NEW ESTIMATES OF EFFICIENT APPROACHES TO THE CONTROL OF GLOBAL WARMING

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New Estimates of Efficient Approaches to the Control of Global Warming[1]

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Abstract

The present study extends earlier research by presenting the results of a new and updated version of the RICE model (Regional Integrated model of Climate and the Economy), labeled the RICE-2009 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. The model allows projections of what will occur with no policies, what an efficient set of policies would be, and how nations can undertake policies to limit climate change (in the current runs to 2 °C). These new estimates indicate that coordinated international policies have a substantial economic benefit. The optimal carbon tax is estimated to be $54 per ton carbon ($16 per ton CO_2) for 2010 in 2005 prices. The economic optimum would limit global temperature rise to an average of 2.1 °C over 1900 levels for the 22nd and 23rd century.

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The economics of global warming has become particularly salient with the engagement of the Obama Administration with proposals to undertake sharp cuts in carbon dioxide (CO_2) emissions. The present study extends earlier research by presenting the results of a new and updated version of the RICE model (Regional Integrated model of Climate and the Economy), labeled the RICE-2009 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. The model allows projections of what will occur with no policies, what an efficient set of policies would be, and with policies to limit climate change (in the current runs to 2 °C).

I. The RICE-2009 Model

I begin with a succinct description of the RICE model, beginning with the economic sectors and then discussing the geophysical sectors. The model is available as an Excel spreadsheet on the author's web page at http://www.econ.yale.edu/~nordhaus/homepage/DICE2007.htm.

A. Economic sectors

The approach used here is to view climate change in the framework of economic growth theory. In the optimal growth model, or Ramsey model, society invests in tangible capital goods, thereby abstaining from consumption today, in order to increase consumption in the future (Ramsey 1928, Koopmans 1965). The DICE/RICE models are the extension of the Ramsey model to include climate investments. The capital stock of the conventional neoclassical growth model is extended to include investments in the environment. Emissions reductions in the extended model are analogous to investment in the mainstream model. That is, we can view concentrations of GHGs as "negative capital," and emissions reductions as lowering the quantity of negative capital. Sacrifices of consumption that lower emissions 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, which optimizes that regions 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 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 in real-world markets (Nordhaus 1994, IPCC Second Assessment, Economics 1995, Stern Review 2007).

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.

Each country or 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 2008. Output estimates are purchasing power parity in 2005 U.S. international prices from the World Bank and the International Monetary Fund and are through 2008 with projections to 2014. 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 emissions to carbon-energy inputs. Technological change is estimated 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 the same units of carbon weight (Nordhaus 1994, Nordhaus and Boyer 2000).

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, Mitigation 2007. Additionally, there is a backstop technology which can replace all carbon fuels at a relatively high price ($1200 per ton C, declining sharply over time, drawn from IPCC Carbon Capture 2001). The supply curve allows for limited (albeit huge) 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 (Hotelling 1931).

B. 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 contains a carbon cycle, a radiative forcing equation, climate-change equations, and a climate-damage relationship.

In the current vintage of models, 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 (Hansen et al. 2006, IPCC Fourth Assessment, Science 2007).

The model uses a three-reservoir model calibrated to existing carbon-cycle models to model 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 (IPCC Fourth Assessment, Science 2007). 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.

Understanding the economic impacts of climate change continues to be the thorniest issue in climate-change economics. The estimates of damages come from Nordhaus 2007. It assumes that the damage-output ratio is a quadratic function of global temperature increase. The damage ratio is 2.6 percent global output at a 3 °C increase and 10.2 percent at a 6 °C increase. We have not differentiated the damage functions by regions because of the vast uncertainties associated with the damage estimates and because that would suggest a spuriously precise set of regional impacts where none in fact can currently be reliably estimated. There have been many recent studies concerned with abrupt and catastrophic climate change (Oppenheimer 1998, National Research Council, Committee on Abrupt Climate Change 2002, Oppenheimer and Alley 2004). 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 some given temperature increase because that has not be reliably determined.

II. Policy Scenarios

In the runs developed here, we present three alternatives:

1. Baseline: No climate change policies
2. Optimal: Climate change policies maximize economic welfare with no participation or other constraints
3. Limit temperature to 2 °C: The optimal policies are taken subject to a constraint that global temperature would not rise above 2 °C. This run is of interest because it has been widely supported by environmental activists.

The baseline can be interpreted as the worst that can happen. It involves no climate policies for 250 years. The Optimal suggest that most efficient, or best possible, climate-change policies. While it is unrealistic, it provides a benchmark against which policies can be measured. The Limit policy is a variant of the Optimal which builds in a precautionary constraint that a specific temperature increase cannot be exceeded. See Nordhaus 2007 for a further description and discussion.

III. Major Results

A. The major cases

There are too many results to report comprehensively on the estimates. The program and results are available in a spreadsheet format at the author's website at
http://www.econ.yale.edu/~nordhaus/homepage/DICE2007.htm.

The major results for the model are shown in Figures 1 through 8. Figure 1 shows the emissions under the three policies. Unrestrained emissions are estimated to grow very rapidly. Emissions under the two policy paths are estimated to be essentially flat for the next four decades, then declining after that. The optimal path finds a cut in global emissions of 50 percent in 2085, while the temperature-limit path indicates a 50 percent global cut around 2060.

Note that these are global figures. Proposals before the international community relate only to high-income countries and are substantially smaller on a global level. For example, if high-income countries reduce their emissions to *zero* in 2035 but no measures are taken in other countries, the RICE model indicates that the global temperature increase will peak at 5.3 °C rather than 6.1 °C in the baseline case

Atmospheric concentrations of CO_2 rise sharply under the baseline path, reaching 775 ppm by 2100. The two control paths have some slight continuation in the rise of concentrations from current levels, peaking between 500 and 550 ppm. Radiative forcings (which include non-CO_2 GHGs) peak at 3.8 W/m^2 in the optimal path and at 3.3 W/m^2 in the temperature limit path.

Global temperature increase rises sharply under the baseline, reaching 5.3 °C in 2200 and peaks at 6.1 °C. The other two paths rise for 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 2.4 °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 2.1 °C.

Figures 5 and 6 as well as Table 1 show the carbon prices in the different runs. The baseline carbon prices (which are actually the Hotelling rents) are essentially zero. The optimal and temperature-limit prices start at a health level of \$54 to \$68 per ton carbon for 2010 in 2005 prices. The optimal price grows sharply until it reaches the projected backstop price late in this century.

Table 2 shows the stakes involved in the overall costs and benefits of a global warming program. Using our model discount rates, the optimal program raises the present value of world income by \$17.1 trillion, or 1.1 percent. This is the equivalent to an annuity of \$86 billion per year. Note that in the optimal case, adding the constraint of 3 °C is relatively inexpensive, costing a present value of \$1.1 trillion, or an annuity of \$6 billion per year.

B. Comparison with earlier results

It will be useful as well as humbling to compare the current round of results with earlier RICE/DICE models. These models have almost two decades of track record, with major revisions in science, economics, modeling, and software along the way (Nordhaus 1994, Nordhaus and Yang 1996, Nordhaus and Boyer 2000, Nordhaus 2007).

Figure 8 shows the projected global temperature increase for the next century. While the estimates have varied, the latest estimate is actually relatively close to the estimates in the Nordhaus 1994 model. The model's geophysics is relatively stable.

Figure 9 shows the calculated optimal carbon price. This has been revised upwards sharply over the last 15 years. The numbers are corrected for inflation but not for other changes in the projections. There are several reasons for the upward revisions. Some are technical issues, such as moving to PPP exchange rates (see Nordhaus 2007, 2007a). Others come from the "stagnationist" assumptions about output in earlier rounds. Some are from major upward revisions in emissions path of developing countries, particularly China and India. A final change is a revision of the treatment of discounting. (Some of these were reviewed in detail in Nordhaus 2007.) The changes in the estimates emphasize the need for timely data and model revisions and updates even for such a long-term question as global warming.

C. A warning about Panglossianism

We discussed above the importance of global participation in any climate-control program. This point is also emphasized by an examination of abatement costs. One of the advantages of the RICE model is that it can show regional costs as well as global costs. Figure 7 shows the estimate abatement costs under the optimal program. The costs rise sharply over time under the optimal program. The most heavily burdened regions are China and United States, while Japan is relatively lightly burdened.

We can also see the difficulty involved in implementing a global program by examining the sum of abatement costs of non-advanced countries (these are comprised of countries outside Japan, the US, the EU, Russia, and other high income countries). Suppose that high income countries endeavored to compensate developing countries for their optimal abatement costs. These costs would be relatively modest in the near-term decades, but rise to $300 billion per year by mid-21st century. The questionable political feasibility of these large transfers suggests either that climate control programs will be limited to incomplete participation (with the unhappy results discussed above) or that a consensus among poorer countries will need to develop rapidly in the near future.

This point emphasizes that the "optimal" and "limits" runs analyzed here are somewhere between optimistic and Panglossian. They assume a well-managed world, globally designed environmental policies, with all countries contributing, with decision makers looking both to the best geosciences and to sound economic policies, and with rich countries bringing the poor and the laggard along sufficient with carrots and sticks to ensure that all are onboard with no free riding. All that we know about human history suggests that this is an unlikely forecast. Where the actual political and environmental outcomes will lie between the optimistic optimum and the fatalistic baseline will depend upon how these various political factors play out in the years ahead.

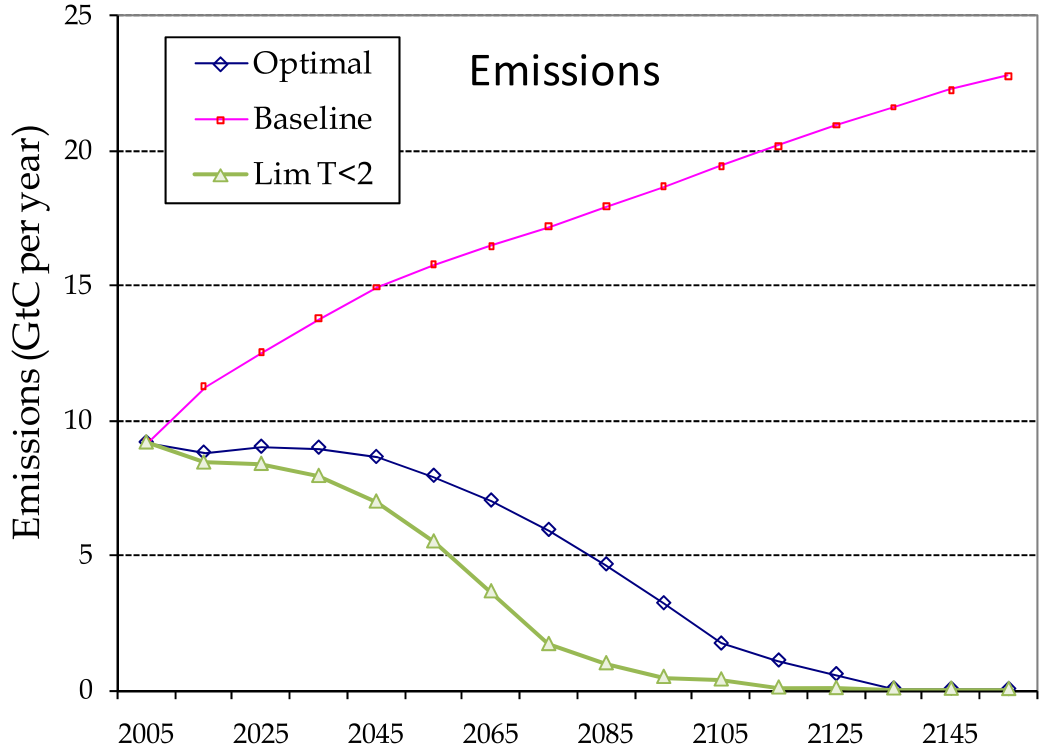

Figure 1. Emissions of CO_2

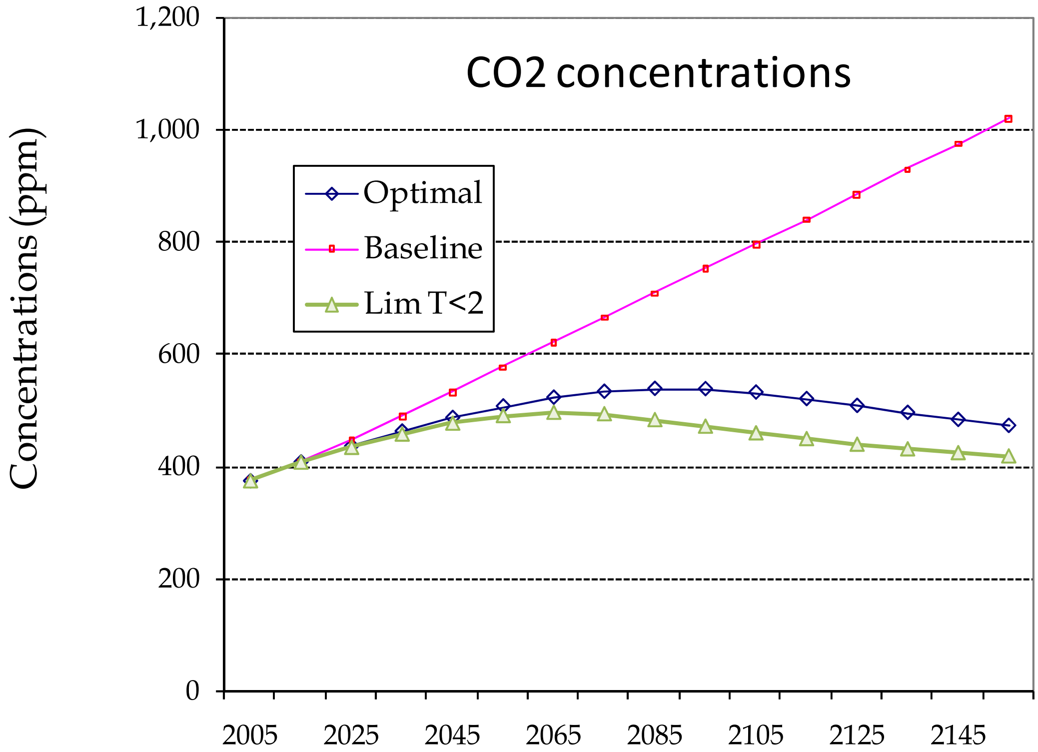

Figure 2. Atmospheric concentrations of CO_2

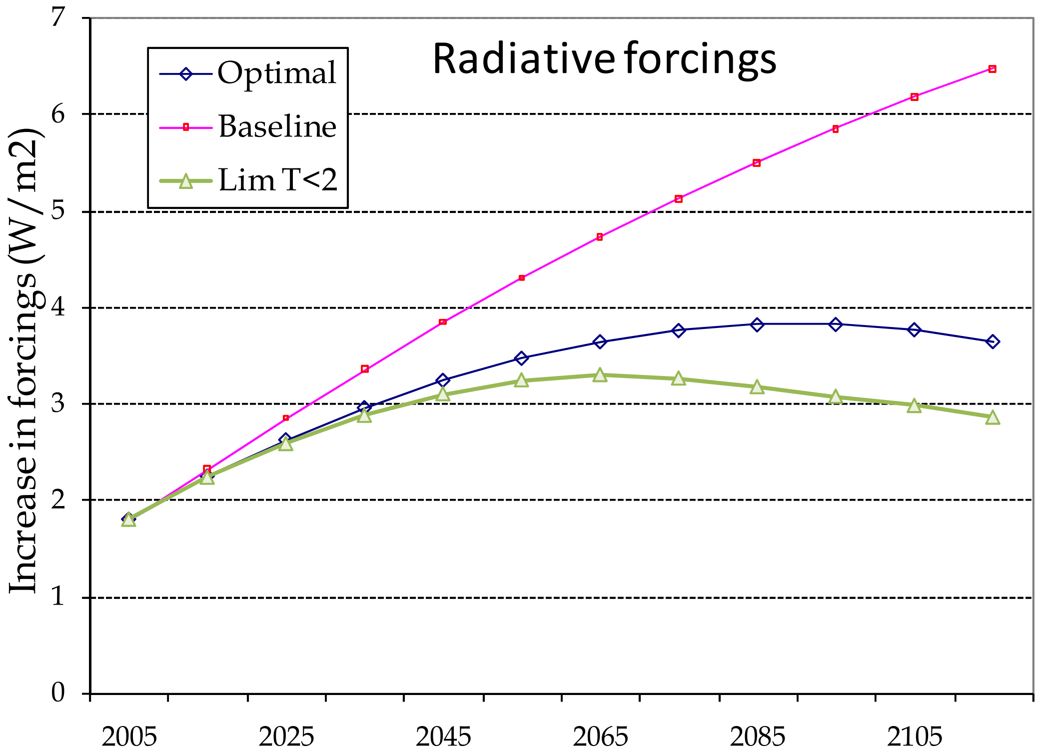

Figure 3. Radiative forcings of greenhouse gases

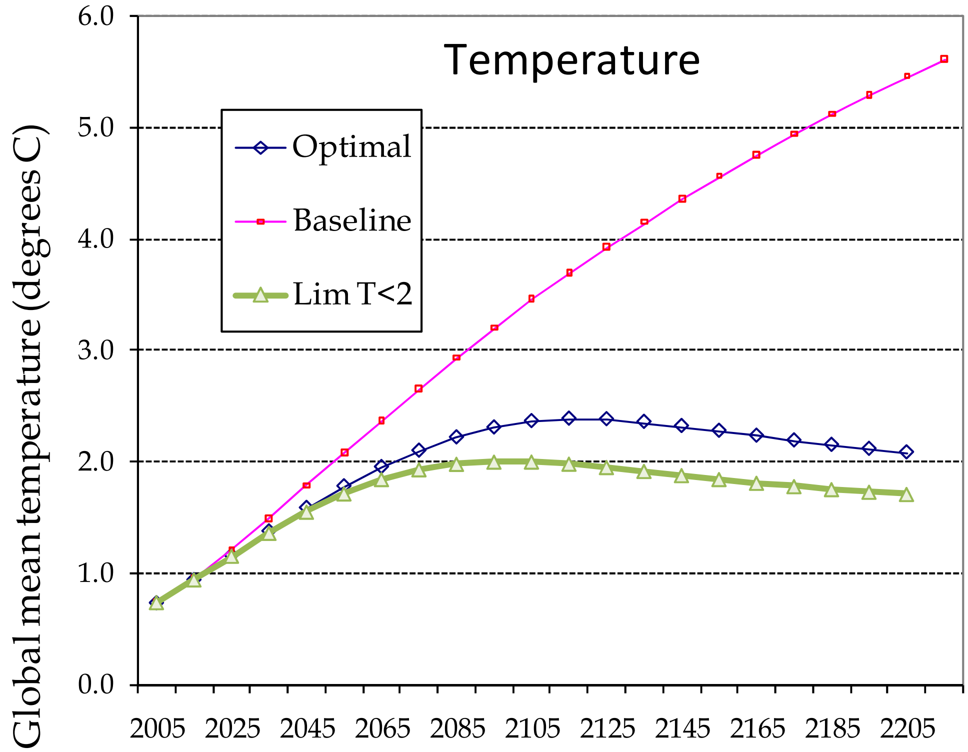

Figure 4. Global temperature increase (°C from 1900)

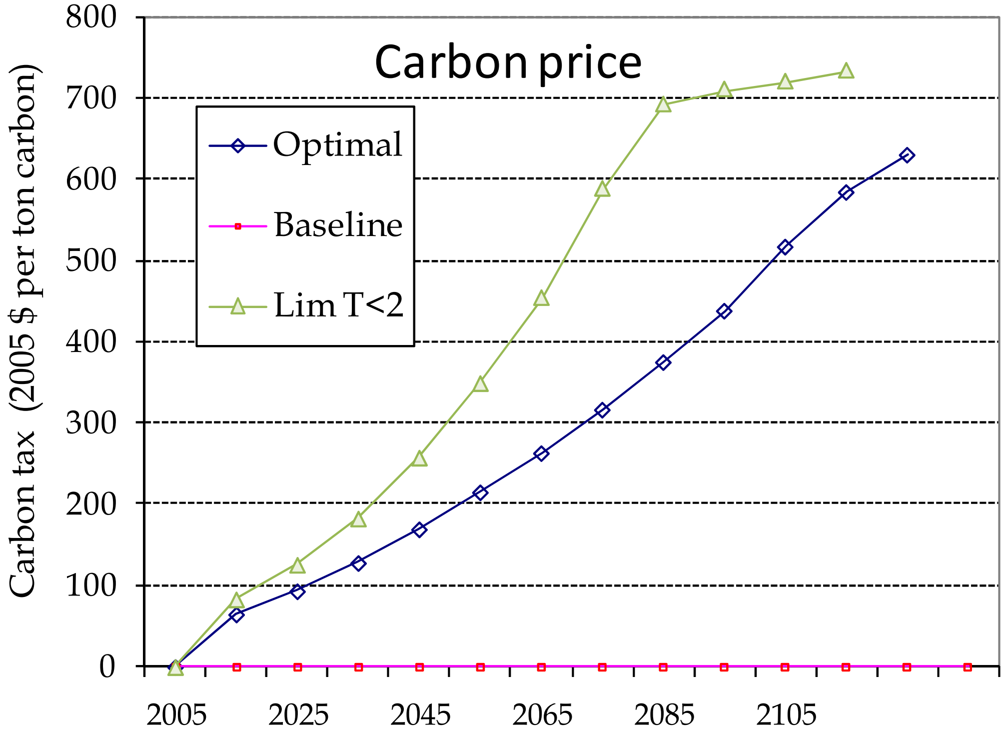

Figure 5. Market price of carbon emissions

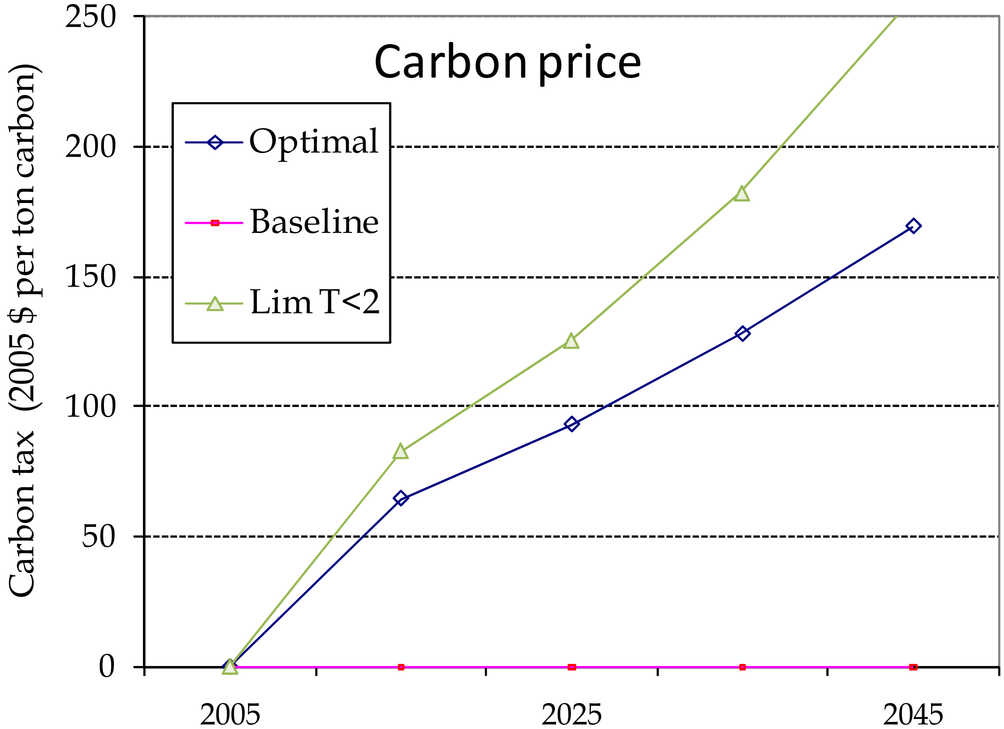

Figure 6. Market price of carbon emissions

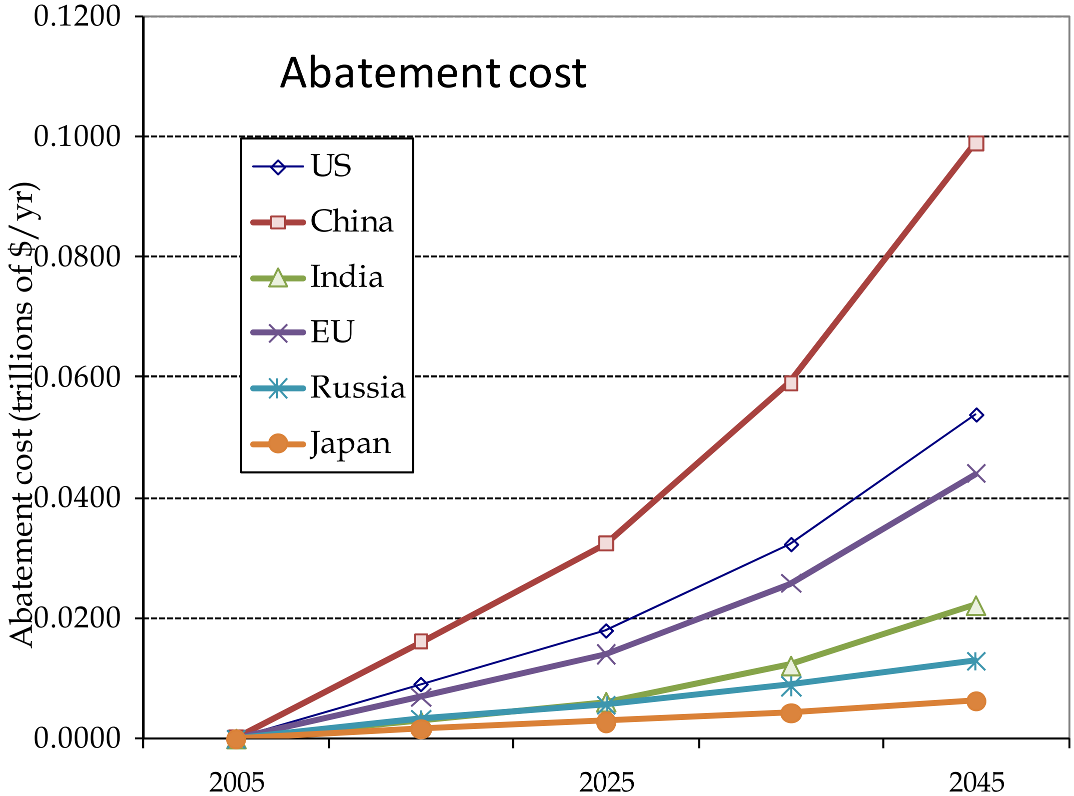

Figure 7. Abatement costs by region in optimal case

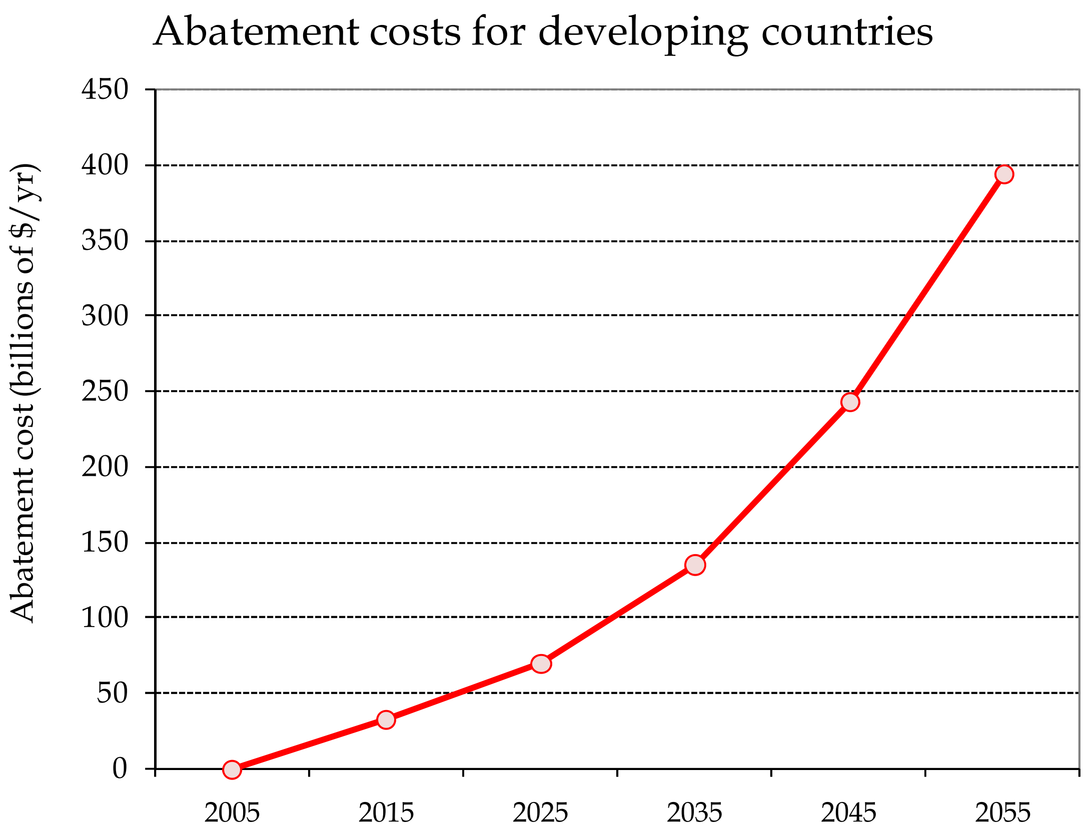

Figure 8. Abatement costs by region in optimal case for developing countries

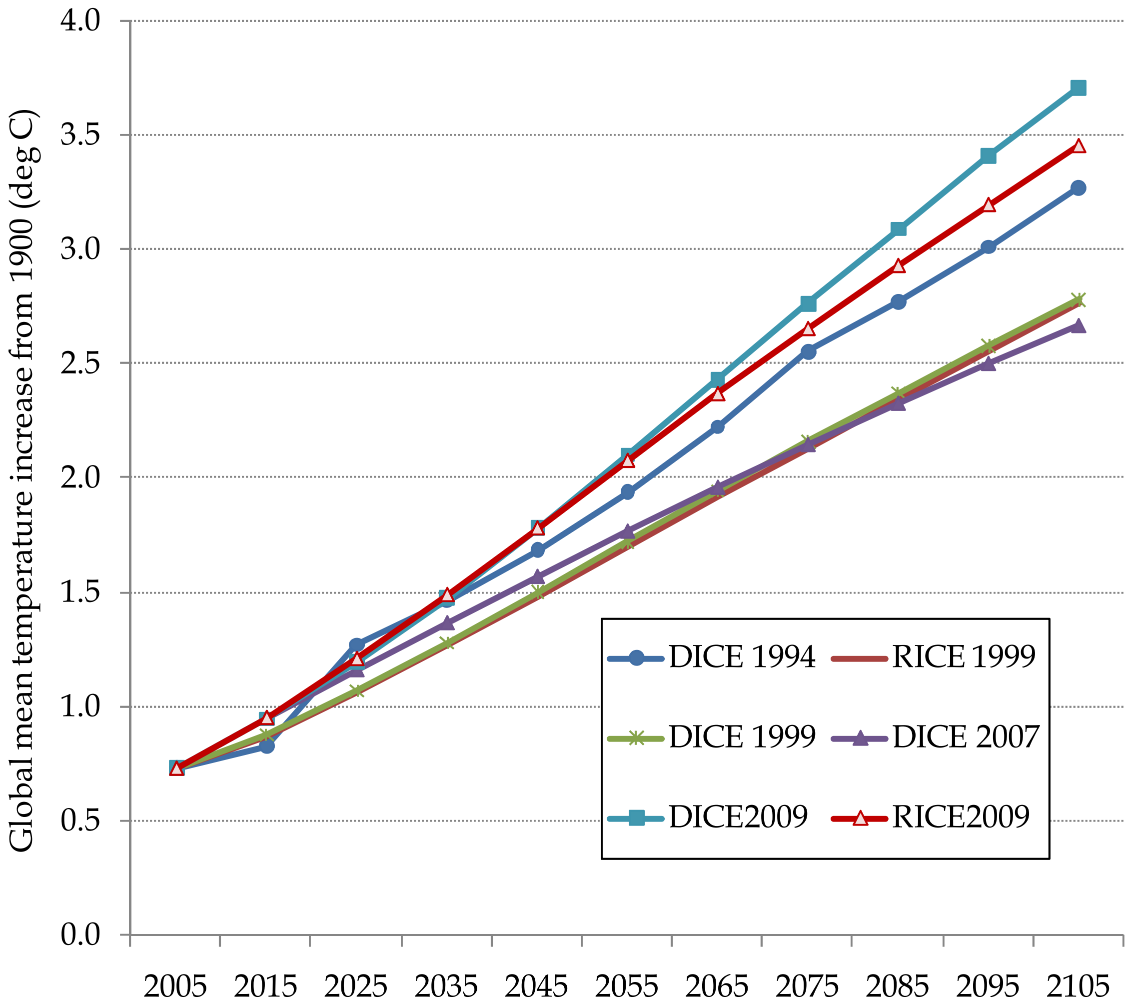

Figure 9. Baseline temperature projections for various vintages of DICE/RICE models

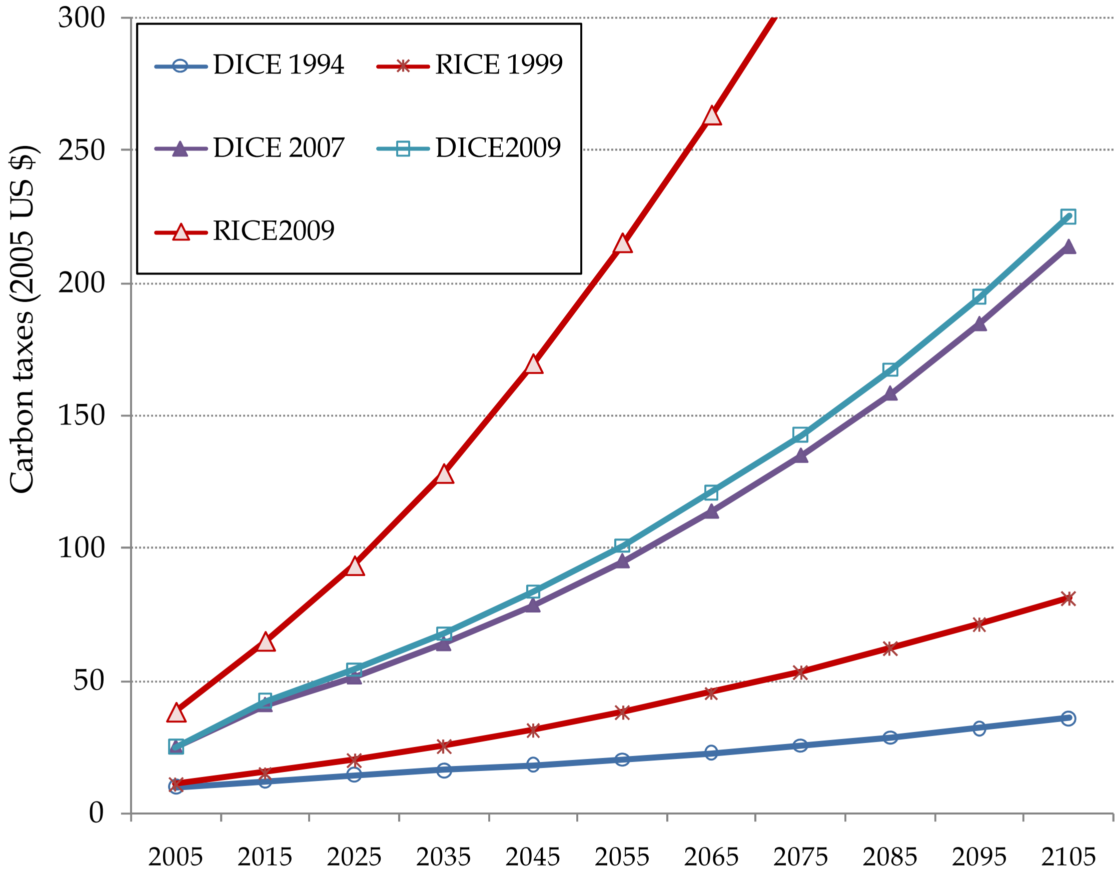

Figure 10. Estimated efficient carbon prices for various vintages of DICE/RICE models

	(2005 prices per ton C)						
Carbon prices	<u>2005</u>	<u>2010</u>	<u>2015</u>	<u>2020</u>	<u>2025</u>	<u>2055</u>	<u>2105</u>
Optimal	0.00	53.94	64.73	77.69	93.24	215.00	517.23
Limit T ≤ 2 °C	0.00	67.66	83.18	102.26	125.71	349.07	720.90
	(2009 prices per ton C)						
Carbon prices							
Optimal	0.00	60.13	72.17	86.62	103.95	239.69	576.64
Limit T ≤ 2 °C	0.00	75.43	92.73	114.00	140.15	389.17	803.71
	(2005 prices per ton CO2)						
Carbon prices	<u>2005</u>	<u>2010</u>	<u>2015</u>	<u>2020</u>	<u>2025</u>	<u>2025</u>	<u>2025</u>
Optimal	0.00	16.40	19.69	23.63	28.36	65.38	157.29
Limit T ≤ 2 °C	0.00	20.58	25.30	31.10	38.23	106.16	219.23
	(2009 prices per ton CO2)						
Carbon prices	2005	2010	2015	2020	2025	2025	2025
Optimal	0.00	16.40	19.69	23.63	28.36	65.38	157.29
Limit T ≤ 2 °C	0.00	20.58	25.30	31.10	38.23	106.16	219.23

Table 1. Carbon prices in the different runs

Policy scenario	PV Utility [Trillions of 2005 $]	Difference [Trillions of 2005 $]	Difference Percent of base	Annualized* [Billions of $ per year]	Annualized* Percent of base
Base	1,558.8	0.0	0.00	0.00	0.00
Optimal	1,575.9	17.1	1.10	85.67	1.10
Limit T ≤ 2 °C	1,574.8	16.0	1.03	80.05	1.03

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

Table 2. Present value of utility (scaled to 2005 US international dollars, 2005 prices)

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