Economic Aspects of Global Warming in a Post-Copenhagen Environment

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Abstract

The science of global warming has reached a consensus on the high likelihood of substantial warming over the coming century. However, nations have taken limited steps to reduce greenhouse gas (GHG) emissions since the first agreement at Kyoto in 1997, and little progress was made at the Copenhagen meeting in December 2009. The present study examines alternative outcomes for emissions, climate change, and climate damages under different policy scenarios. It uses a new and updated version of the RICE model (Regional Integrated model of Climate and the Economy), denoted the RICE-2010 model. The model is a regionalized, dynamic model that incorporates an end-to-end treatment of economic growth, emissions, climate change, damages, and emissions controls. New projections suggest that there will be substantial future warming if no policies are implemented. The model also calculates the path of carbon prices that are necessary to remain within the 2 °C limits in an efficient manner. The estimated 2-degree-C-limiting carbon price for 2010 is estimated to be $64 per ton carbon (2005 prices), whereas the effective globally average carbon price today is around $5 per ton C.

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The world is far along in what Roger Ravelle and Hans Seuss called "our great geophysical experiment."[1] The failure of nations at Copenhagen in December 2009 to reach a concrete agreement to extend and broaden the Kyoto Protocol raises the prospect that attempts to limit carbon dioxide (CO_2) concentrations or global temperature increases may prove politically difficult. The purpose of this study is to provide improved estimates of the likely trajectories of global output, emissions, climate change, and damages in the coming decades.

Climatologists and other scientists have warned for more than a half-century that the accumulations of CO_2 and other greenhouse gases (GHGs) are leading to global warming and other significant climatic, ecological, and societal changes. However, the economic, political, and institutional issues involved in limiting GHGs have only begun to be considered over the last decade. The difficulty arises because reducing emissions is an extreme "public good," meaning that individuals or even nations gain little of the benefits of emission reductions.[2] The intellectual challenge here is daunting – raising formidable issues of data, modeling, uncertainty, international coordination, and institutional design. In addition, the economic stakes in climate-change policy are huge.

What are the stakes if nations fail to reach meaningful agreements? What are the climatic and economic consequences of uncontrolled emissions of GHGs over the coming decades? These questions become particularly salient given the apparent difficulties of reaching a binding and effective international agreement. Surprisingly, the impressive work of scientific bodies such as the Intergovernmental Panel on Climate Change (IPCC) does not in fact address the likely trajectory of uncontrolled emissions, either in the last two rounds of assessments, nor prospectively in the coming fifth round. The present study attempts to explain the issues and provide some tentative answers.

The Copenhagen Accord

The framework for all climate-change deliberations was the United Nations Framework Convention on Climate Change, ratified in 1994. This stated, "The ultimate objective … is to achieve … stabilization of greenhouse gas concentrations

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[1] Revelle, Roger, and Hans E. Suess, "Carbon Dioxide Exchange between Atmosphere and Ocean and the Question of an Increase of Atmospheric CO_2 During the Past Decades," *Tellus* 9: 18-27.

[2] Samuelson, Paul A., "The Pure Theory of Public Expenditure," *The Review of Economics and Statistics,* Vol. 36, No. 4, Nov., 1954, pp. 387-389.

in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system."[3] The Framework Convention was implemented in the Kyoto Protocol (KP) in 1997, in which high-income and transition countries agreed to binding emissions limits for the 2008-2012 period. The reality of global warming policy has lagged far behind scientific prescriptions. This is seen in the attrition in covered emissions under the KP. The original KP covered about 66 percent of 1990 emissions. However, with the departure of the U.S. and the relative decline in the emissions of rich countries, currently the KP covers only about 30 percent of global emissions.

The Copenhagen meeting in December 2009 was designed to negotiate a successor agreement for the post-KP period. Because of deep divisions about goals and the distribution of emissions reductions, the meeting concluded without a concrete agreement. However, it did produce a fuzzy "Copenhagen Accord."[4] The major points of the Accord are: First, it adopts a climatic target of limiting temperature increase, using the justification of "…recognizing the scientific view that the increase in global temperature should be below 2 degrees Celsius..." Those looking for a silver lining behind the cloudy outcome have pointed to the fact that developing countries joined the Accord. A close look reveals, however, that developing countries agreed to very little. They only agreed to "communicate" their "nationally appropriate mitigation actions seeking international support efforts," but there were no specific targets or plans for developing countries. In fact, most countries have communicated their plans as of January 2010.

The reality behind the Accord is not encouraging. To begin with, even if high-income countries fulfilled their commitments, these would not necessarily lead to the 2 °C target. Second, progress on reaching an agreement has been glacial at best. At present, a global agreement is waiting for the U.S. to take credible legislated steps. While the Obama Administration and the Democratic Congress made ambitious proposals to undertake sharp cuts in CO_2 emissions, the prospects for those are dim in the short run with a shift in political sentiments toward conservative policies. Delayed adoption of climate-change policies by the U.S. may lead to a domino effect in which other countries follow the U.S. inaction.

Given these developments, it is useful to review the prospects for climate change both with controls as envisioned by the Copenhagen Accord and if a continued stalemate occurs. The present report presents the results of a new and

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[3] The convention came into force in 1994 and is available at http://unfccc.int/2860.php.

[4] The Accord is found at http://unfccc.int/resource/docs/2009/cop15/eng/l07.pdf.

updated version of the RICE model (Regional Integrated model of Climate and the Economy), denoted the RICE-2010 model. The model is a regionalized, dynamic model that incorporates an end-to-end treatment of economic growth, emissions, the carbon cycle, climate change, damages, and emissions controls. The model allows internally consistent projections of the effects of alternative policy regimes.

The RICE-2010 Model

To analyze the economic implications of success and failure of the Copenhagen Accords, I embed the commitments into an Integrated Assessment Model (IAM) of the global economy and climate change called the RICE-2010 model. I begin with a succinct description of the RICE model. The equations of the RICE model along with key assumptions are available as Supplementary Information (SI). Additionally The model is available as an Excel spreadsheet on the author's web page at http://www.econ.yale.edu/ ~nordhaus/ homepage/. These results are based on the version of January 27, 2010.

The RICE model views climate change in the framework of economic growth theory. In the optimal growth model, or Ramsey model, society invests in capital goods, thereby abstaining from consumption today, in order to increase consumption in the future.[5] The RICE model modifies the Ramsey model to include climate investments. The capital stock of the conventional neoclassical growth model is extended to include investments in the environment ("natural capital"). Emissions reductions in the extended model are analogous to capital investments in the mainstream model. That is, we can view concentrations of GHGs as "negative natural capital," and emissions reductions as lowering the quantity of negative natural capital. Emissions reductions lower consumption today but prevent economically harmful climate change and thereby increase consumption possibilities in the future.

The world is divided into 12 regions. Some are large countries (such as the U.S. or China); others are large regions (like the European Union or Latin America). Each region is assumed to have a well-defined set of preferences, represented by a social welfare function. Each region optimizes its consumption, greenhouse gas policies, and investment over time. The social welfare function is increasing in the per capita consumption of each generation, with diminishing marginal utility of consumption. The importance of a generation's per capita consumption depends on

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[5] Ramsey, Frank P., "A Mathematical Theory of Saving," *Economic Journal,* vol. 38, 1928, pp. 543–559; Koopmans, Tjalling C., "On the Concept of Optimal Economic Growth," *Academiae Scientiarum Scripta Varia* 28(1), 1965, pp. 1-75 (available for download at http://cowles.econ.yale.edu/P/au/p_koopmans.htm).

its relative size. The relative importance of different generations is measured using a pure rate of time preference, and the shape of the utility function is given by the elasticity of the marginal utility of consumption. These parameters are calibrated to ensure that the model real interest rate is close to the average real interest rate and real return on capital in real-world markets.[6]

The model contains both a traditional economic sector found in many economic models and geophysical relationships designed for climate-change modeling. We first describe the traditional sector of the economy — the economy without any considerations of climate change.

Economic sectors. Each region is assumed to produce a single commodity, which can be used for either consumption or investment. Each region is endowed with an initial stock of capital and labor and with an initial and region-specific level of technology. Population data are from United Nations 2004 updated with more recent estimates through 2009, with projections using the U.N.'s estimates to 2300.[7] Output is measured as standard gross domestic product (GDP) in constant prices, and the GDPs of different countries are converted using purchasing-power-parity exchange rates into 2005 U.S. international prices. Output data are from the World Bank and the International Monetary Fund (IMF) and are through 2009, with projections to 2014 from the IMF.[8] CO_2 emissions are from the U.S. Energy Information Administration and are generally through 2006.

Population growth and technological change are exogenous in the baseline model, while capital accumulation is determined by optimizing the flow of consumption over time. Output is produced with a Cobb-Douglas production function in capital, labor, and carbon-energy inputs. Technological change takes two forms: economy-wide technological change and carbon-energy-saving technological change. Economy-wide technological change is Hicks neutral, while energy-saving technological change is modeled as reducing the ratio of CO_2

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[6] Nordhaus, William D., *Managing the Global Commons: The Economics of Climate Change*, MIT Press, Cambridge, MA, USA, 1994; IPCC Second Assessment, *Climate Change 1995 – Economic and Social Dimensions of Climate Change,* Eds. Bruce J., H. Lee, and E. Haites, 1995, Cambridge, UK: Cambridge University Press, pp. 125–44.

[7] United Nations, *World Population to 2300,* Department of Economic and Social Affairs, Population Division, United Nations, ST/ESA/SER.A/236, New York.

[8] International Monetary Fund, *World Economic and Financial Surveys, World Economic Outlook Database,* April 2009 Edition, available online at http://www.imf.org/external/pubs/ft/weo/2009/01/data/index.aspx .

emissions to carbon-energy inputs. Technological change is projected for a frontier region (the U.S.), and other countries are assumed to have partial convergence to the frontier. For convenience, both carbon-energy and industrial emissions are measured in units of carbon weight.[9] Growth rates for different regions are provides in Table ST1.

We calibrate the energy-related parameters using data on historical and projected GDP and CO_2 emissions, and particularly the CO_2-GDP ratio by region. We specify a cost function for CO_2 emissions reductions that is drawn from more detailed models at the national and regional levels from IPCC Fourth Assessment Report.[10] Additionally, there is a backstop technology that can replace all carbon fuels at a relatively high price ($1200 per ton C for the United States, declining over time, drawn from IPCC surveys and other sources[11]). It is assumed that the backstop technology becomes increasingly competitive after 2250, so emissions decline rapidly after that point. The supply curve allows for limited (albeit very large) long-run supplies of carbon fuels. Because of the optimal-growth framework, emissions are efficiently allocated across time, which implies that low-cost carbon resources have scarcity prices (called "Hotelling rents") and that carbon-energy prices rise over time.[12]

Solution of a multi-country general-economic equilibrium model poses major modeling issues. We have used a modification of the Negishi procedure introduced in Nordhaus and Yang.[13] The modification is that the welfare weights

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[9] Nordhaus, William D., *Managing the Global Commons: The Economics of Climate Change*, MIT Press, 1994, Cambridge, MA, USA; Nordhaus, William D. and Joseph Boyer, *Warming the World: Economic Modeling of Global Warming*, 2000, Cambridge: MIT Press.

[10] Intergovernmental Panel On Climate Change, *Climate Change 2007: Mitigation, Working Group III Contribution to the Intergovernmental Panel on Climate Change,* Cambridge University Press, Cambridge, UK, 2007, available online at http://www.ipcc.ch/.

[11] *IPCC Special Report on Carbon dioxide Capture and Storage*, Eds., Bert Metz, Ogunlade Davidson, Heleen de Coninck, Manuela Loos, and Leo Meyer, available at http://www.ipcc.ch/activity/srccs/index.htm.

[12] Hotelling, Harold, "The Economics of Exhaustible Resources," *Journal of Political Economy,* Vol. 39, 1931, pp. 137-175.

[13] Nordhaus, William D. and Zili Yang, "A Regional Dynamic General-Equilibrium Model of Alternative Climate-Change Strategies," *American Economic Review,* 1996, 86: 741-765.

are set to equalize the period-by-period marginal utilities using the weighted average marginal utility, where the region-period weights are the region's share of the global capital stock.[14]

Geophysical sectors. The geophysical part of the model contains a number of geophysical relationships that link together the different forces affecting climate change. This part includes simplified relationships to capture CO_2 emissions, a carbon cycle, radiative forcings, a simple climate model, and regional climate-damage relationships. Each of these is drawn from more complex models and can be seen as MVSS (models of very simplified structure). Emissions include all GHG emissions, although they are most easily viewed as CO_2. The RICE-2010 is the latest vintage of a series of economic models representing the relationship between economic activity and climate change. Details are available in on-line documentation, and the entire model can be accessed by users as an Excel system of spreadsheets.

In the current model, endogenous emissions are limited to industrial CO_2. Chlorofluorocarbons (CFCs) are now outside the climate-change control strategy. Other contributions to global warming are taken as exogenous. These include CO_2 emissions from land-use changes, non-CO_2 greenhouse gases, and sulfate aerosols.[15]

The model uses a three-reservoir model calibrated to existing carbon-cycle models to calculate the carbon cycle. Climate change is represented by global mean surface temperature, and the relationship uses the results of the Fourth Assessment Report of the IPCC to estimate the lag structure and the equilibrium.[16] The RICE-2010 model contains a new module with calculations of sea-level rise (SLR). This experimental model contains estimates of the SLR associated with different

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[14] Rutherford, Thomas F., "Strategies for Calibrating Ramsey Models with Non-Stationary Growth," Lecture Notes, May 24, 2009.

[15] Hansen, James, Makiko Sato, Reto Ruedy, Ken Lo, David W. Lea, and Martin Medina-Elizade, "Global temperature change," *PNAS,* 2009, 103: 14288-14293; Intergovernmental Panel on Climate Change, *Climate Change 2007: The Physical Science Basis,* Contribution of Working Group I to the Fourth Assessment Report of the IPCC, 2007, available online at http://ipcc-wg1.ucar.edu/wg1/wg1-report.html.

[16] Intergovernmental Panel on Climate Change, *Climate Change 2007: The Physical Science Basis,* Contribution of Working Group I to the Fourth Assessment Report of the IPCC, 2007, available online at http://ipcc-wg1.ucar.edu/wg1/wg1-report.html.

temperature trajectories. The current version assumes that the equilibrium temperature-sensitivity coefficient is 3 °C per CO_2 doubling. The model has also been checked by comparing results with those of MAGICC 2009.[17]

Understanding the economic impacts of climate change continues to be the thorniest issue in climate-change economics. The model provides a revised set of damage estimates based on a recent review of the literature. [18] Damages are a function of temperature, sea-level rise, and CO_2 concentrations. They are region-specific. To give an idea of the estimated damages in 2100 in the uncontrolled case, damages are $12 trillion or 3.0 percent of output for a global temperature increase of 3.4 °C above 1900 levels.

There have been many recent studies concerned with abrupt and catastrophic climate change.[19] Estimates for the economic costs of abrupt and catastrophic climate change are included in the damage estimates in the RICE model, but the model does not build in a precise tipping point at a given temperature increase because that has not be reliably determined.

Policy Scenarios

We have examined the economic and climate trajectories associated with five different international policy approaches:

1. *Baseline:* No climate-change policies.

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[17] Model for the Assessment of Greenhouse-gas Induced Climate Change, Tom Wigley, Sarah Raper, Mike Salmon and Tim Osborn, developers, 2009, available at http://www.cgd.ucar.edu/cas/wigley/magicc/index.html.

[18] See particularly Tol, Richard, "The Economic Effects of Climate Change," *Journal of Economic Perspectives*, vol. 23, no. 2, Spring 2009, pp. 29–51. The results are consistent with the summary in Intergovernmental Panel On Climate Change, *Climate Change 2007: Impacts, Adaptation and Vulnerability, Working Group II Contribution to the Intergovernmental Panel on Climate Change*, Summary for Policymakers, 2007, available online at http://www.ipcc.ch/.

[19] Oppenheimer, Michael," Global Warming and the Stability of the West Antarctic Ice Sheet," *Nature*, vol. 393, 1998, pp. 325–332; Oppenheimer, Michael and Richard B. Alley, "The West Antarctic Ice Sheet and Long Term Climate Policy," *Climatic Change,* 2004, vol. 64, 1–10; National Research Council, Committee on Abrupt Climate Change, *Abrupt Climate Change: Inevitable Surprises,* National Academy Press, 2002, Washington, D.C.

2. *Optimal:* Climate-change policies maximize economic welfare with full participation starting in 2010 and no climatic constraints.
3. *Limit temperature to 2 °C:* The optimal policies are taken subject to a further constraint that global temperature would not increase more than 2 °C above the 1900 average.
4. *Copenhagen Accord:* High-income countries implement deep emissions reductions (similar to those included in the current U.S. proposals), with developing countries following in the next 2 – 5 decades.
5. *Copenhagen Accord with only rich countries:* This policy assumes that high-income countries implement deep reductions as in case 4, but developing countries do not participate (as in the current Kyoto Protocol).

The baseline can be interpreted as complete inaction and stalemate on climate policies. The Optimal run provides the most efficient climate-change policies; in this context, efficiency involves a balancing of costs of abatement and benefits of reduced climate damages. While it is unrealistic, it provides an economic benchmark against which other policies can be measured. The Limit policy is a variant of the Optimal policy that builds in a precautionary constraint that a specific temperature increase cannot be exceeded. The Copenhagen Accord policy takes the announced emissions reduction policies for high-income countries for the near term. It then extends these to 2050 to parallel the U.S. proposed reductions. Developing countries are assumed to follow within a few decades. Table 1 shows the base and commitment years for different regions. The fifth case is the same as the Copenhagen Accord, but developing countries do not participate until 2150. For this run, high-income participants are US, EU, Japan, Russia, and Other High Income countries.

Major Results

The major cases

Before presenting the results, a word of caution is in order. The results should be viewed as suggestive and illustrative. They come from a single model and modeling perspective, and most of the relationships are subject to large uncertainties (we quantify some of these below). Particularly as the projections move into the distant future, the error bars grow and results should be viewed with caution.

There are too many results to report comprehensively on the estimates. Further results are available in the Supplementary Information. The major results for the model are shown in Figures 1 through 6. Figure 1 shows global CO2 emissions under the five policies. Unrestrained emissions are estimated to grow very rapidly. Emissions under the optimal and temperature-limited paths are essentially flat for the next two to six decades and then decline after that. The optimal path imposes cut in global emissions of 50 percent from 2005 in 100 years, while the 2 °C temperature limit path prescribes zero emissions at about 2085.

Atmospheric concentrations of CO_2 rise sharply under the baseline path, reaching 778 ppm by 2100 (see Figure 2 with numerical table is ST6). The two control paths have some slight continuation in the rise of concentrations from current levels, peaking between 500 and 600 ppm. (Note these refer to CO_2, not to CO_2-equivalent.) Radiative forcings (not shown) peak at 4.3 W/m^2 in the optimal path and at 3.2 W/m^2 in the temperature-limit path. These forcings include other GHG as well as estimates of other anthropogenic forcings such as sulfates.

Global temperature projections, shown in Figure 3, rise sharply under the baseline, reaching 3.5 °C in 2100, 5.6 °C in 2200 and peak at 6.7 °C (all relative to 1900). The other two paths rise in the early 21st century because of the momentum of past emissions. They then bend down as emissions reductions take place, peaking at 2 °C (obviously) for the temperature limit path and 2.8 °C for the optimal path. One important point to note is that the optimal path has a relatively low maximum temperature, and that the temperature increase averaged over the 2100-2300 period for the optimal case is 2.5 °C.

Perhaps the most important output of integrated economic models are the near-term "carbon prices." These indicate the extent to which economic penalties must be placed on GHG emissions to attain the objectives. We can also judge different policies against benchmarks by examining their near-term carbon prices. Figures 4 and 5 as well as Table 2 show the carbon prices in the different runs. The baseline carbon prices (which are the Hotelling rents on carbon fuels) are essentially zero. The optimal and temperature-limit prices start at $39 and $82 per ton carbon respectively for 2015 in 2005 prices. The optimal prices grow sharply until they reach the projected backstop price.

The global average carbon prices under the Copenhagen Accord are sharply lower for the first two decades reflecting the gradual introduction as well as in complete participation. Note in Figure 5 that the effective carbon price today (around $5 per ton C) is well below either the optimal or the temperature-limit required carbon price. Numerical values for carbon prices for the different runs are in Table ST2, while those for the non-traded Copenhagen Accord are provided in ST3. We also present the associated emissions-control rates in ST4 and ST5.

Table 3 shows the large stakes involved in climate-change policies as measured by aggregate costs and benefits. Using our model discount rates, the optimal program raises the present value of world income by $8.05 trillion, or 0.35 percent of discounted income. This is the equivalent to an annuity of $402 billion per year at a 5 percent discount rate. Imposing the 2 °C temperature constraint is quite costly, reducing the net benefit by almost half, because of the difficulty of attaining the 2 °C target. The Copenhagen Accord with phased in participation of developing countries has substantial net benefits, but lack of participation reduces these substantially. Figure 6 shows the path of net costs as a percent of income for major regions. Costs rise gradually over the coming decades and reach around 1 percent of national income for high-income countries in the late 21st century.

Comparison with other studies and uncertainties

The results here can be compared with earlier versions of the RICE/DICE models as well as other modeling groups. The details of the comparisons are available as Supplementary Information, and the major points will be discussed here. The RICE 2010 model shows substantially similar temperature projections as the earliest vintages (see Figure SF1). The damage ratio (climate damages to output) are similar to earlier versions for the first century, but the latest version has higher damage ratios in the further future because of inclusion of sea-level rise (Figure SF2). The optimal carbon price in the near term is substantially higher than in earlier versions (Figure SF3). For example, the optimal carbon price for 2015 is approximately $40 per ton C whereas in the early vintages the optimal carbon price was in the $10-15 range. The major differences are a major upward revision of global output and a lower discount rate on goods.

A second set of comparisons can be made with the latest round of model comparisons done for the Energy Modeling Forum 22 (EMF-22).[20] The comparisons are not exact as somewhat different assumptions were made in that study. The EMF study focused on the cost of stabilizing emissions and radiative forcings. The scenario that was closest to the present study's 2-degree-C limit was "scenario 1" with a radiative forcings limit to 3.7 W/m^2. For that scenario, the 10th, 50th, and 90th percentile of carbon prices among the models were $86, $207, and $308 per ton

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[20] These are available in *International, U.S. and E.U. Climate Change Control Scenarios: Results from EMF 22,* Eds., Clarke, Leon, Böhringer, Christoph, and Rutherford, Tom F., *Energy Economics,* Volume 31, Supplement 2, Pages S63-S306, December 2009. Scenario 1 is closest to the temperature limit scenario.

carbon, whereas the RICE model's estimate was $176 per ton C (see SF 4 for a more detailed comparison).[21]

Another approach to understanding the robustness of the results is to undertake a formal uncertainty analysis.[22] We have examined the uncertainties of several important driving variables as well as the impacts of the uncertainties on the major endogenous variables. The results will be presented in a forthcoming study, but one result is shown in Figure 3. The bar lines show the estimated 10th and 90th percentile of the distribution of 2105 temperature for the Monte Carle estimates for the uncontrolled run. The underlying uncertainties are provided in Table ST7. Note that these are genuine estimates of uncertainties rather than the uncertainties across models across ensembles that are often presented as "uncertainties" in the IPCC estimates. This analysis confirms our intuition that there are indeed vast uncertainties about future climate change.

Cautionary notes

Analyses using integrated assessment economic models present an unrealistically smooth and harmonious picture of the functioning of economic and political systems in much the way that global climate models miss the turbulence of small-scale weather systems. We conclude with three cautionary observations about the deep difficulties that arise in forging effective programs to slow climate change.

A first issue arises because of the strategic relationship between costs of abatement (which are thoroughly local costs) and climate damages (which are a widely dispersed Samuelsonian public good). The structure of local costs and dispersed benefits leads to strong incentives to free riding – where each country has little incentive to take action and will benefit greatly if everybody else abates. This situation is analyzed using the concept of a Nash equilibrium from game theory. A Nash or non-cooperative equilibrium is a set of strategies in which no player can find a strategy to improve its payoff assuming that the other players stick to their original strategies.[23] Lack of cooperation does not imply that there would be no climate-change policies in a non-cooperative equilibrium. Rather, if countries act

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[21] *Id.*

[22] Nordhaus, William D., *A Question of Balance: Economic Models of Climate Change*, Yale University Press, 2007, New Haven, CT, USA.

[23] Nash, John, "Equilibrium points in n-person games" *Proceedings of the National Academy of Sciences*, 1950, 36(1), pp. 48-49.

non-cooperatively, they will take abatement actions only to the extent that they will benefit, and the benefits to the rest of the world will be ignored. Earlier studies have found that a Nash equilibrium would lead to carbon prices and emissions reductions that are much lower than the optimal levels.[24] Similar results are found in RICE-2010, with the non-cooperative carbon prices being approximately one-tenth of the optimal levels. The strategic significance of this finding is that countries will have strong incentives to "cheat" on strong climate-change agreements. If they hide emissions or overstate reductions, their own economic welfare will improve even though others' will deteriorate.

The difficulty of escaping from a low-level non-cooperative equilibrium is amplified by a second factor, the intertemporal tradeoff. Climate-change policies require costly abatement in the near term to reduce climate damages in the distant future. The generational tradeoff is shown in Table 4. The last line shows the global discounted damages and discounted abatement costs through 2055 under the Copenhagen Accord. Abatement costs are six times averted damages. If we examine the period after 2055 (not shown), the ratio is reversed with discounted damages averted more than four times abatement costs. Asking present generations – who are by assumption in most projections less well off than future generations – to shoulder large abatement costs is asking for a level of political maturity that is rarely observed. The delayed payoffs reinforce the incentives of the non-cooperative equilibrium, so the temptation is very high to postpone taking the costly steps to reduce emissions.

A third issue arises because of the spatial asymmetry between winners and losers among countries. The trajectory of net costs for selected countries is shown in Figure 6 while the net costs are shown in the last column of Table 4. The countries designated to take the largest emissions reductions under the Copenhagen Accord are the U.S. and the E.U. – with the price tag for these regions each in the order of $1 trillion of discounted costs through 2055. Several regions, particularly Russia, have substantial benefits because they have been allocated excess emissions permits. While poor countries can present reasoned arguments why rich countries should take the major emissions cuts, rich countries look at their own costs and attempt to share the burden more widely. This asymmetry reinforces the tendency

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[24] Nordhaus, William and Yang, Zili, "A Regional Dynamic General-Equilibrium Model of Alternative Climate-Change Strategies," with Zili Yang, *American Economic Review*, vol. 86, No. 4, September 1996, pp. 741-765; Yang, Zili, *Strategic Bargaining and Cooperation in Greenhouse Gas Mitigations: An Integrated Assessment Modeling Approach,* MIT Press, Cambridge, MA, US, 2007; Carraro, Carlo and Christian Egenhofer, *Climate and trade policy: bottom-up approaches towards global agreement,* Edward Elgar, Cheltenham, UK, 2007.

of countries to move to their non-cooperative equilibrium and make result in an "après vous" syndrome in which no country takes substantial steps.

A further difficulty arises because the Kyoto-Copenhagen regimes have adopted a cap-and-trade structure. These systems have the theoretical advantage that they can coordinate emissions reductions across countries in an efficient manner. But these theoretical advantages have to date proven illusory. Analysts who have examined the actual functioning of similar quantitative restrictions in different sectors note many difficulties with cap-and-trade that are not fully appreciated in the scientific community, including the following.[25] They are completely untested in the international context; they have been unable to attain anything close to universal participation; they lose precious fiscal revenues unless permits are auctioned; they lead to volatile prices of permits; and they are an invitation to rent-seeking behavior within and across countries.

Additionally, they rely on substantial fiscal transfers among countries to induce poor countries to join, and these may prove politically unviable when the magnitudes are made transparent. For example, the Accord analyzed here has rapidly growing transfers to developing countries. The estimated global value of permit purchases reaches around $1 trillion per year in 2035 and continues to grow after that. The most important disadvantage is that cap-and-trade systems have proven unattractive regime for countries to join; indeed as noted above there has been severe attrition of covered emissions under the Kyoto Protocol. Economists often point to harmonized carbon taxes as more efficient and attractive regimes, but these have been generally shunned in negotiations, particularly in the U.S., because of the taboo of considering tax systems.[26]

The results of the present study suggest that there are several policies that can limit the "dangerous interferences" with the climate system at modest costs. However, such policies would require a well-managed world, globally designed environmental policies, with most countries contributing, with decision makers looking both to the best geosciences and to sound economic policies, and with rich

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[25] Cooper, Richard N, "Toward a Real Global Warming Treaty," *Foreign Affairs,* vol. 77, no. 2, Mar. - Apr., 1998, pp. 66-79; Nordhaus, William D. "To Tax or Not to Tax: Alternative Approaches to Slowing Global Warming, "*Review of Environmental Economics and Policy*, 2007, vol. 1, no. 1, pp. 26-44.

[26] Metcalf, Gilbert E., "Designing a Carbon Tax to Reduce U.S. Greenhouse Gas Emissions, *Review of Environmental Economics and Policy*, 2007, vol. 3, no. 1, pp. 63-83.

countries bringing the poor, the unenthusiastic, and the laggard along sufficient with carrots and sticks to ensure that all are onboard with limited free riding. The checkered history of international agreements – in areas as diverse as finance, trade, and nuclear non-proliferation –indicates how steep is the hill to reaching effective international agreements.[27]

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[27] Cooper, Richard N. Eichengreen, Barry, Henning, C. Randall, Holtham, Gerald, and Putman, Robert D., *Can Nations Agree? Issues in International Economic Cooperation,* The Brookings Institution, Washington, DC, 1989.

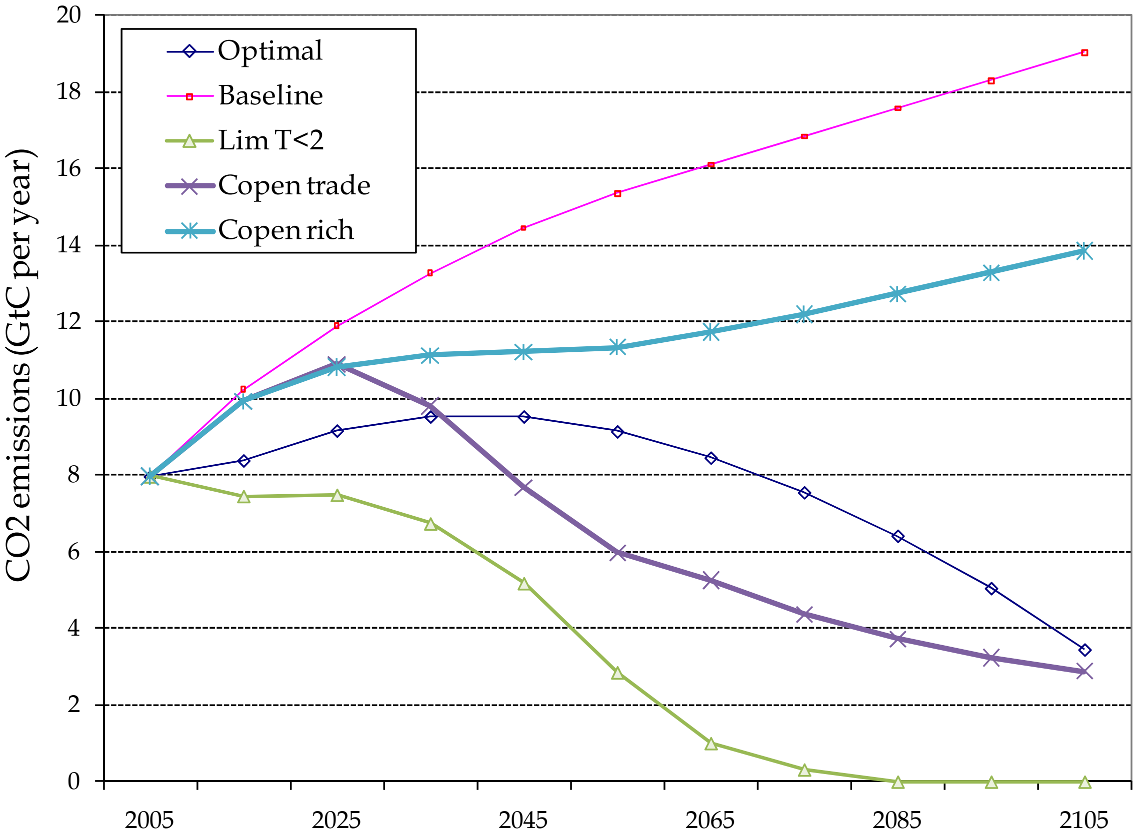

Figure 1. Projected emissions of CO_2 under alternative policies
Figure shows the projected emissions of industrial CO_2 associated with different policies. Policies are explained in text. Note that other GHGs are taken to be exogenous in the projections.

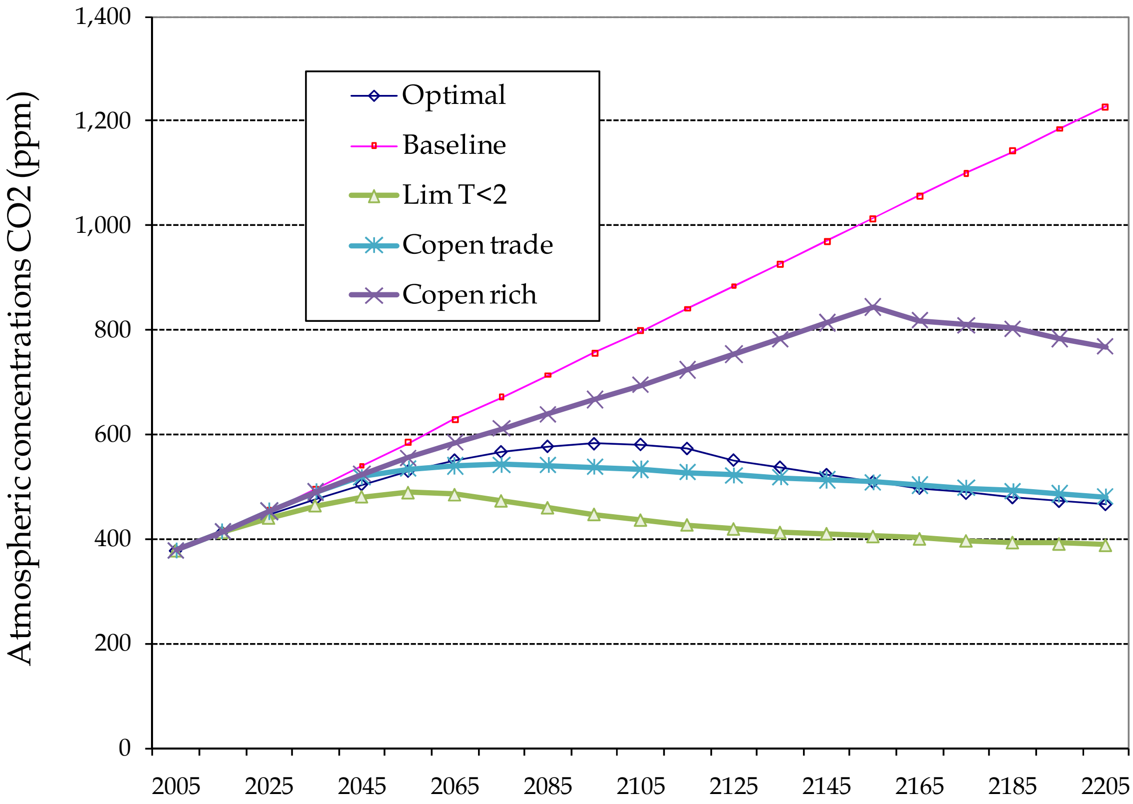

Figure 2. Atmospheric concentrations of CO_2 under alternative policies

Figure shows the projected atmospheric concentrations of CO_2 associated with different policies. The concentrations include emissions from land-use changes. Policies are explained in text.

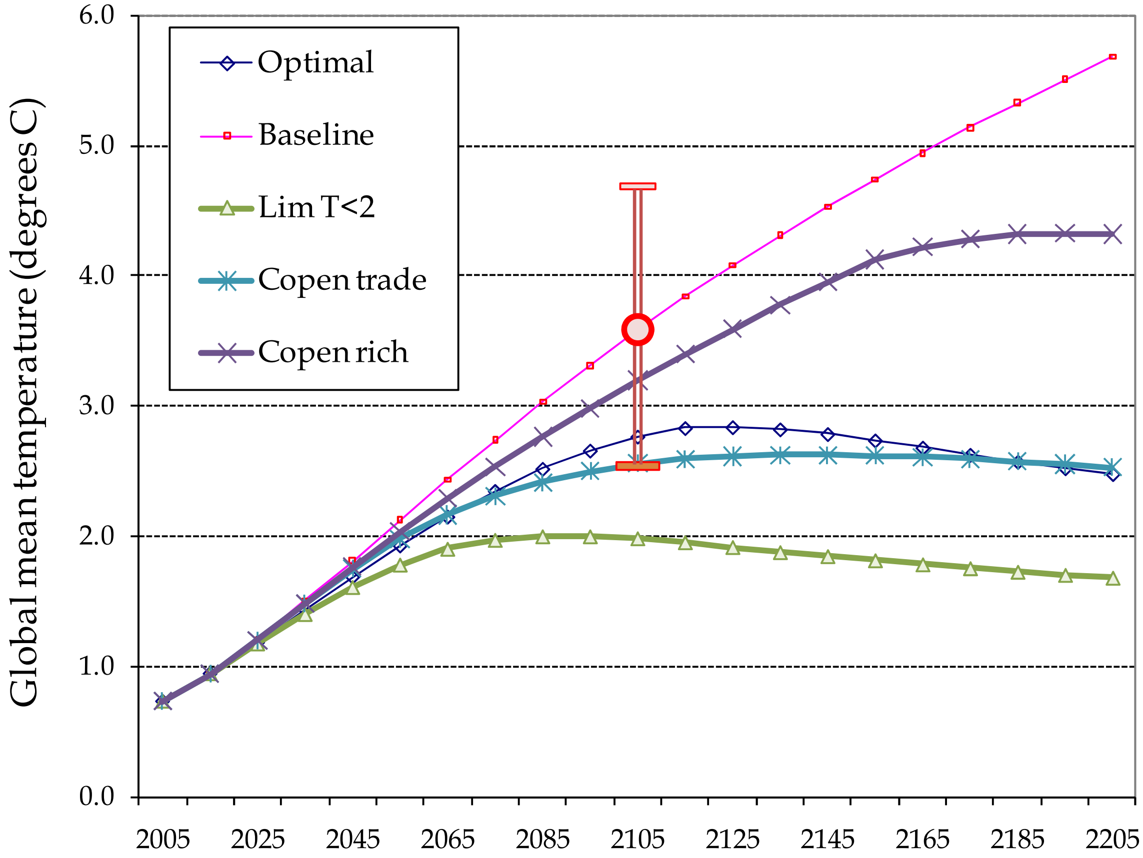

Figure 3. Global temperature increase (°C from 1900) under alternative policies

Figure shows the projected global mean temperature paths associated with different policies. The bars and circles at 2105 are the estimates of the 10th and 90th percentiles of Monte Carlo estimates of temperature for the baseline case with uncertainties of major variables.

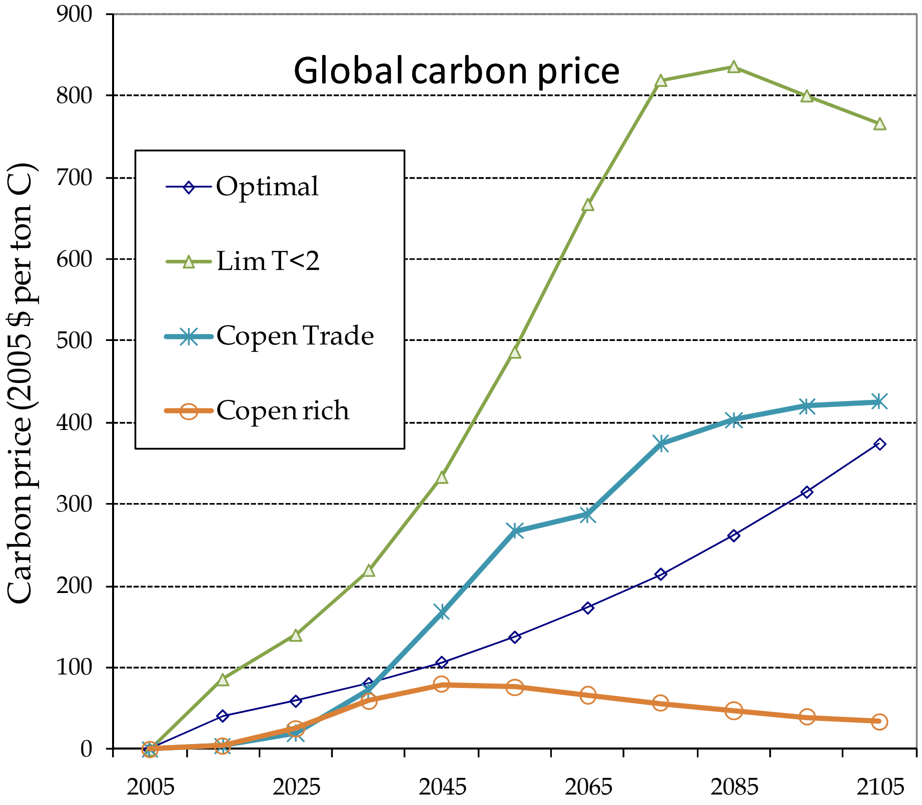

Figure 4. Market price of carbon emissions

Figure shows the calculated globally averaged market price of carbon under different regimes. Prices of CO_2 are calculated by dividing the price by 3.67. Note that under the Copenhagen regimes, the prices will differ by region, and some regions have zero prices.

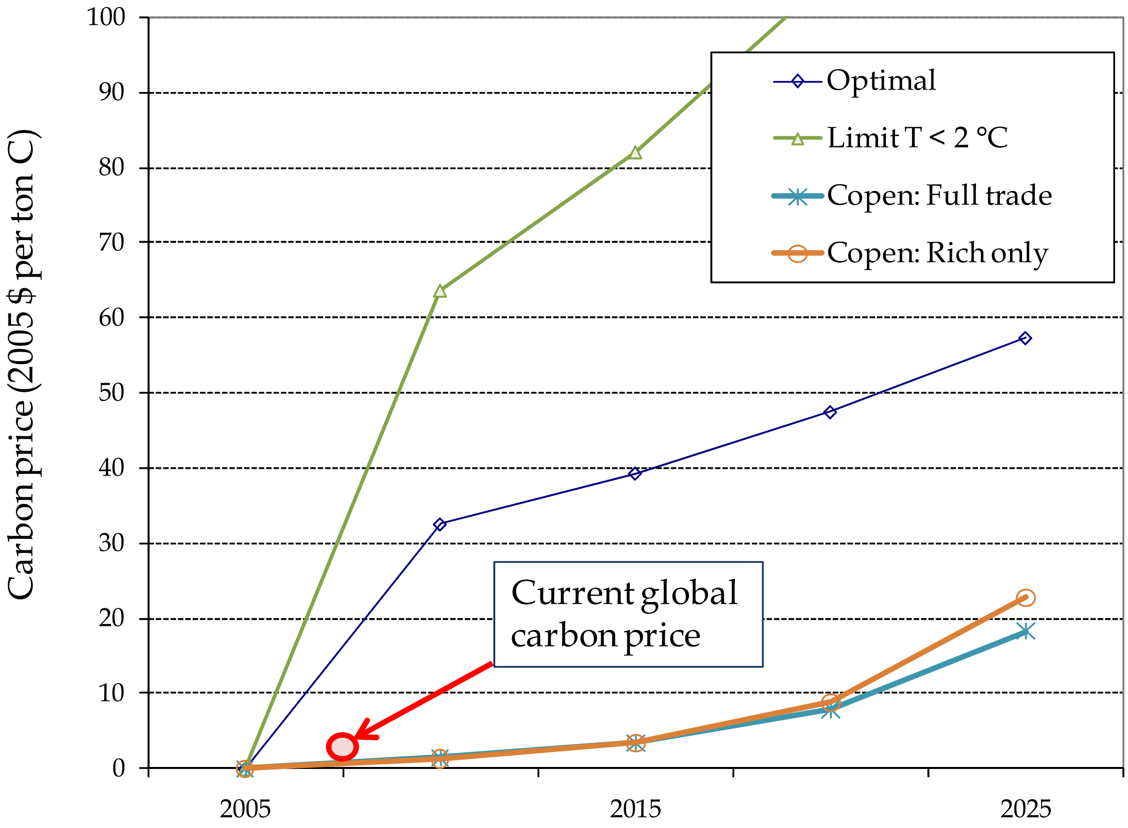

Figure 5. Market price of carbon emissions with actual price

Figure shows the calculated globally averaged market price of carbon under different regimes. The actual price takes the weighted average of different regions as of January 2010 and calculates the global equivalent.

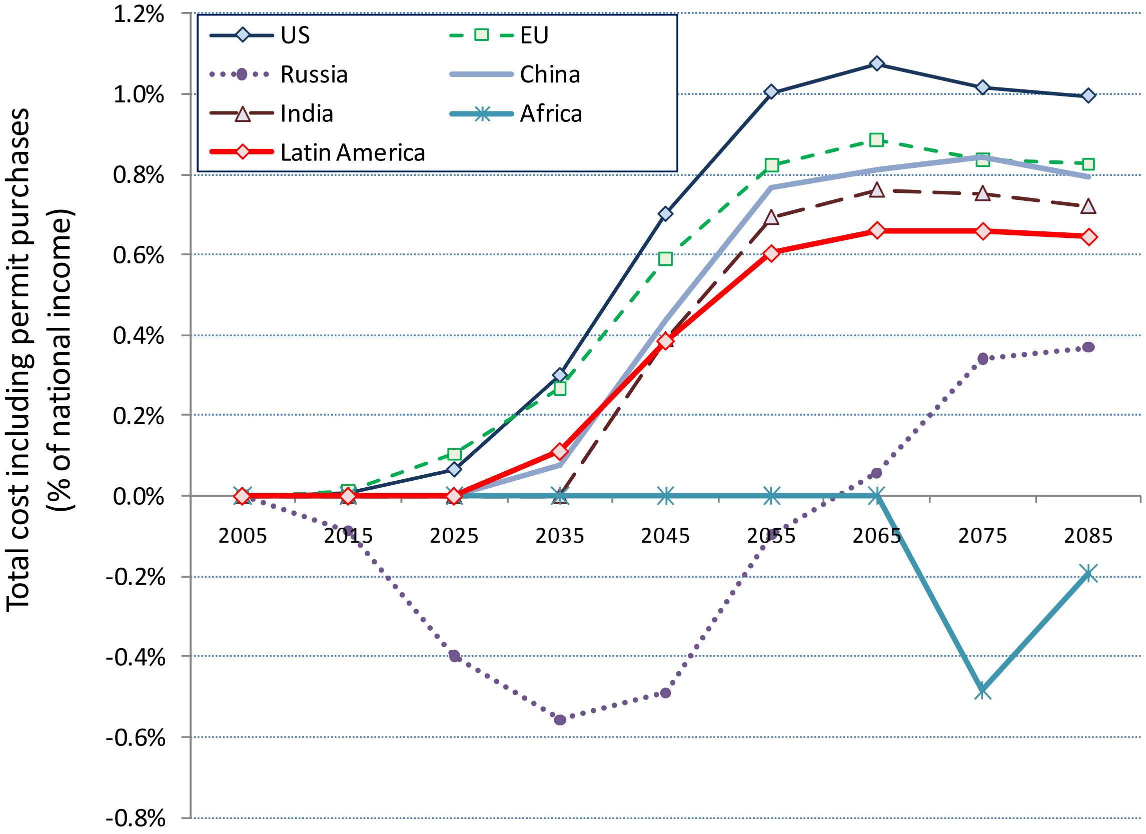

Figure 6. Total costs of compliance as percent of national income

The total costs equal the abatement costs plus the net purchases of emissions permits from other regions under full participation and full trading. These are then divided by net national income for the region.

Capping region:	Date of participation	Base year	Commitment year	Fraction of base year in commitment year	Further reductions tied to
US	2015	2005	2015	0.97	House bill
EU	2005	1990	1995	0.80	US
Japan	2005	1990	1995	0.94	US
Russia	2005	1990	2005	1.00	US
Eurasia	2020	1990	2020	1.00	US
China	2030	2030	2030	1.00	US
India	2040	2040	2040	1.00	US
Middle East	2050	2050	2050	1.00	US
Africa	2070	2070	2070	1.00	US
Latin America	2030	2030	2030	1.00	US
OHI	2015	2015	2015	1.00	US
Other non-OECD Asia	2040	2040	2040	1.00	US

Table 1. Participation rates in limited participation runs

Different regions are assumed to join the Copenhagen Accord at different times. Most high-income countries join in the first post-Kyoto period. Developing countries join from 2030 to 2070. Countries join at their historical emissions and then reduce emission parallel to the U.S. reductions.

(2005 prices per ton C)

Carbon prices	2005	2010	2015	2020	2025	2055	2105
Optimal	0.00	32.58	39.35	47.51	57.38	138.61	393.11
Limit T < 2 °C	0.00	63.66	82.05	105.75	136.30	488.77	766.64
Copen: Full trade	0.00	1.46	3.40	7.88	18.29	270.74	418.51
Copen: Rich only	0.00	1.31	3.40	8.79	22.77	68.20	28.94

Table 2. Carbon prices in the different runs

The carbon prices are the market prices that are requires to attain the policy objectives. These assume full trading and participation in all regions that are in the regime.

Policy scenario	PV Utility	Difference		Annualized*	
	[Trillions of 2005 $]	[Trillions of 2005 $]	Percent of base	[Billions of $ per year]	Percent of base
Base	2,286.9	0.00	0.00%	0.0	0.00%
Optimal	2,295.0	8.05	0.35%	402.4	0.35%
Limit T < 2 °C	2,291.8	4.88	0.21%	243.8	0.21%
Copen: Full Trade	2,293.8	6.85	0.30%	342.7	0.30%
Copen: No trade	2,293.0	6.05	0.26%	302.7	0.26%
Copen: Rich only	2,290.1	3.15	0.14%	157.6	0.14%

* Annual value of consumption at discount rate of 5 percent per year.

Table 3. Present value of consumption, different policies (scaled to 2005 US international dollars, 2005 prices)

The estimates are the present value of consumption equivalent for the entire period. The difference in numerical column 2 shows the difference between the control run and the no-policy or base run. Incomes of countries are calculated using purchasing-power parity exchange rates and an international interest rate that is the capital-weighted average of the real interest rates for different countries.

Region	Costs and benefits (billions, discounted to 2055)			
	Change in damages	Abatement	Permit purchases	Net costs
US	-41	297	335	591
EU	-48	230	360	541
Japan	-9	42	27	60
Russia	-4	97	-207	-114
Eurasia	-5	83	-122	-44
China	-42	543	-263	238
India	-43	152	-80	29
Middle East	-20	60	-58	-18
Africa	-48	0	0	-48
Latin Americ	-27	158	20	152
OHI	-12	101	38	126
Other	-34	139	-50	55
World	**-334**	**1,900**	**0**	**1,566**

Table 4. Costs and benefits of Copenhagen Accord through 2055

The table illustrates the temporal asymmetry of the Copenhagen Accord. The estimates take the present value of abatement costs and averted damages using the capital-weighted international real interest rate. The last column is the sum of the first three columns.