HARVARD Kennedy School
JOHN F. KENNEDY SCHOOL OF GOVERNMENT

The Harvard Project on International Climate Agreements

September 2008
Discussion Paper 08-06

Revised Emissions Growth Projections for China: Why Post-Kyoto Climate Policy Must Look East

Geoffrey J. Blanford
Electric Power Research Institute
USA

Richard G. Richels
Electric Power Research Institute
USA

Thomas F. Rutherford
Swiss Federal Institute of Technology
Switzerland

Email: **climate@harvard.edu** Website: **www.belfercenter.org/climate**

Revised Emissions Growth Projections for China: Why Post-Kyoto Climate Policy Must Look East

Geoffrey J. Blanford
Project Manager, Global Climate Change Research Program
Electric Power Research Institute
gblanford@epri.com

Richard Richels
Director, Global Climate Change Research Program
Electric Power Research Institute
rrichels@epri.com

Thomas Rutherford
Professor, Economics
Swiss Federal Institute of Technology
trutherford@ethz.ch

Prepared for
The Harvard Project on International Climate Agreements

THE HARVARD PROJECT ON INTERNATIONAL CLIMATE AGREEMENTS

The goal of the Harvard Project on International Climate Agreements is to help identify key design elements of a scientifically sound, economically rational, and politically pragmatic post-2012 international policy architecture for global climate change. It draws upon leading thinkers from academia, private industry, government, and non-governmental organizations from around the world to construct a small set of promising policy frameworks and then disseminate and discuss the design elements and frameworks with decision-makers. The Project is co-directed by Robert N. Stavins, Albert Pratt Professor of Business and Government, John F. Kennedy School of Government, Harvard University, and Joseph E. Aldy, Fellow, Resources for the Future. For more information, see the Project's website: http://belfercenter.ksg.harvard.edu/climate

Acknowledgements

Major funding for the Harvard Project on International Climate Agreements has been provided by a grant from the Climate Change Initiative of the Doris Duke Charitable Foundation. Additional support has been provided by Christopher P. Kaneb (Harvard AB 1990); the James M. and Cathleen D. Stone Foundation; Paul Josefowitz (Harvard AB 1974, MBA 1977) and Nicholas Josefowitz (Harvard AB 2005); the Enel Endowment for Environmental Economics at Harvard University; the Belfer Center for Science and International Affairs at the Harvard Kennedy School; and the Mossavar-Rahmani Center for Business and Government at the Harvard Kennedy School.

Citation Information

Blanford, Geoffrey J. Richard G. Richels, and Thomas F. Rutherford. "Revised Emissions Growth Projections for China: Why Post-Kyoto Climate Policy Must Look East." Discussion Paper 2008-06, Cambridge, Mass.: Harvard Project on International Climate Agreements, September 2008.

Abstract

Recent growth in carbon dioxide emissions from China's energy sector has exceeded expectations. In a major US government study of future emissions released in 2007 (1), participating models appear to have substantially underestimated the near-term rate of increase in China's emissions. We present a recalibration of one of those models to be consistent with both current observations and historical development patterns. The implications of the new specification for the feasibility of commonly discussed stabilization targets, particularly when considering incomplete global participation, are profound. Unless China's emissions begin to depart soon from their (newly projected) business-as-usual path, stringent stabilization goals may be unattainable. The current round of global policy negotiations must engage China and other developing countries, not to the exclusion of emissions reductions in the developed world and possibly with the help of significant financial incentives, if such goals are to be achieved. It is in all nations' interests to work cooperatively to limit our interference with the global climate.

Revised Emissions Growth Projections for China: Why Post-Kyoto Climate Policy Must Look East

Geoffrey J. Blanford[1*], Richard G. Richels[2], Thomas F. Rutherford[3]

Introduction

Growth rates in energy-related emissions of carbon dioxide in developing countries, particularly the People's Republic of China, have increased rapidly in recent years. Emissions from the original signatories to the Kyoto Protocol (known as "Annex B countries"), essentially the developed world and economies in transition, will almost certainly be surpassed by non-Annex B emissions before 2010. This crossing point had been projected by previous analyses to occur in 2020 or later (2). The main source of unexpected emissions growth is China. According to the historical record provided by Marland et al. (3), since 2000 the average annual growth rate in China's emissions has exceeded 10%, compared to 2.8% in the 1990's. Globally, the average growth rate since 2000 has been 3.3%, compared to 1.1% in the 1990's.

Raupach et al. (4) decompose emissions growth in several regions into the factors of the Kaya identity: population, per capita income, energy intensity of gross domestic product (GDP), and carbon intensity of energy. In China, the first and last factors have been stable: population growth is slow, and carbon intensity has remained consistently high due to heavy reliance on coal. Emissions growth has been driven by a combination of rapid economic development and the reversal of the past trend of energy intensity decline. Between 1980 and 2000, energy intensity in China had been falling faster than in any other major economy. This decline has been attributed to efficiency improvements at the firm level as market reforms privatized formerly state-operated enterprises (5). However, since 2000, energy use has not only kept pace with, but slightly exceeded aggregate economic growth, driven primarily by industrial demand and coal-fired electric generation (6,7) (Figure 1). The International Energy Agency (IEA) reports that over 100 GW of new electric generation capacity was added in 2006, of which at least 80 GW was coal-fired (8). While this rate may not be indicative of an annual average, it represents coal plant construction in a single year equivalent to one quarter of the US coal fleet. Despite some uncertainty about the accuracy of China's national data sources, it has likely become the world leader in carbon emissions, surpassing the US in 2006 (9).

[1] Electric Power Research Institute, Palo Alto, California 94304, USA.
[2] Electric Power Research Institute, Washington, DC 20036, USA.
[3] Swiss Federal Institute of Technology (ETH), Zürich CH-8032, Switzerland.

* Corresponding author: gblanford@epri.com.

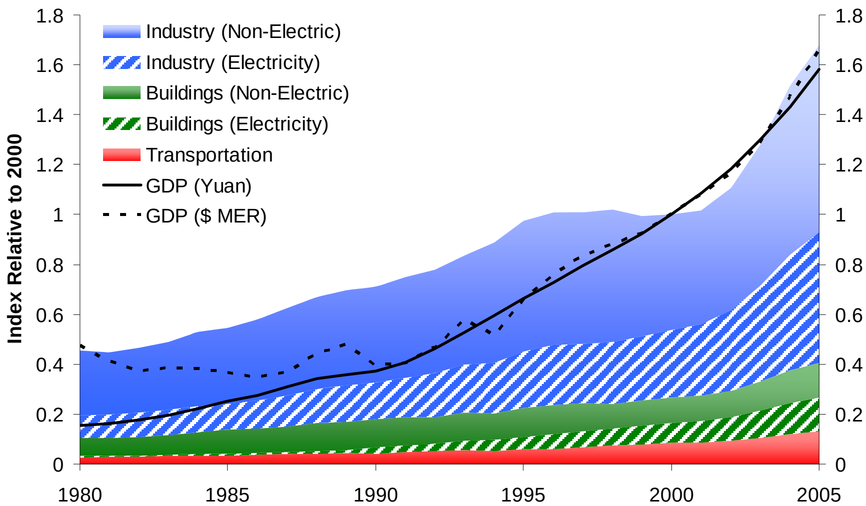

Figure 1. Primary energy in China relative to economic growth.

Real GDP grew faster than primary energy in China between 1980 and 2000. Since 2000, energy has grown faster than the economy. Dollar figures are converted using market exchange rates (MER). Growth in constant dollars converted using purchasing power parity (PPP) rates coincides with growth in constant local currency.

Baseline (i.e. business-as-usual) projections of growth in China's emissions in the near- to medium-term (e.g. through 2030) have until very recently been modest. The IEA's World Energy Outlook (WEO) for 2000 (10) reported an average growth rate of 3% in its reference case over its 1997 – 2020 time horizon. The 2005 edition of the WEO (11) revised the rate downwards to 2.4% between 2003 and 2030. This projection likely seemed plausible at the time, given the 1-2 year lag in accurate observations and the anomalous dip in emissions statistics in the late 1990's (3). However, as a pattern of rapid growth became evident, the 2007 WEO (8) reported a 2030 total over 50% higher than the 2005 edition's projection. The IEA's projections are significant because many modeling studies use them to calibrate baseline emissions paths, either formally or informally. A prominent example in the US was the report commissioned by the federal government's Climate Change Science Program (CCSP), written in 2006 and released in 2007 (1), comparing reference and coordinated stabilization scenarios by three economic modeling teams.[4] Two of the models used year 2000 emissions as a starting point, while the third used 2005, but in all three the growth rates in China matched the IEA's unadjusted projections of the 2000-05 era. Figure 2 shows the various IEA reference forecasts, along with the CCSP report range, in the context of observed historical emissions as reported by the Oak Ridge National Laboratory (ORNL) (3) [including the Netherlands Environmental Assessment Agency (MNP) figure for 2007 (12)].

The latest IEA estimates may even still be underestimating China's potential growth. Auffhammer and Carson (13) give econometric forecasts of China's emissions path through 2010 using a province-level dataset up to 2004 and applying a variety of alternative model structures. The models with the best dynamic fit to the sample data indicate the potential

[4] These included the MERGE model, the MiniCAM model, and the IGSM/EPPA model.

for annual fossil fuel emissions to reach 2.25 billion tons of carbon (GtC) by 2010 (also depicted in Figure 2), a sharp increase from the MNP's reported total of 1.65 GtC for 2007. This estimate for 2010 is almost double the IEA's 2005 forecast of 1.25 GtC for that year, and significantly larger than the linearly interpolated 2010 level of 1.87 GtC from the 2007 forecast. Thus growth in China is so rapid that it is difficult to predict emissions just two years from now.

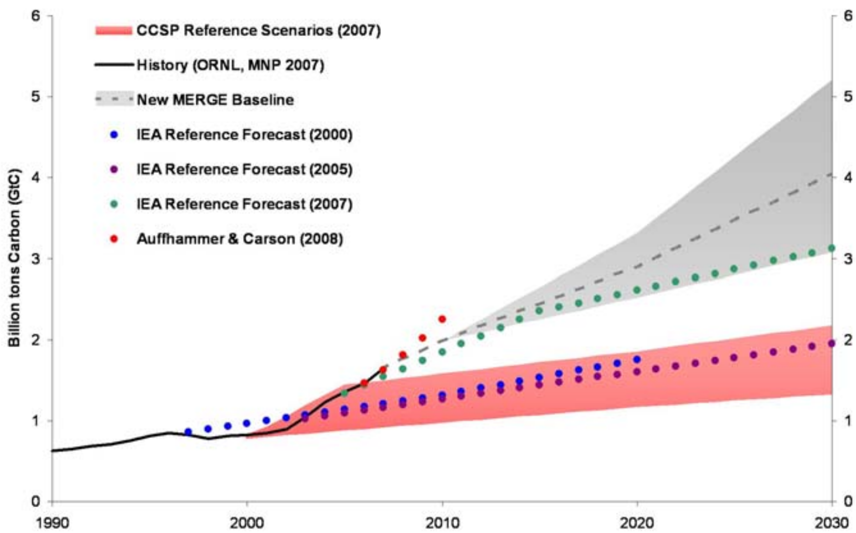

Figure 2. Energy-related CO_2 emissions in China.

Historical emissions began increasingly rapidly after 2001. IEA forecasts did not detect the acceleration until after 2005, and projections in the 2007 CCSP report reflected earlier forecasts. A 2008 econometric study projects an exponential extrapolation of the current annual growth rate through 2010. The new MERGE baseline projections reach 4 GtC by 2030 (dashed line) in the reference growth scenario, 3.1 GtC in the low scenario, and 5.2 GtC in the high scenario (bounds of the gray shaded region).

Model Calibration

These observations warrant an update to assumptions about future growth used by the economic modeling community in climate policy studies. Accordingly, we have recalibrated one of the models used in the US CCSP report, the MERGE model (14,15). MERGE is an intertemporal optimization model with a top-down general equilibrium representation of the economy and a bottom-up process representation of energy technologies. In each region, exogenous trajectories for population and reference economic growth are used to derive a growth scenario for labor productivity (equivalent to per capita income). A nested production function is used to describe how aggregate economic output depends upon the inputs of capital, labor, electric and non-electric energy. Energy prices are determined endogenously in the model as a result of resource scarcity, technological change, and policy constraints. For more details about technology in MERGE, please see Appendix A.

The rate of increase in energy demand relative to economic growth is determined both by price-induced shifts among inputs to production (as determined by elasticities in the production function) and by autonomous (i.e. non price-induced) changes in energy intensity. Such changes can occur due to both technological progress (e.g. end-use efficiency) and structural changes in the economy (e.g. shifts away from manufactured goods toward services). All sources of non-price-induced changes in energy intensity are summarized in MERGE by a single "autonomous energy efficiency index" (AEEI) parameter, which operates as a scaling factor on the energy input into production. The exogenous choices of growth rate and AEEI are the key parameters for incorporating updated assumptions about development patterns and energy use in emerging economies.

MERGE operates in 10 year time steps with 2000 as the base year. To ensure that the model replicates observed growth during the current decade, we use GDP projections from IMF (2008) for 2010 to determine the average annual growth rate since 2000. To best capture real growth as a driver for energy demand, we observe the rate of growth in terms of constant local currency. For aggregated regions, observed growth rates are calculated using purchasing power parity (PPP) weights. However, the relative size of economies in the model's base year is measured in terms of market exchange rates. After 2010, we consider three possible growth scenarios for developing countries: a reference scenario and two outliers. Table 1 shows the annual average growth rates in aggregate GDP, population, and labor productivity / per capita income through 2030 in China and India for the three scenarios. Although the economic component of MERGE runs on a 100-year timescale, we focus here on the approaching decades.

Table 1. Exogenous Annual Growth Rates in MERGE

		Aggregate GDP			Population			Labor Productivity		
		2000 – 2010	2010 – 2020	2020 – 2030	2000 – 2010	2010 – 2020	2020 – 2030	2000 – 2010	2010 – 2020	2020 – 2030
China	Low		4.5%	3.6%					4.0%	3.3%
	Ref	**9.9%**	6.0%	4.8%	0.6%	0.5%	0.3%	**9.2%**	5.5%	4.5%
	High		7.5%	6.0%					7.0%	5.7%
India	Low		4.9%	4.1%					3.6%	3.2%
	Ref	**7.5%**	6.5%	5.5%	1.5%	1.2%	0.9%	**5.9%**	5.2%	4.6%
	High		8.1%	6.9%					6.8%	5.9%

The reference scenario growth rates are roughly consistent with projections in IEA (2007). In the case of China, the high growth rates match those used by modelers in that country (e.g. Jiang and Hu, 2006) to represent the continued achievement of the government's goals. The low growth scenario reflects the possibility of a (relative) slowdown, perhaps due to short-term bottlenecks in material inputs as capacity expands. Population growth rates are based on the most recent central UN estimate. Over the remainder of the century, we assume that growth rates gradually decline, reaching 1% for both aggregate and per capita GDP with a stabilized population.

Choosing appropriate values for the AEEI parameter is less straightforward. The autonomous component of energy intensity change can be difficult to separate from price effects in the observed record. For the developed economies such as the US, previous work has supported the assumption of roughly 1% per year decline in energy intensity due to non-price-induced changes. This decline is the net effect of shifts toward less energy intensive industries, improvements in end-use energy efficiency (energy requirement per service unit), and increases in service demand with wealth (a diminishing effect at high income levels). For economies in earlier stages of development, the pattern could be very different. A casual observer might conclude that because developing countries tend to rely on energy intensive industries to begin building their economies, and tend to increase service demand more rapidly as incomes rise, these two effects will dominate efficiency improvements initially, leading to an autonomous increase in energy intensity during this stage rather than a decline. On the other hand, it has also been proposed that faster economic growth leads to a higher turnover rate in the capital stock, which in turn accelerates the introduction of end-use efficiency improvements. The latter proposal has been applied in previous MERGE studies by assuming a faster rate of autonomous decline in China and India than in the US.

The reality is that each country's experience is unique. China and India provide two very distinct pictures. As discussed above, changes in China's institutions in recent decades allowed a correction from very inefficient industrial practices, overwhelming all other effects and driving a steep decline in energy intensity from very high levels (similar to current trends in the Former Soviet Union). With the saturation of this effect and the emergence of strong growth in energy intensive industries in China, the current decade has seen an abrupt return to the more conventional model of rising energy intensity. Meanwhile, in India, energy intensity prior to the current decade had remained fairly constant, rising slightly but much lower than in China, and has fallen rapidly in the current decade, driven by a different and less energy-intensive industry mix. In choosing the AEEI parameter for developing countries, we have attempted to take into account current trends as well as judgments about the relevant stage and patterns of development.

The combined implications of our AEEI choices, elasticities, and energy prices in a no- policy baseline are reflected in Table 2, which shows average annual rates of change in primary energy and energy intensity for the decades in question in China and India. Note that while primary energy diverges across the three growth scenarios, energy intensity changes very little. There is undoubtedly uncertainty as to the future path of energy intensity, but we have elected to hold the AEEI parameter fixed and let the variation in economic growth rates determine the range of growth in primary energy and therefore emissions.

Table 2. Annual Rates of Change in Total Primary Energy and Intensity

		Total Primary Energy			Energy Intensity		
		2000 – 2010	2010 – 2020	2020 – 2030	2000 – 2010	2010 – 2020	2020 – 2030
China	Low	**9.2%**	2.4%	2.1%	**-0.6%**	-1.9%	-1.3%
	Ref		3.8%	3.4%		-2.1%	-1.3%
	High		5.1%	4.5%		-2.3%	-1.4%
India	Low	**3.9%**	2.8%	2.8%	**-3.4%**	-1.9%	-1.2%
	Ref		4.2%	4.4%		-2.1%	-1.1%
	High		5.4%	6.0%		-2.5%	-1.0%

Figure 2 shows new baseline energy-related carbon emissions projections in China, allowing for a range of possible growth rates. In the new projections, emissions reach 2 GtC by 2010 and 3.1 to 5.2 GtC by 2030, two to three times higher than in the CCSP study released in 2007. The IEA's 2007 forecast follows the low end of our projected range. In comparison to previous MERGE studies, total baseline emissions projections from non-Annex B countries in the year 2030 have nearly doubled with the new reference specification; 80% of the increase is due to the revised treatment of China. Although India is often placed in the same category as China with respect to growth, its current emissions are one quarter the level of China's, and that fraction is likely to be smaller by the end of the decade.

Historical Comparison

While current observations inform modeling choices about the beginning of the time horizon, it can be instructive to use historical experience in similar countries as a guide for future periods. The key variables are the rate of economic growth and changes in energy intensity. In the case of China, we consider time series data from four predominant Asian economies (Japan, Taiwan, Korea, and Malaysia)[5] lagged to match China's 2006 income level of roughly $4,000 (in constant 2000 dollars using the World Bank's recently updated PPP exchange rates) (6,7,16). Per capita income in Malaysia reached this level in 1979, Korea in 1977, Taiwan in 1973, and Japan in 1959.[6] Figure 3 shows model projections for per capita

[5] There are seven Asian countries whose per capita income currently exceeds that of China: Singapore, Hong Kong, Japan, Taiwan, Korea, Malaysia, and Thailand. However, we eliminated Singapore and Hong Kong as special cases and Thailand as too recent.

[6] Economic data from IMF (2008) based on the World Bank's 2006 estimates of the PPP value of GDP only extend back to 1980. For earlier years, we have used Penn World Table 6.2 (PWT) data, scaled so that the two data series are equal in 1980. Although China's PPP value of GDP was significantly reduced in the 2006 revision relative to estimates used in PWT, the adjustment for the other four countries was minimal.

income, energy intensity, and per capita energy use compared to the range of experience in these four countries.

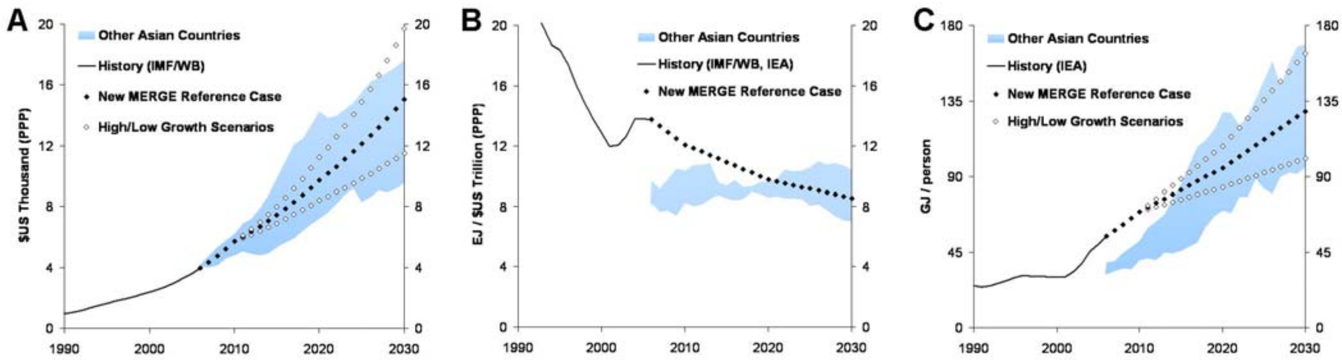

Figure 3. MERGE projections relative to historical experience in Asia.

(**A**) Growth rates in per capita income (measured in constant 2000 PPP dollars) in other Asian countries were similar to current projections for China. (**B**) Energy intensity changes, the net effect of structural shifts in the economy, improvements in end-use energy efficiency, and increases in service demand with wealth, were minimal in other Asian countries while decline is projected for China (only one scenario is considered). (**C**) Per capita energy use has risen more quickly in China, but it is projected to follow historical patterns as energy intensity declines.

From the $4,000 level, incomes in the sample countries grew over the subsequent 24 years to between $10,000 and $18,000, with Taiwan representing the high end of the range, Malaysia the low end. The central MERGE projection reaches $15,000 by 2030, and the outliers of its range correspond closely to the sample range. Thus the economic growth rates underlying our updated specification are consistent with the historical Asian experience. As discussed above, China's energy intensity was in decline prior to 2000, after which it has risen slightly. The sample countries all had lower energy intensity than China in 2006 in the year their income level stood at $4,000. However, during the subsequent period of growth, energy intensity did not decline in any of the sample countries. This observation reinforces the pattern of energy-fueled development into which China may be entering. On the other hand, China's government has stated its goals for economic rebalancing towards a less intensive mix (17,18), and energy prices for the foreseeable future (though subsidized in China) will likely be higher than in the period captured by the sample data. Some early projections for 2006 and 2007 indicate that energy intensity in China has in fact begun to decline again. Using estimates of total primary energy from the 2008 BP Statistical Review (19) and the IMF's estimates for GDP (6), intensity fell by roughly 3% between 2006 and 2007. Therefore we assume a small net decline from 2000 in the current decade, followed by continued decline afterwards so that by 2030 China is in line with the historical range. Finally we compare total primary energy use per capita. This metric is attractive because it summarizes the implications of growth assumptions without relying on the conversion of economic quantities across time and space, which are often speculative and based on limited data. Although per capita energy use was lower in the sample countries in the starting year (a consequence of lower energy intensity at the same income level), growth in subsequent years was rapid. China appears to have taken off slightly earlier than its predecessors in the Asian sphere, but with the comparatively fast reduction in energy intensity, our projections to 2030 again correspond closely to the sample range. The MERGE reference case projects roughly 130 GJ per capita in China by 2030 (current use in Japan and Western Europe is roughly 175 GJ; in the US, 330 GJ).

Differences in per capita energy use across countries with similar wealth levels reflect concrete factors such as average temperature and population density, as well as cultural preferences and development patterns. Whichever model China follows in the long run, our projections for energy use in the upcoming decades are entirely plausible given the experience of its neighbors. Certainly the results would be different with a sample of countries outside of Asia. For example, recent growth in Latin American countries such as Brazil, Mexico, Chile, and Argentina has been both slower and less energy-intensive. However, the emerging Chinese economy bears a much closer resemblance to the Asian countries examined here. While not an econometric study, this comparison provides a useful check for the validity of our projections. Additionally, other recently calibrated models project similar rates of growth over this time horizon for China (20).

Policy Implications

If China and other developing countries are growing much faster than anticipated, what are the implications for stabilization goals currently being discussed by policy-makers in Annex B? The US CCSP report examined four stabilization scenarios, the two most stringent corresponding to atmospheric carbon dioxide concentrations of 450 and 550 ppmv.[7] For each scenario, modelers calculated the pathway of global carbon emissions consistent with the stabilization target. The updated growth rates bring a new urgency to the question of incomplete global participation in abatement. As shown in Figure 4, emissions from the non-Annex B countries alone meet or exceed the global allowable total for stabilization regimes in the near future. The current and expected future rates of growth in developing countries juxtaposed with the proximity of the targets under discussion reveal a very narrow window of feasibility. If the price of carbon outside of Annex B is effectively zero for roughly the next decade, Annex B emissions must be completely eliminated by 2020, followed by rapid reductions outside of Annex B after 2020, in order to keep atmospheric CO2 concentrations below 450 ppmv. With a 550 target, the window is only a decade wider, and both are even smaller if growth in emissions follows the high scenario. Moreover, reductions in Annex B emissions at this pace are likely not realistic.

[7] The two most stringent stabilization scenarios were defined in terms of limits on the total radiative forcing from the Kyoto gases of 3.4 and 4.7 W/m^2, respectively, chosen so that the resulting atmospheric concentrations of CO_2 roughly matched the frequently discussed targets of 450 and 550 ppmv.

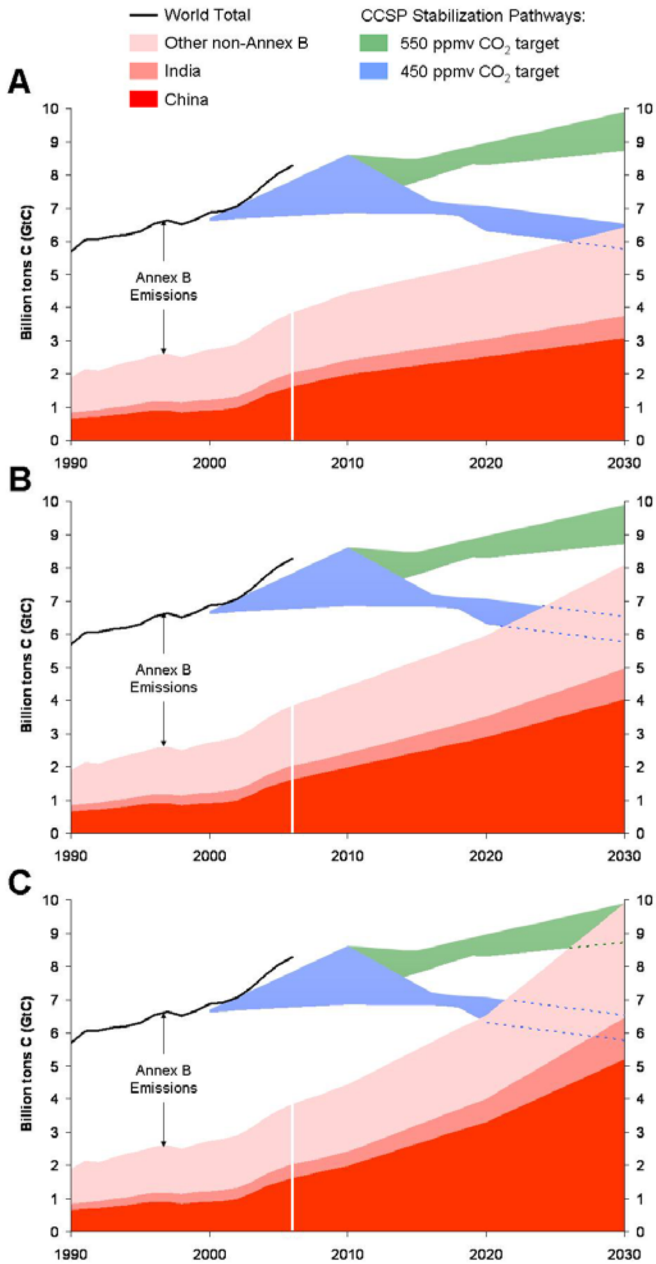

Figure 4. New baseline emission projections relative to stabilization pathways.

Historical global emissions allocated to Annex B, China, India, and other non-Annex B countries are shown. After 2006, the data reflect new MERGE projections for baseline emissions through 2030 in non-Annex B countries, with growth rates corresponding to the low scenario (**A**), reference scenario (**B**), and high scenario (**C**). The range of global emissions consistent with the 450 (CO_2 only) stabilization target in the CCSP report intersects non-Annex B baseline emissions between 2020 and 2025; for the 550 target, the intersection occurs in 2025 for the high growth scenario and after 2030 for the other scenarios.

These results illustrate that the discussion of post-Kyoto international policy frameworks must focus on the participation of developing countries in the very near future. The remainder of the paper examines representative policy choices by applying MERGE in alternative solution modes. As a point of reference to the CCSP report (1), we begin by re-calculating the optimal stabilization paths for the two most stringent targets discussed above. Next we consider three scenarios that take into account constraints limiting developing country involvement. In the first scenario, we assume no developing country participation before 2050. In the second scenario, developing countries gradually adopt the first-best carbon price. In the third, countries take on quantitative targets as their incomes rise according to a rule based on the 1997 Kyoto negotiations. In each case we focus on the first half of the 21st century, although the specification for the more distant future remains important.[8] Finally, we discuss the implications for cost and long-term temperature increase associated with the various scenarios.

Optimal Stabilization

In the newly recalibrated formulation of MERGE, following the reference growth path assumptions for developing countries, the most stringent target assessed in the CCSP report (3.4 W/m^2 or 450 ppmv CO_2 only) is dramatically more costly than in the 2007 study, even with all nations participating on an intertemporally optimal schedule (i.e., even with perfect when and where flexibility). As shown in Figure 5, emissions reductions must begin immediately with a 35% drop from BAU by 2020, which corresponds to a carbon price of over $2,000 per ton carbon (tC) in that year (roughly equivalent to a gasoline tax of $6 per gallon). As such, a target of this stringency is likely to be politically unacceptable.

The second-most stringent stabilization level in the CCSP report is 4.7 W/m^2 or 550 ppmv CO_2 only. The global pathway for energy-related CO_2 consistent with optimal stabilization at this level consists of immediate reductions from the baseline with slow growth peaking between 2020 and 2030, then returning to roughly 2005 levels by 2050 and declining quickly thereafter. While global emissions return to their 2005 level by 2050, the profiles of the various regions differ significantly. Annex B emissions, which grow very little in the business-as-usual case, are reduced to roughly 60% below their 2005 level. On the other hand, non-Annex B emissions, where baseline growth is rapid, are around 60% above their 2005 level in 2050 in the optimal stabilization scenario. Comparing the carbon price for these two stabilization scenarios with the prices reported by MERGE in the CCSP report, it is clear that the 550 target now appears to be almost as difficult to attain as our previous understanding of the 450 target; the latter is now almost out of reach. Indeed, the carbon price for the new optimal 550 path in 2020, the first decision period in the analysis, is almost identical to the price in the CCSP 450 path in 2010, that study's first decision period. This shift is the result not only of our updated growth assumptions, but also the fact that emissions and concentrations have continued to climb towards rapidly approaching thresholds.

[8] The economic component of MERGE operates through 2100, but the climate module runs through 2200 to capture the long-term effects of accumulating atmospheric concentrations on temperature.

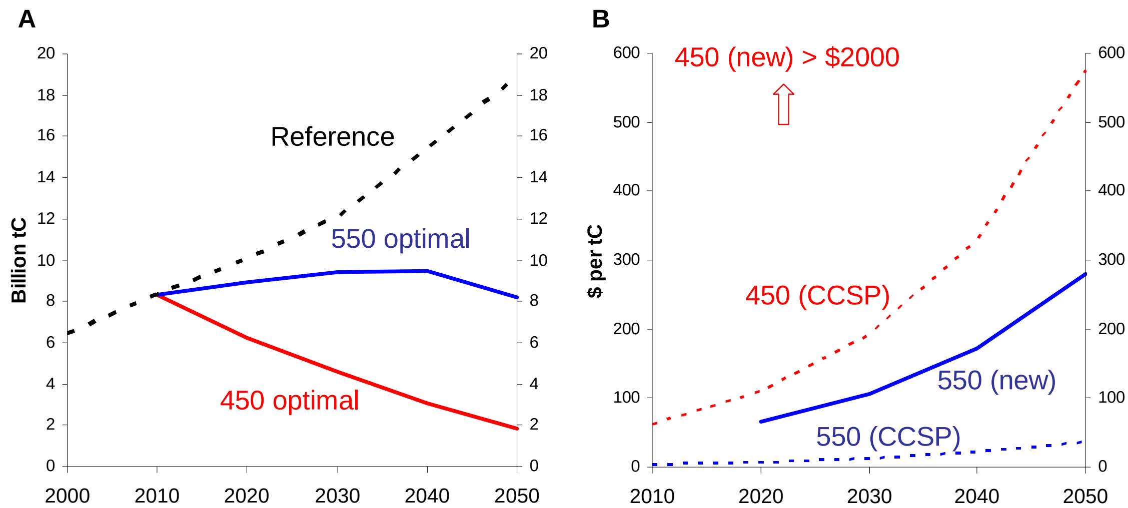

Figure 5. Emissions (A) and carbon price (B) for optimal stabilization pathways.
The optimal stabilization scenarios from the CCSP report were re-run using the new growth rate assumptions. While the respective pathways for global emissions are similar to those depicted in Figure 4, strong business-as-usual growth results in much higher corresponding carbon prices.

With perfect when and where flexibility, abatement effort is allocated optimally across and time and space. In other words, the effective carbon price in all regions is equal to a single world price, which rises smoothly at approximately the rate of interest from a starting point determined by the stringency of the target. Note that this allocation of abatement effort maximizes efficiency (i.e. minimizes total economic cost) without specifying an allocation of costs. Financial transfers in a variety of forms can be arranged to address concerns about equity and burden-sharing. Still, even with the potential for incentives of this kind from developed countries, most observers of the current state of international negotiations would agree that developing countries are not prepared to join a system with a single world price. The lack of sufficient institutional capital in these countries to implement effective abatement policies likely means that for at least the next decade, or longer in some cases, the carbon price upon which investments in energy supply and demand are made will be effectively close to zero.

Graduated Accession

To examine alternative modes of engagement for developing countries, we hold emissions in Annex B countries constant along a path consistent with optimal stabilization at 550, for which 2050 emissions are 60% below the 2005 level. Equivalently, we assume that the effective carbon price in Annex B is the one shown above in Figure 5 for this stabilization target, passing through $65/tC in 2020 and rising to $280/tC in 2050. For non-Annex B, we first examine a "worst-case" policy environment in which no other countries adopt meaningful abatement measures (including hosting CDM-type projects) for several decades, so that emissions in these countries follow their baseline path at least through 2050. In such a scenario, as we have seen above, no matter how aggressive is the action taken in Annex B, global energy-related carbon emissions will continue to rise rapidly. Figure 6 shows global emissions by region through 2050 when the optimal 550 price is applied in Annex B immediately, but the rest of the world follows its reference path. Because Annex B represents a diminishing fraction of global emissions, this scenario results in only a slight reduction from the global reference path. Even if a rapid post-2050 decline is achieved, emissions will have peaked at a level far higher than that consistent with stabilization goals.[9]

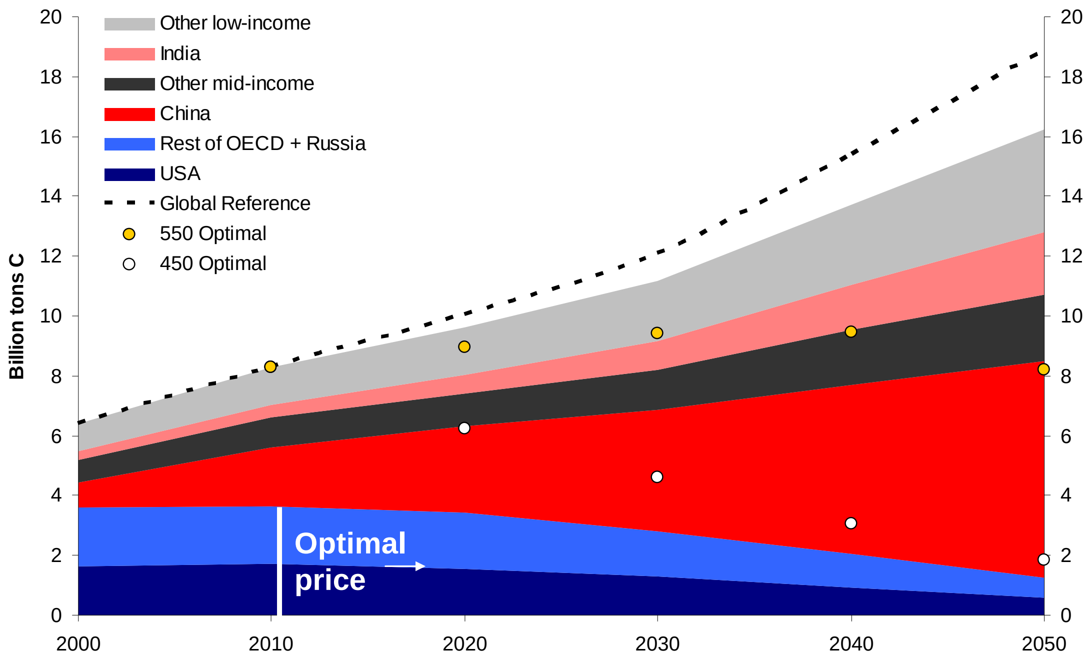

Figure 6: Global emissions with abatement in Annex B only.
Annex B adopts the optimal 550 price beginning after 2010, while Non-Annex B countries follow their reference path. Global emissions depart only slightly from the reference scenario.

Against this backdrop, we next consider a graduated accession scenario. China is undoubtedly the most important player in any global policy regime. While it is unrealistic to assume that China would adopt the same price regime as Annex B initially, they may opt in to a global agreement in the future (21). In addition, several nations outside of Annex B may be willing to participate before others, the so-called "other mid-income" region in the figures (these include, for example, Korea, Brazil, Mexico, and South Africa – see Appendix B for complete regional breakdown). In this case, to "join" the coalition means to adopt the same carbon price as Annex B, the optimal 550 stabilization path. We assume China is joined by the mid-income group of countries in the global regime beginning after 2020. For lower income countries, we assume India does not join until 2040, and other poorer

[9] While "overshoot" is always possible, i.e. returning to a stabilization level after exceeding it, effects on temperature and climate will be determined by the integral of the radiative forcing time path, not its ultimate equilibrium. That is, how far we exceed a stabilization target, and for how long, matters.

countries do not join at all before 2050. Figure 7 shows global emissions in this scenario, termed the "graduated 550 tax" scenario. Since not all countries are adopting the optimal price throughout the time horizon, the resulting emissions path exceeds the optimal path. Still, emissions in this scenario have begun to decline before 2050, and the target is within reach.

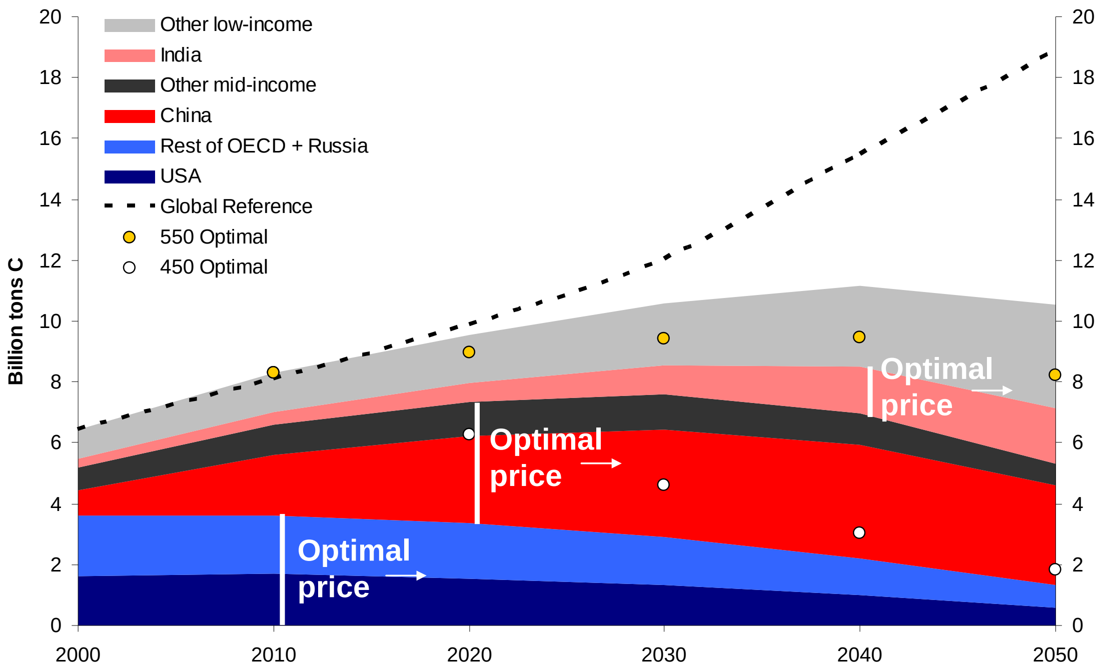

Figure 7: Global emissions in the "graduated 550 tax" scenario.
Annex B adopts the optimal 550 price beginning after 2010. Non-Annex B countries adopt the same price path in future years after following the reference path until graduation.

In this scenario, before "graduation" a country follows its reference case; afterwards it adopts the optimal 550 stabilization price. For participating countries, the price rises at approximately the rate of interest, which helps to create incentives for abatement in earlier years in an intertemporal optimization model such as MERGE. To simulate the lack of institutional capacity for creating abatement incentives in non-participating countries, we hold energy-related variables fixed prior to "graduation" to eliminate this anticipation effect. If graduating countries were modeled without constraints in the pre-accession time periods, so that energy technology investments were made with perfect foresight about the post-accession price, emissions prior to graduation would be only slightly higher than the optimal stabilization path. That is, if a country agrees to adopt a high carbon price in a future time period and the announcement is credible among market participants, this policy is not far from the optimal policy of participation from the beginning. Such is the magnitude of the "shadow" cast back by future prices on investment decisions by fully rational, forward-looking actors. For many observers, this is not a fitting description of pre-accession behavior for developing countries, whose governments are currently both unwilling and unable to set a credible future price on carbon. Instead, our scenario reflects a world in which "graduation" corresponds to the establishment of credible abatement incentives.

Progressive Targets

The graduated accession scenario assumed that as countries join the coalition, they immediately adopt the world optimal carbon price, which is growing over time at approximately the rate of interest. A more realistic political outcome may be that the stringency of the target adopted gradually increases over time. Frankel (2007) observed that targets agreed to for the first commitment period of the Kyoto Protocol, when converted to implicit percentage reductions from a projected baseline, were progressively correlated with per capita income at the time of negotiation (22). Poorer countries were willing to adopt targets that represented smaller percentage reductions from business-as-usual emissions than higher-income countries. This relationship suggests a simple rule that could be used to estimate reasonable targets for developing countries as their incomes rise. The threshold for accepting positive emissions reductions in 2010 was a per capita income of around $4,500 (in year 2000 currency) in 1996.[10] At the upper end of the range, a large group of countries with incomes around $30,000 in 1996 adopted targets that were roughly 25% below their projected BAU emissions for 2010. Using these two points and assuming a logarithmic relationship (as indicated by the data), we construct a simple rule for determining an "acceptable" quantitative reduction target based on per capita income (with a ~15-year lag). The following table shows results for the four non-Annex B regions, using exogenous growth projections in MERGE as the basis for the average income levels (which begin with the IMF (2008) figures for 2005 in PPP terms).

Table 3: Progressive Emissions Reduction Targets

	Per Capita Income (thousands 2000 $US)				Corresponding Emissions Reduction target below BAU			
	2005	2015	2025	2035	2020	2030	2040	2050
China	3.6	7.5	12.1	18.3	---	7%	13%	18%
Other mid-income	10.8	13.9	17.0	21.4	12%	15%	17%	21%
India	2.0	3.4	5.5	8.6	---	---	3%	8%
Other low-income	2.9	4.0	5.4	7.2	---	---	2%	6%

Based on our simple rule, only the mid-income group of regions had an average income level high enough in 2005 to indicate that participation beginning in the next commitment period (i.e. between 2010 and 2020) is likely. China would be the next to join the coalition, but only with a 7% reduction from BAU by 2030. In the previous scenario, when they adopted the optimal stabilization price in 2030, abatement by that year reached

[10] We will interpret this income level as representative of real purchasing power for the purposes of comparison to future income projections. If, as is more likely, it reflects a conversion at market exchange rates, the true purchasing power value of the threshold income would be higher. Thus we are potentially underestimating the level of wealth necessary for a country to accept a positive reduction target.

12%, followed by 35% below BAU in 2040. India and other low-income countries are unwilling to adopt targets before 2040, and still have not significantly reduced emissions by 2050. Figure 8 shows the global emissions pathway through 2050 that would evolve if these targets were adopted and met (termed the "progressive targets" scenario), again assuming that the optimal 550 carbon price is applied in Annex B.

In this case, the progressive reduction targets do not lead to a global downturn in emissions before 2050. Under such a scheme, stabilization even at the 550 level appears doubtful. This is particularly true if we assume that the same rule applies to commitments beyond 2050. In the "graduated 550 tax" scenario shown in Figure 7, we

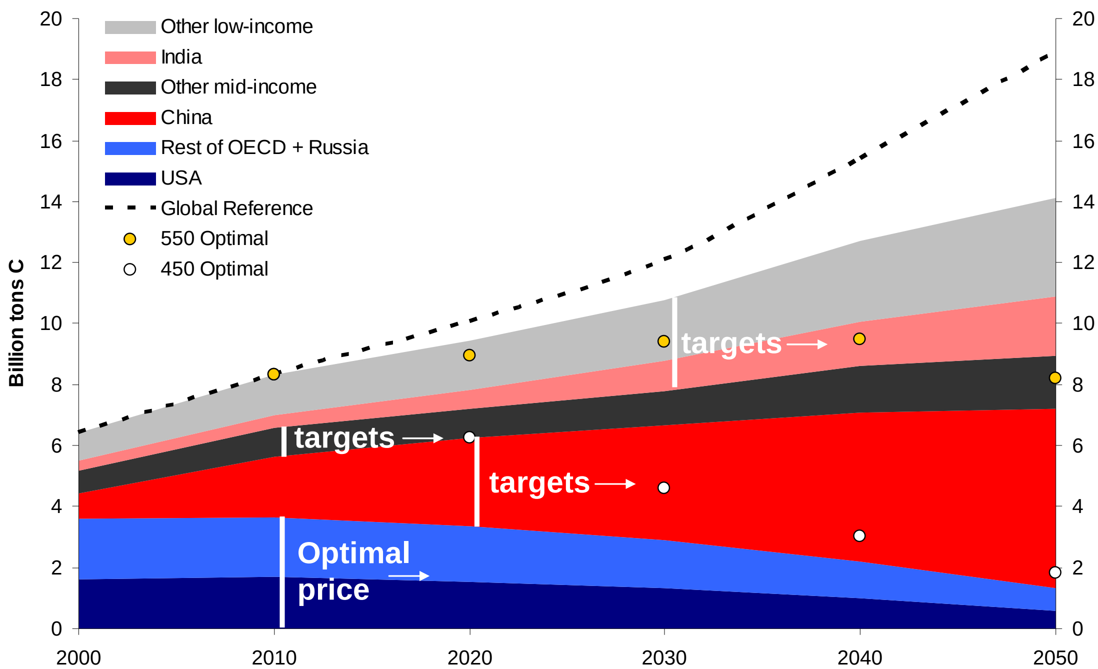

Figure 8: Global emissions in the "progressive targets" scenario.
Non-Annex B countries adopt targets as a function of per capita income levels consistent with observed outcomes in Kyoto negotiations. Annex B adopts the optimal 550 price. Global emissions do not begin to decline by 2050 in this scenario.

assumed that "graduating" countries adopted the optimal world price, so that in the long run, emissions returned to close to the stabilization path. In the "progressive targets" scenario, even if we assume that once countries reach the $30,000 income level they begin to converge to the optimal stabilization price, the long-run global emissions path remains high. Figure 9 shows these two scenarios over the full 100 year time horizon. With the progressive target rule, emissions from the lowest-income countries alone rise to 8 GtC, approximately today's global total. If the targets are interpreted as allocations of permits and global trading is allowed among regions above the income threshold, many developing countries would export their permits to Annex B. In this case the regional distribution of emissions would change, but the global total would not. Thus if developing countries are only willing to adopt targets commensurate with Annex B commitments during the initial Kyoto negotiations, long-term climate stabilization will likely not be possible.

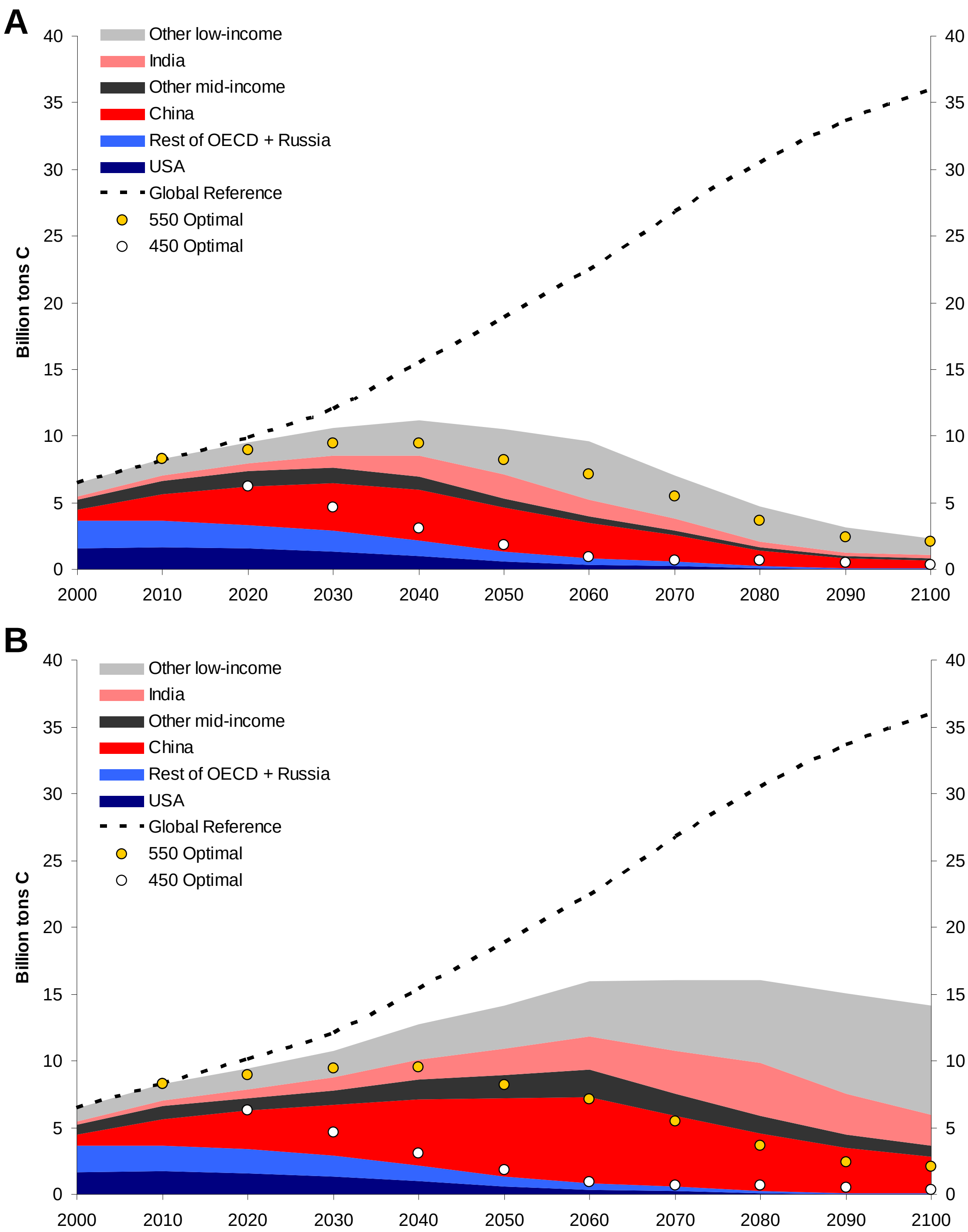

Figure 9. Global emissions through 2100.
In the "graduated 550 tax" scenario (A), global emissions remain only slightly higher than in the optimal 550 path as countries adopt the global price. In the "progressive targets" scenario (B), the quantitative target rule does not result in an emissions path consistent with stabilization.

Costs of Alternative Proposals

We now turn to an examination of the economic costs involved for the various scenarios under consideration, as well as the potential environmental outcomes.

Abatement Costs

When policies are introduced to create incentives for emissions reductions, more expensive, cleaner energy technologies are deployed (to the extent that they are available). This shift leads to direct costs in terms of lost consumption due to higher energy expenditures, but also to deadweight loss in terms of reductions in energy use and economic activity. When more advanced low-emitting technologies are available for deployment at the necessary scale, the costs associated with achieving a particular emissions reduction goal are reduced.[11] We measure the total cost of the abatement effort at a given point in time in a given region by the loss in gross domestic product (GDP) relative to the no-policy reference scenario. Costs can also be summed across regions to measure the total burden of a particular scenario. Figure 10 shows the effects on gross world product (GWP) for the two optimal stabilization cases, as well as the two alternative scenarios.

First, observe that policy costs of the optimal 450 stabilization scenario rise quickly to nearly 10% of global income. Along with an initial carbon price of over $2000 per ton C, these are indications that such a scenario would almost certainly be deemed excessively onerous by the world's policy-makers. The costs of the 550 scenario (although considerably higher than those calculated by MERGE for the same target in the CCSP report), are lower than the 450 scenario, rising to 2% of global income by 2050 and to 3.5% by 2100. In the graduated 550 tax scenario, costs are lower initially because not all countries are undertaking abatement.[12] However, in the long run, even though emissions are not as low as in the optimal 550 case (i.e. the target is not being met), policy costs are higher because long-lived investments in carbon-emitting technologies such as coal-fired electric power plants made in the interim by non-participating regions have made the transition more difficult. This result helps to illustrate that not only are global environmental goals jeopardized the longer developing countries remain outside the coalition, but also the global cost burden of a given target is increased by their adherence to a business-as-usual path. Finally, global costs are the lowest in the progressive targets scenario because emissions remain substantially above levels required for stabilization at 550. If targets are allocated as globally tradable permits, total GWP losses are slightly less than if the targets reflect actual reductions realized in each region.

---

[11] See Richels and Blanford (2008) for an application of the MERGE model to the value of technology in development in the context of the US electric sector (24).

[12] Because MERGE is an intertemporal optimization model, consumption can be shifted over time to maximize welfare, which sometimes results in negative costs in non-participating regions. This is a minor effect.

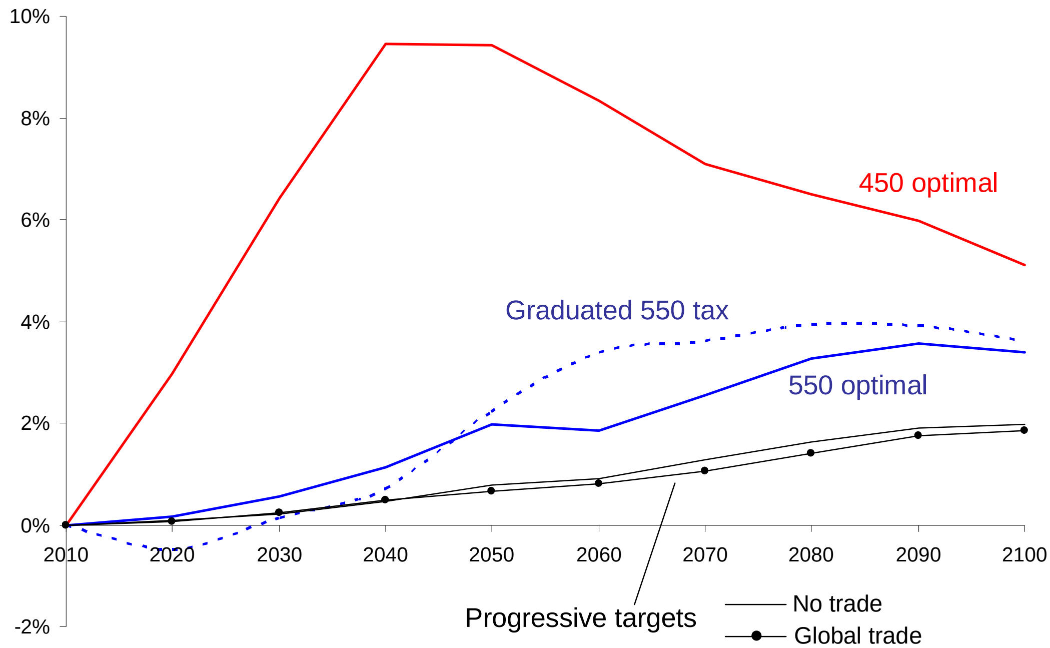

Figure 10: Loss in Gross World Product from reference under various mitigation scenarios. The 450 stabilization target is excessively costly. In the graduated 550 tax scenario, non-participating countries do not anticipate joining the coalition, thus increasing costs after graduation relative to the intertemporally optimal path.[12] The progressive targets scenario involves less stringent emissions reductions and therefore lower cost.

GDP losses in a particular region depend on both the stringency of target adopted (e.g. the region's effective carbon price), and on physical characteristics such as the set of available technologies and the initial conditions of energy use in the economy and the age of the capital stock.[13] Regional costs also depend importantly on the implementation of the policy, which can set rules for allocating the global cost burden across countries according to equity principles or the outcome of international negotiations. We do not investigate the implications of alternative burden-sharing schemes in this analysis. However, our results do offer some insight into the way abatement effort affects regional economies independent of equity-related transfers. Figure 11 maps emissions reductions on the x-axis to economic cost on the y-axis for each region and each time period up until 2050 for the 550 optimal case. On the left side of the figure (A), abatement and cost are expressed in terms of percentage reductions from reference, while on the right side (B), reductions are expressed in absolute terms. In this first-best scenario, marginal abatement cost is equalized across regions in optimally satisfying the long-term constraint, and each country bears the cost of reductions in its emissions up to the efficient price. The correlation of total abatement cost exhibited in Figure 11(B) suggests in addition that intrinsic emissions reduction opportunities are similar

[13] Because MERGE assumes an exogenous growth path, as discussed in the model calibration section, it does not include a link between energy costs and total factor productivity growth. Particularly for developing countries, abatement costs could be larger than our estimates if increased energy expenditures induce a negative feedback on productivity growth.

across regions; they vary only in scale, with China by far the largest. On the other hand, Figure 11(A) shows that in rapidly growing countries such as China and India, the same percentage reduction in emissions corresponds to a greater percentage reduction in GDP than in Annex B. It is discrepancies in this dimension that drive the need for equity-based adjustments. If such adjustments cannot be accomplished with compensating financial transfers, parity in percentage based GDP impact can only be achieved by limiting the percentage reductions in emissions in countries like China and India, as in the progressive targets scenario. However, this approach has been demonstrated above to yield comparatively little environmental protection.

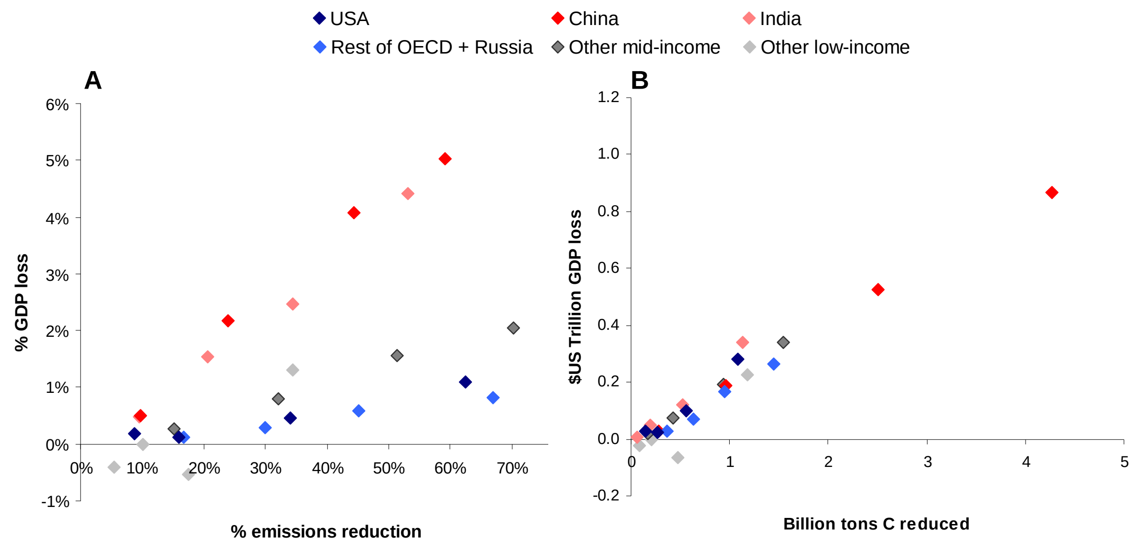

Figure 11. Distribution of abatement cost in 550 optimal scenario, 2020 - 2050.
Regional abatement and GDP loss are shown in percentage terms (A) and absolute terms (B), relative to the business-as-usual reference case. While regional costs are similar in the absolute dimension, abatement as a share of GDP is higher for developing countries.

Environmental Costs

Ultimately, society must choose an appropriate balance between the near-term economic cost of abatement and the long-term environmental risks posed by increased global temperature. We do not undertake such a benefit-cost analysis here, but we provide an estimate of how these emissions scenarios translate into environmental outcomes. In the extremely stringent optimal 450 scenario, radiative forcing from the Kyoto gases was by definition limited to 3.4 W/m2. When combined with other forcing agents held constant in our analysis, principally the gases regulated under the Montreal protocol and the cooling effect (i.e. negative forcing) from sulfur aerosols, total radiative forcing stabilized at approximately 3.0 W/m2. The equilibrium temperature increase above pre-industrial associated with sustained forcing of this magnitude depends on our assumption about climate sensitivity. This parameter, the key uncertainty in understanding our impact on the climate system, is defined as the equilibrium temperature increased associated with a doubling of atmospheric CO2, which corresponds to 3.7 W/m2. The latest IPCC assessment (23) reports 3°C for the median value of climate sensitivity. Accordingly, our 450 scenario leads to a median temperature increase 2.4°C.[14]

This result implies that enforcing a limit on global average surface temperature increase (precisely, our median estimate of temperature increase) in the 2 – 2.5°C range would be so costly as to be practically impossible. For the 550 scenario, Kyoto gas forcing is held to 4.7 W/m2, resulting in a total forcing of 4.2 W/m2. In this case, we observe a median temperature increase of 3.4° C. In the graduated 550 tax scenario, total radiative forcing is not stabilized; it reaches 4.5 W/m2 by the end of the century and continues to rise. This leads to a temperature increase of 3.8°C by 2200. In the progressive targets scenario, radiative forcing is much higher at the end of the century, around 6.2 W/m2, with temperature increase exceeding 5°C (depending how quickly emissions are reduced after 2100). These results are summarized in Table 4, which includes temperature outcomes for a broad range of climate sensitivity assumptions corresponding to the IPCC's 90% confidence interval.

Table 4. Radiative Forcing and Temperature Outcomes

	Radiative forcing (W/m^2) in 2100		Temperature increase (°C above pre-industrial) by 2100 (2200) with alternative climate sensitivities		
	From Kyoto gases	Total (including aerosols)	1.5 (5th %-ile)	3.0 (50th %-ile)	6.0 [14] (95th %-ile)
450 Optimal	3.4	3.0 (stabilized)	1.2 (1.2)	2.2 (2.4)	2.6 (3.7)
550 Optimal	4.7	4.2 (stabilized)	1.7 (1.7)	3.1 (3.4)	3.4 (5.1)
Graduated 550 Tax	5.0	4.5 (not stabilized)	1.8 (2.0)	3.3 (3.8)	3.5 (5.6)
Progressive Targets	6.7	6.2 (not stabilized)	2.4 (3+)	4.0 (5+)	3.9 (7+)
Reference	8.3	7.8 (not stabilized)	2.9 (4+)	4.6 (8+)	4.4 (10+)

Conclusion

The recent acceleration of energy-related emissions in the developing world, particularly China, has taken many analysts by surprise. Our results indicate that with an updated view of the near-term prospects for growth and opportunities for abatement,

---

[14] The equilibrium temperature response to forcing levels other than 3.7 W/m^2 is proportional to climate sensitivity. E.g., in the 450 optimal case, equilibrium temperature is equal to $(3 / 3.7) \times 3 = 2.4$°C. For median and lower climate sensitivity, the equilibrium response is realized by 2200. For higher climate sensitivities, we must assume a slower response time for consistency with current observations, so that even when forcing is stabilized by 2100 or before, equilibrium temperature is not reached by 2200.

keeping atmospheric CO2 below the 450 ppmv level is no longer an option. At the same time, a target in the range of 550 ppmv has become as difficult to achieve as the 450 ppmv target appeared just a few years ago. This trend will continue as long as growth in global emissions continues unabated. Therefore the most critical design element for post-Kyoto international climate policy should be the establishment of incentives for abatement outside of Annex B. Global policy measures must engage developing countries, especially China, in a meaningful way soon if stringent stabilization goals are to be achieved. Such engagement must be accompanied not only by emissions reductions in Annex B, but may also require significant financial incentives from the developed world, depending on the negotiated burden-sharing scheme. It is in all nations' interests to work cooperatively to limit our interference with the global climate.

References

1. Clarke, L. *et al.* (2007). Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations. Sub-report 2.1A of Synthesis and Assessment Product 2.1 by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Department of Energy, Office of Biological & Environmental Research, Washington, DC, USA.

2. Weyant, J.P. *et al.* (1999). The costs of the Kyoto Protocol: a multi-model evaluation. *Energy Journal*, Special Issue.

3. Marland, G. *et al.* (2007). Global, Regional, and National Fossil Fuel CO_2 Emissions. In Trends: A Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., USA.

4. Raupach, M. *et al.* (2007). Global and regional drivers of accelerating CO_2 emissions. Proceedings of the National Academy of Sciences, USA.

5. Fisher-Vanden, K., G.H. Jefferson, H. Liu, and Q. Tao (2004). What is driving China's decline in energy intensity? *Resource and Energy Economics* **26**:1, pp 77-97.

6. IMF (2008). World Economic Outlook 2008. International Monetary Fund, Washington, DC, USA.

7. IEA (2007a). World Energy Statistics 2007. International Energy Agency, Paris, France.

8. IEA (2007b). World Energy Outlook 2007. International Energy Agency, Paris, France.

9. Gregg, J.S., R.J. Andres, and G. Marland (2008). China: Emissions patterns of the world leader of CO_2 emissions from fossil fuel consumption and cement production. *Geophys. Res. Lett.*, **35**, L08806, doi:10.1029/2007GL032887.

10. IEA (2000). World Energy Outlook 2000. International Energy Agency, Paris, France.

11. IEA (2005). World Energy Outlook 2005. International Energy Agency, Paris, France.

12. MNP (2008). Global CO_2 emissions: increase continued in 2007. Netherlands Environmental Assessment Agency.

13. Auffhammer, M. and R.T. Carson (2008). Forecasting the path of China's CO_2 emissions using province-level information. *J. Environ. Econ. Manage.*, doi:10.1016/j.jeem.2007.10.002..

14. Manne, A.S. and R.G. Richels (2005). MERGE: An Integrated Assessment Model for Global Climate Change. In *Energy and Environment*, R. Loulou, J. Waaub, and G. Zaccour, eds., pp 175-189. Springer, New York, NY, USA.

15. Richels, R.G., T.F. Rutherford, G.J. Blanford, and L. Clarke (2007). Managing the transition to climate stabilization. *Climate Policy* **7**:5, pp 409-428.

16. Heston, A., R. Summers, and B. Aten (2006). Penn World Table Version 6.2, Center for International Comparisons of Production, Income and Prices at the University of Pennsylvania, USA.

17. Jiang, K. and X. Hu (2006). Energy demand and emissions in China: scenarios and policy options. *Environ. Pol. Stud.* **7** pp 233-250.

18. He, J. and L. Kuijs (2007). Rebalancing China's economy: modeling a policy package. World Bank China Research Paper No. 7.

19. BP (2008). BP Statistical Review of Energy.

20. McKibben, W.J., P.J. Wilcoxen, and W.T. Woo (2008). Preventing the Tragedy of the CO_2 Commons. Brookings Global Economy and Development Working Paper 22.

21. Wiener, J.B. (2008). Climate change policy and policy change in China. UCLA Law Review **55**, pp 1805-1826.

22. Frankel, J. (2007). Formulas for Quantitative Emissions Targets. In *Architectures for Agreement*, Aldy, J.E. and R.N. Stavins, eds. Cambridge University Press, pp 31-56.

23. IPCC (2007). Fourth Assessment Report.

24. Richels, R.G. and G.J. Blanford (2008). The value of technological advance in decarbonizing the US economy. *Energy Economics*, dx.doi.org/10.1016/j.eneco.2008.06.005.

Acknowledgements

We thank participants in a workshop at the Pacific Northwest National Laboratory for helpful comments. This research was funded by the Electric Power Research Institute (EPRI). The views presented here are solely those of the individual authors, and do not necessarily represent the views of EPRI or its members.

Appendix A. Technology in MERGE

Table A1 describes technological options in the electric sector. Parameter ranges reflect the improvement path over time. For Annex B countries, coal with capture and new nuclear plants are first available in 2020, with improvement beginning in subsequent decades through 2050. In other regions, we assume the same technologies become available, lagged by one decade in the case of China and other mid-income countries, and two decades in the case of India and other low-income countries. Table A2 shows our assumptions for non-electric energy technologies.

Table A1. Electric Generation Technology Assumptions

Existing Technologies*	
Coal	LCOE° = \$25 / MWh Efficiency = 33%
Natural Gas	LCOE° = \$52 / MWh[#] Efficiency = 40%
Nuclear	LCOE° = \$25 / MWh
Hydroelectric, etc.[†]	LCOE° = \$20 / MWh
New Technologies	
Coal (without CCS)	LCOE° = \$57 - \$41 / MWh Efficiency = 38% - 46%
Coal with CCS	First available in 2020 LCOE° = \$80 - \$56 / MWh Efficiency = 31% - 42% Capture rate = 90%
Natural Gas (without CCS)	LCOE° = \$50 - \$70 / MWh[#] Efficiency = 49% - 60%
Natural Gas with CCS	First available in 2020 LCOE° = \$84 - \$110 / MWh[#] Efficiency = 39% - 42% Capture rate = 90%
Nuclear (new ALWR)[‡]	First available in 2020 LCOE° = \$40 - \$37 / MWh Non-market cost[‡] = \$10 / MWh
Wind	LCOE° = \$86 - \$62 / MWh
Biomass	LCOE° = \$86 - \$69 / MWh
Solar (thermal)	LCOE° = \$144 - \$66 / MWh
Solar (photovoltaic)	LCOE° = \$225 - \$81 / MWh

* Capital costs are assumed to be fully recovered for existing generation assets and hence are omitted from the levelized cost calculation.

° LCOE refers to full levelized cost of electricity.
LCOE for existing natural gas generation is shown for the base year price for natural gas. The full range of natural gas prices reported in the model are shown in the LCOE projections for new natural gas generation.
† This category, while predominantly hydroelectric, includes all categories of renewables in place in the base year.
‡ ALWR refers to advanced light water reactor. We assume that the cost of nuclear generation has a market and non-market component. The latter, which is calibrated to current usage, rises proportionally to market share and is intended to represent public concerns about security and environmental risks in the technology and associated nuclear fuel cycle. Non-market costs are not included in the LCOE calculation.

Table A2. Non-Electric Energy Technology Assumptions

Coal (for direct use)	Cost = $2 - $3 / GJ
Petroleum (cost rises with extraction and depends on region)	Cost = $3 - $20 / GJ
Natural Gas (cost rises with extraction and depends on region)	Cost = $4 - $20 / GJ
Synthetic (coal-based) Liquids	Cost = $11 / GJ
Biofuels	Cost = $10 / GJ
Non-Electric Backstop	Cost = $25 / GJ

Appendix B. Scenario Descriptions

Table B1 provides an overview of the scenarios presented in the policy analysis section of this paper. All scenarios use the reference assumption for growth in developing countries discussed in the earlier part of the paper.

Table B1. Overview of Scenarios.

	450 and 550 Optimal	Graduated 550 Tax	Progressive Targets
Policies Enacted			
Annex B	Optimal price	Optimal price (550)	Optimal price (550)
Non-Annex B	Optimal price	Optimal price (550) after graduation	Quantity targets corresponding to income
Year after which participation begins			
Annex B	2010	2010	2010
China	2010	2020	2020
Other mid-income	2010	2020	2010
India	2010	2040	2030
Other low-income	2010	2050	2030

Table B2 gives details of the composition of regions in the analysis. Note in particular the "rest of OECD" includes only those members of the OECD which were also parties to the Kyoto Protocol, that is, it excludes Korea, Mexico, and Turkey. The distinction between the mid-income country grouping and the low-income country grouping was made on the basis of current per capita income. The dividing threshold was roughly $6,000 per capita (in year 2000 $US PPP). One exception is the wealthy oil-exporting countries of Kuwait, Qatar, and United Arab Emirates, which were placed in the low-income group along with other oil-exporters. Also, relatively high-income countries who are not members of the OECD or Annex B, such as Israel and Singapore, are placed in the mid-income group.

Table B2. Regional Composition

Rest of OECD	Other Mid-Income	Other Low-Income
EU27 + Iceland, Norway and Switzerland Australia Canada Japan New Zealand	Argentina Brazil Chile Korea Malaysia Mexico South Africa Taiwan Thailand Turkey Other small high- and mid-income countries	OPEC countries Other Asia Other Latin America Other Middle East Low-income Former Soviet Republics Sub-Saharan Africa