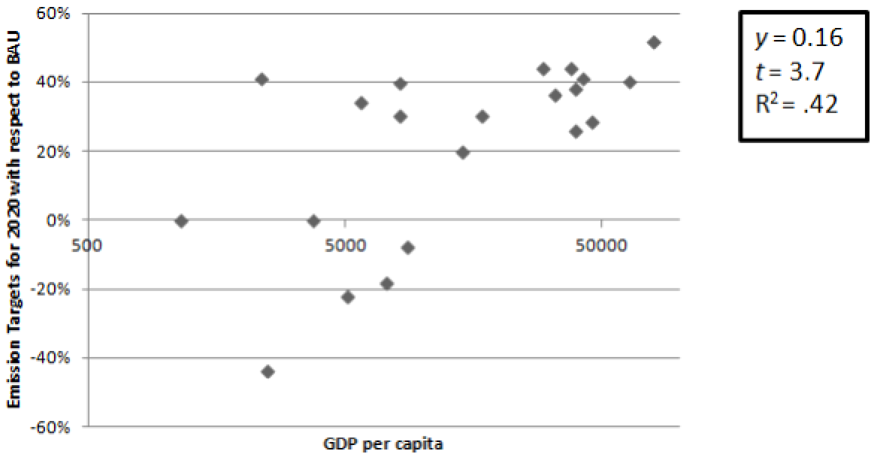
In Table B.1, we regress emission cuts in 2020 derived from countries statements (expressed with respect to baseline emissions, BAU) against current income per capita, including all the Cancun targets, corresponding to Fig. B.1. Progressivity is highly significant: the t-statistic is 3.7 and the R^2 is 0.42. The estimated parameter is 0.16. When we eliminate excess over BAU in the emission targets (hot air) for the four former Soviet countries as illustrated in Fig. B.2, the results are even more highly significant. The t-statistic is 3.9 and the R^2 is 0.44. The estimated parameter is 0.13. This is an encouraging result. The estimated progressivity parameter is not just statistically significant, but extraordinarily close to the estimate on a very different set of numbers determined 13 years earlier, at the time of the Kyoto Protocol. The current estimates, 0.13 and 0.16, bracket the earlier estimate, 0.14. We are happy with this bit of external validation of the theory. We see no need to update the estimate of the progressivity parameter γ used in the model, since the new estimates lie so close to the old one.

Next we use the Copenhagen–Cancun submissions to estimate the parameters for latecomer catch-up at the same time as the progressivity parameter. Results are presented in Table 2(b). The idea is that countries that are not restraining emissions should not be rewarded for emitting while others are making mitigation efforts.

Table B.1. Estimation of progressivity.

Cancun emission target cuts, expressed relative to BAU, regressed against income per capita (21 country observations, counting EU27 as one)

	Countries submitting negative cuts relative to BAU are:			
	taken at face value		set = 0	
	Intercept	γ	Intercept	γ
Coefficient estimate	0.018	−0.162	0.008	−0.130
Standard error	0.065	0.043	0.050	0.034
t-statistic	0.07	−3.72	0.16	−3.87
P value	0.789	0.001	0.878	0.001
R^2	0.421		0.441	



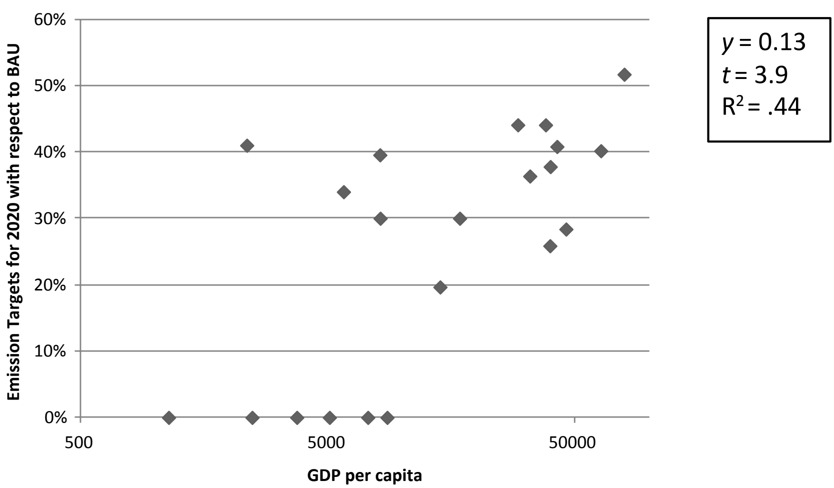
Source: WITCH model projections are used for estimates of targets and future GDP figures.

Figure B.1. Estimated progressivity in Cancun targets, including former Soviet countries

$$\text{LnTarget 2020} = c - \gamma(\ln \text{income/cap}) + (1-\beta)(\ln\text{BAU}_{2020}) + \beta[(\lambda)(\ln \text{emissions}_{1990}) + (1-\lambda)(\ln \text{emissions}_{2007})], \quad \text{(B.1)}$$

where

$\gamma \equiv$ progressivity;
$(1-\beta) \equiv$ weight on BAU emissions in 2020;
$\lambda \equiv$ strength of latecomers' catch-up.



Source: WITCH model projections are used for estimates of targets and future GDP figures.

Figure B.2. Estimated progressivity in Cancun targets, setting former Soviet country targets to BAU

Table B.2. Estimation of progressivity and latecomer catch-up factors.

Dependent variable: (lnTarget 2020–lnBAU 2020)	Coef.	Std. Err.	t	$P > t$	[95% Conf.	Interval]
ln income per capita	−0.156	0.031	−5.07	0	−0.22	−0.09
ln emissions_{2007} − lnBAU2020	0.376	0.100	3.76	0.002	0.16	0.59
ln emissions_{2007} − ln emissions_{1990}	−0.328	0.091	−3.58	0.002	−0.52	−0.13
Constant term	1.384	0.300	4.62	0	0.75	2.02

Source	SS	df	Number of observations	21
			F(3, 17)	13.02
Model	1.092	3	Prob > F	0.0001
Residual	0.475	17	R^2	0.697
			Adj R^2	0.643
Total	1.567	20	Root MSE	0.167

We estimate the formula shown in Eq. (B.1) by running the regression:

$$\begin{aligned}(\text{LnTarget 2020} - \text{lnBAU 2020}) \\ = c - \gamma(\ln \text{income}/\text{cap}) + \beta(\ln \text{emissions}_{2007} \\ - \text{lnBAU2020}) - \beta\lambda(\ln \text{emissions}_{2007} - \ln \text{emission}_{1990})\end{aligned} \quad (B.2)$$

All three coefficients come out showing the hypothesized sign and high statistical significance. This looks like further evidence in favor of our political economy theory. Indeed, one could hardly have wished for a stronger outcome of the hypothesis test. The point estimates of the coefficients are $c = 1.384$, $\lambda = 0.156$, $\beta = 0.376$, and $\beta\lambda = 0.328$. The progressivity parameter is still very close to its preceding value $\gamma = 0.16$, even though we are now controlling for other factors. Take the ratio of the last two coefficients to get the estimate $\lambda = 0.872$. We use these estimates to update the parameters in our formulas.

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