Climate Change Impacts, Energy, and Development

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Annual World Bank Conference on Development Economics 2007, Global (c) 2007 The International Bank for Reconstruction and Development / The World Bank

Climate change poses a major challenge, but responding to it creates opportunities as well as threats to development. The balance between them will to a large degree be a function of how public policy responds. In particular, rapidly expanding investment in carbon-intensive infrastructure increases both the environmental risks faced by developing countries, and the financial risk of such investments becoming 'stranded assets' as carbon controls tighten over time. This creates a compelling case for broad-based action now to switch investment towards improving energy efficiency and lower carbon sources.

Specific policy responses will vary based on national circumstances, but must combine three basic elements: carbon pricing, implemented mainly through cap-and-trade systems; policies to address a variety of informational, behavioral, and structural barriers to optimal responses; and policies to reflect long-term public benefits associated with low-carbon infrastructure and innovation-related investments.

General acceptance that climate is a real and pressing problem is moving the issue from scientific debate and observation toward questions about the impact of climate change on economic development and the implications of measures to tackle it. This article briefly summarizes the scientific evidence and nature of the problem before discussing the implications and relation to economic and development policy. Its focus is the implications of climate change for development, with an emphasis on investment and infrastructure, in accordance with the theme of this year's ABCDE conference.

The article is divided into four main sections. The first section summarizes the scientific evidence, presents projections, and discusses key points on evaluating impacts, particularly for developing countries. The second section presents some empirical evidence on the relation between emissions and economic development, presenting four facts about and four opportunities created by the relation between development and CO_2 emissions. The third section analyzes the global macroeconomics of emissions mitigation, including the role of infrastructure and innovation. The fourth section concludes with a brief survey of policy instruments that can be adopted to tackle emissions while minimizing costs and maximizing opportunities.

Although the article takes the form of a wide-ranging review, it has a unifying theme: that the problem of climate change can be tackled and that, although countries face hugely different circumstances and are at very different stages of development, it is in the interest of every country to take appropriate action to do so. The magnitude of the problem, and the inertia inherent in responses, mean that waiting—or blaming others—is no longer a credible option.

- **Science and the Nature of the Challenge**

Emissions of various gases from industrial and other human activities are changing the atmosphere.[1] *Climate change* encapsulates the wide variety of accompanying impacts on temperature, weather patterns, and other natural systems. Despite decades of research, important questions remain uncertain, but much is also now established beyond reasonable doubt.

The fundamentals of climate change have long been well understood, because they involve the same basic physics that keeps the earth habitable. Heat-trapping greenhouse gases in the atmosphere (of which the two most important are water vapor and carbon dioxide [CO_2]) let through short-wave radiation from the sun but absorb the long-wave heat radiation coming back from the earth's surface and reradiate it. These gases act like a blanket, keeping the surface and the lower atmosphere about 33˚ Celsius warmer than it would be without them.

Primarily as a result of the burning of fossil fuels and deforestation, humans have been increasing the concentration of CO_2 and other greenhouse gases in the atmosphere since the Industrial Revolution began, thickening the greenhouse blanket. Surface warming in recent decades is established beyond doubt (figure 1). So too is cooling of the stratosphere (the layer above the main blanket), as would be expected from greenhouse warming that traps more heat near the surface. Direct temperature records back to the middle of the nineteenth century are considered to be reliable enough to establish that recent temperatures are warmer than any since direct measurements began. Since the 1980s, partly as the result of the clean-up of other industrial pollutants (some of which had masked underlying warming), the underlying long-term greenhouse warming has emerged more clearly: all of the 10 warmest years have occurred since 1990, including each year since 1995. Better accounting for these and other factors can now generate a good fit between the observed temperature trend and the results of computer simulations that incorporate these multiple factors.

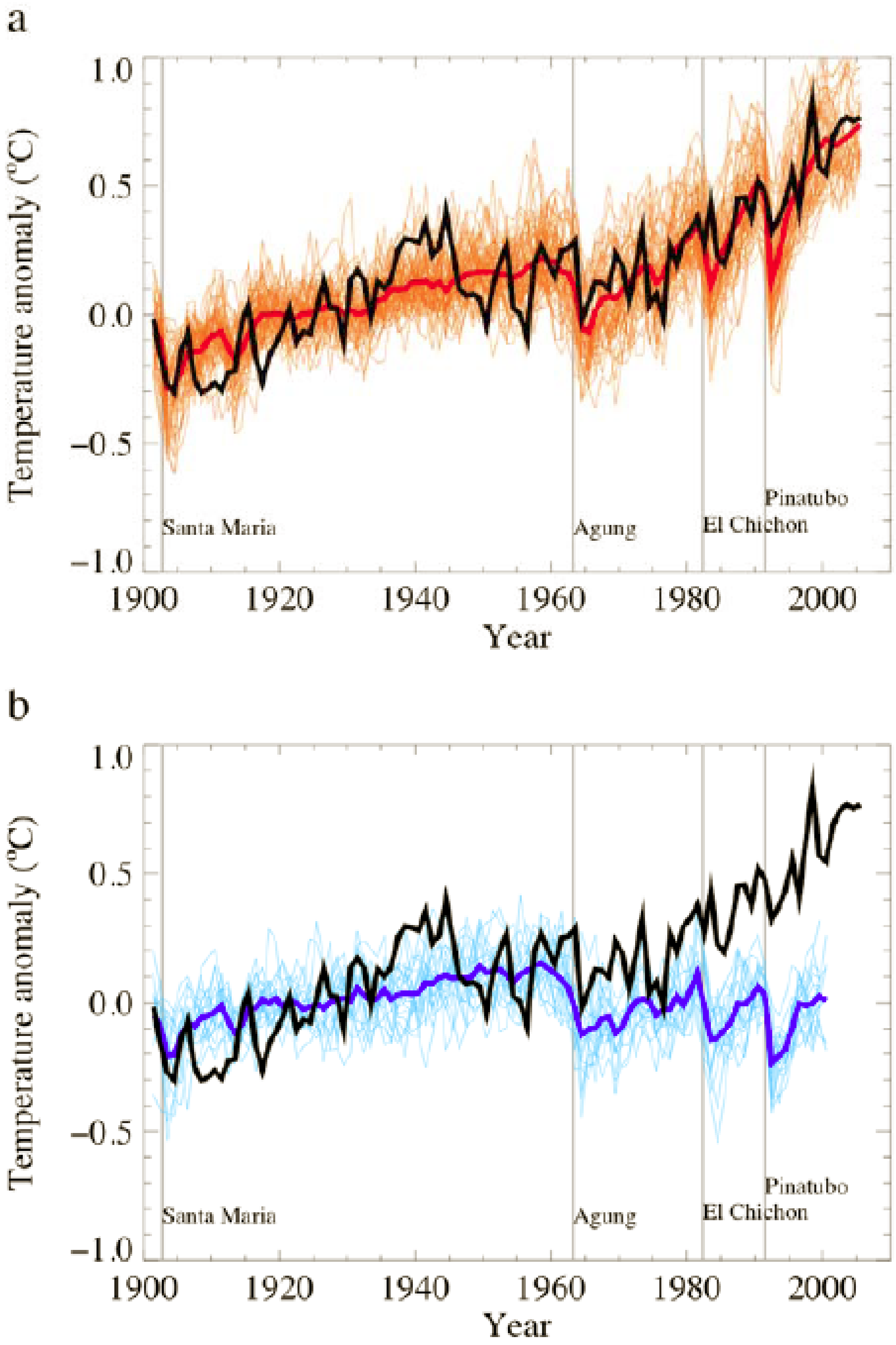


Figure 1. Temperature variances relative to 1901-1950 as observed (dark line), compared to multi-model simulated global temperature anomalies with both a natural and anthropogenic (human-induced) influences (upper panel), and simulated anomalies from natural forcing only (lower panel).
Source: IPCC 2007a

Although debate continues about the exact temperatures during medieval times, a wide variety of proxy indicators (tree rings, coral layering, glacier records) give a high level of confidence that the warming observed today is unprecedented. Indeed, it appears that annual global average temperatures have varied by less than one degree Celsius for thousands of years and probably during the entire post–Ice Age period (during which human civilization developed), suggesting that recent years have probably been the warmest in more than 100,000 years. Scientists have been unable to identify natural factors that could explain either the degree or the pattern of the surface warming and stratosphere cooling observed over recent decades. Understanding is still incomplete, but the fundamentals are clear and supported by a long list of other accumulating impacts.

The list of observed changes other than temperature and sea level is growing rapidly. These include "the thawing of permafrost, later freezing and earlier break-up of ice on rivers and lakes, lengthening of mid- to high-latitude growing seasons, poleward and altitudinal shifts of plant and animal ranges, declines of some plant and animal populations, and earlier flowering of trees, emergence of insects, and egg-laying in birds" (IPCC 2001c. pp. 3)

Perhaps the clearest, most prominent and consistent indicator of warming is the retreat of mountain glaciers, which has occurred throughout most of the world. Impacts on ice are also clear around the poles. The Arctic ice cap is shrinking, and the Larsen Ice Shelf around the Antarctic Peninsula has undergone unprecedented disintegration. Coral reefs have been bleaching, at least partly because of rising sea-surface temperatures.

Many areas have seen fewer long cold spells and more long hot spells, in ways that are consistent with the predictions of climate models. Warming increases evaporation and precipitation, and both aggregate rainfall and the occurrences of "heavy precipitation events" in northern midlatitudes (such as Europe and the United States)—the principal cause of flooding—have increased in recent decades. In tropical regions, the potential for more intense hurricanes and typhoons increases in a warmer world, but the data are sufficiently sparse and complex that the trend remains in dispute.

Since by definition extreme events occur infrequently, trends are hard to prove. Unlike the general trends of temperature, ice level, and sea level, it may always be questionable to attribute any one particular weather event to climate change, because all weather events have multiple causes. So the question "was X due to climate change?" cannot be answered simply, whether X is record temperatures, exceptional storms, floods, or droughts. Nevertheless, science may increasingly be able to estimate how much past emissions increase the risk of extreme high temperatures and in some areas droughts and flood events.[2]

There is little dispute however about the potential for weather-related extreme events to inflict devastating human and economic impact, even in relation to national GDP for smaller countries. In recent years there have been events with impacts that range "from 4 to 6% of GDP (Mozambique flooding: Cairncross and Alvarinho 2005) to 3% (El Niño in Central America: www.eclac.cl/mexico/: "desastres") to 7% (Hurricane Mitch)" (IPCC 2007b, pp: 32). The extent to which such events might be increased or exacerbated by climate change is thus a critical concern – but an unavoidably complex one.

- ***Projected Impacts of Climate Change***

The distinction between climate and weather is a bit like that between sea level and waves. Sea level sets average conditions, which vary locally according to tides and coastline, but understanding these factors does not mean that one can easily pick out trends from individual waves or predict them in detail. The complexities and uncertainties around climate change should not obscure the basic facts, however. The fundamental mechanics of climate change are well understood: the world is warming, and much of the warming is due to human emissions of greenhouse gases.

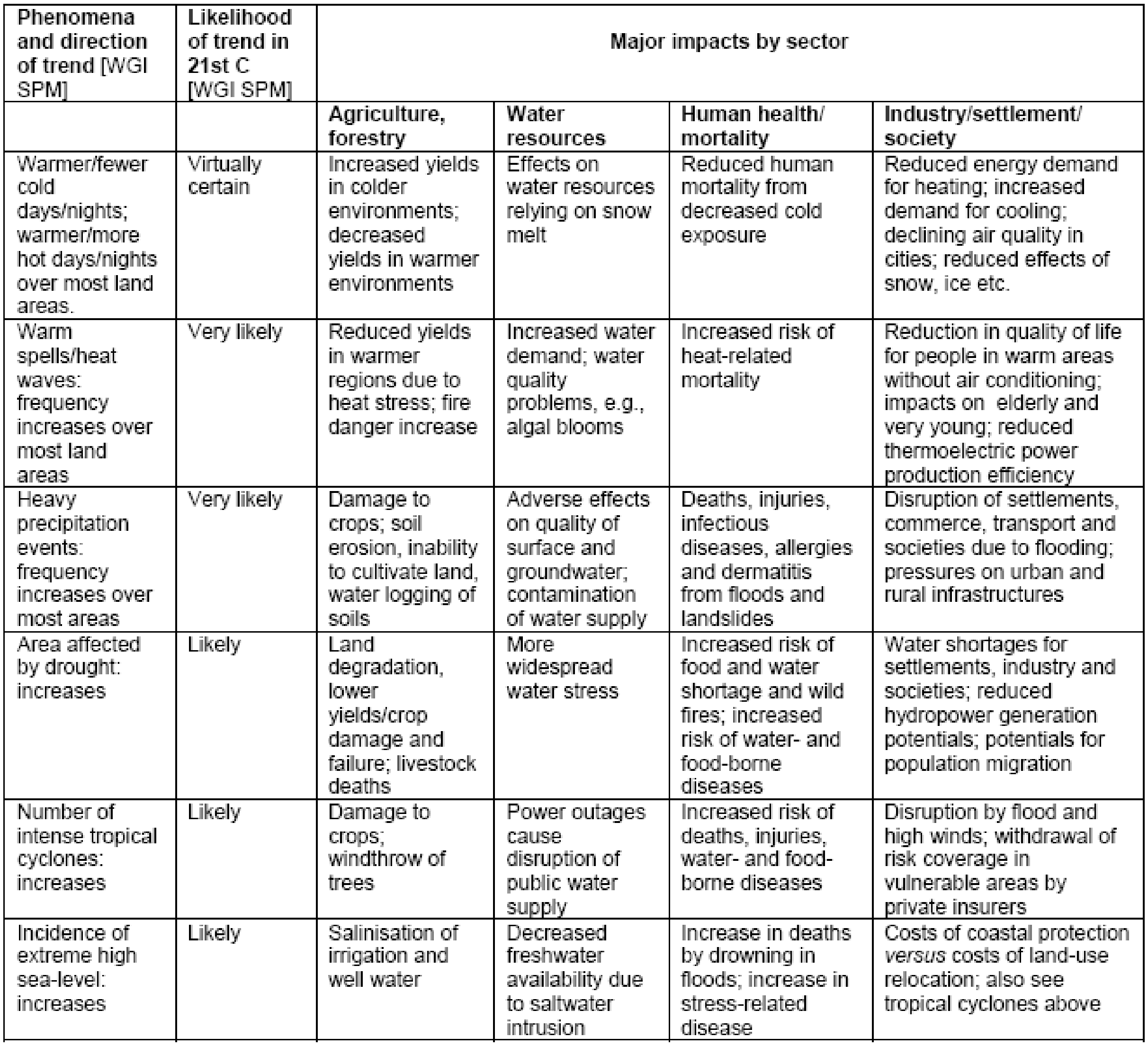
Some persistent trends can already be projected with confidence. The snows of Kilimanjaro, for example, already much shrunk, are expected to disappear entirely within the next few decades—it is already too late to avert this (Alverson and others 2001). Glaciers and sea ice will continue to shrink, and there may be no Arctic Sea ice in the summer by the end of this century. Being in a much colder climate, the Antarctic ice sheet is less likely to lose mass, but some ice shelves around it will disappear.

Existing zones of preferred vegetation and associated crops will migrate toward the poles, forcing farming practices and ecosystems to adapt. Many species and ecosystems have limited scope to move, however, because of variety of barriers. The most comprehensive study to date estimates that about a quarter of the world’s known animals and plants—more than a million species—will eventually die out because of the warming projected to take place in the next 50 years (Thomas and others, 2004).

In addition to the broad physical and biological trends of warming and glacier retreat, sea-level rise, and the migration and loss of species and ecosystems, other predicted impacts of climate change are many and varied. And as research continues and experience begins to accumulate, the list grows longer.

The most authoritative source of analysis is the Intergovernmental Panel on Climate Change (IPCC), which has recently completed its Fourth Assessment. Table 1 gives an overview of projected impacts by category and sector, at various levels of confidence, as summarized in the IPCC’s Impacts and Adaptation report (IPCC 2007b).

Table 1 Possible impacts of climate change due to changes in extreme weather and climate events, based on projections to the mid to late 21st century.



Phenomena and direction of trend [WGI SPM]	Likelihood of trend in 21st C [WGI SPM]	Major impacts by sector			
		Agriculture, forestry	**Water resources**	**Human health/ mortality**	**Industry/settlement/ society**
Warmer/fewer cold days/nights; warmer/more hot days/nights over most land areas.	Virtually certain	Increased yields in colder environments; decreased yields in warmer environments	Effects on water resources relying on snow melt	Reduced human mortality from decreased cold exposure	Reduced energy demand for heating; increased demand for cooling; declining air quality in cities; reduced effects of snow, ice etc.
Warm spells/heat waves: frequency increases over most land areas	Very likely	Reduced yields in warmer regions due to heat stress; fire danger increase	Increased water demand; water quality problems, e.g., algal blooms	Increased risk of heat-related mortality	Reduction in quality of life for people in warm areas without air conditioning; impacts on elderly and very young; reduced thermoelectric power production efficiency
Heavy precipitation events: frequency increases over most areas	Very likely	Damage to crops; soil erosion, inability to cultivate land, water logging of soils	Adverse effects on quality of surface and groundwater; contamination of water supply	Deaths, injuries, infectious diseases, allergies and dermatitis from floods and landslides	Disruption of settlements, commerce, transport and societies due to flooding; pressures on urban and rural infrastructures
Area affected by drought: increases	Likely	Land degradation, lower yields/crop damage and failure; livestock deaths	More widespread water stress	Increased risk of food and water shortage and wild fires; increased risk of water- and food-borne diseases	Water shortages for settlements, industry and societies; reduced hydropower generation potentials; potentials for population migration
Number of intense tropical cyclones: increases	Likely	Damage to crops; windthrow of trees	Power outages cause disruption of public water supply	Increased risk of deaths, injuries, water- and food-borne diseases	Disruption by flood and high winds; withdrawal of risk coverage in vulnerable areas by private insurers
Incidence of extreme high sea-level: increases	Likely	Salinisation of irrigation and well water	Decreased freshwater availability due to saltwater intrusion	Increase in deaths by drowning in floods; increase in stress-related disease	Costs of coastal protection *versus* costs of land-use relocation; also see tropical cyclones above

Source: IPCC 2007c pg 14. Note: the likelihood (confidence) categories are defined as *Virtually certain* > 99% probability of occurrence, *Extremely likely* > 95%, *Very likely* > 90%, *Likely* > 66%.

There are several broad approaches to thinking about the potential implications of such impacts for human economies and societies. During the 1990s, scientific emphases on physical impacts and risks tended to contrast with economic studies that tended to be far more optimistic. The economic debate was stimulated largely by Nordhaus (1991), who argued that quantifiable impacts of a warmer climate would be modest and justified only very limited action to mitigate emissions, and by Cline (1992), who adopted broadly comparable methods but found quite different results depending largely on discounting assumptions. Mendelsohn, Nordhaus, and Shaw (1994) developed more detailed analyses of agricultural impacts in the United States, concluding that moderate levels of climate change could boost U.S. agricultural output. During the 1990s these analysts extended this work to other sectors and other countries. These studies, considered below, indicated that impacts will be highly diverse, with gains in some regions and the brunt of damage falling on low-latitude developing countries.

These relatively optimistic economic analyses have been based primarily on projections of aggregate average warming (or comparative static) patterns and effective adaptation to them. For these reasons, they have come under extensive criticism. Certainly, any evaluation of human implications needs to start from a more comprehensive understanding of the likely nature of impacts than displayed in these early economic evaluations, as discussed below. Moreover, human impacts depend on specific changes in regions and localities. Localized changes are likely to be both more varied and harder to predict than global averages. All projections are thus still quite speculative.

Two regional examples help illustrate possible consequences.[3] Summer drying and heat waves in and around the Mediterranean could further stress water supplies in some regions that are already politically less stable and heavily dependent on irrigation for agriculture. Such changes could also drive expanded migration into northern Europe, which might itself come under growing pressure from increased floods and heat waves.

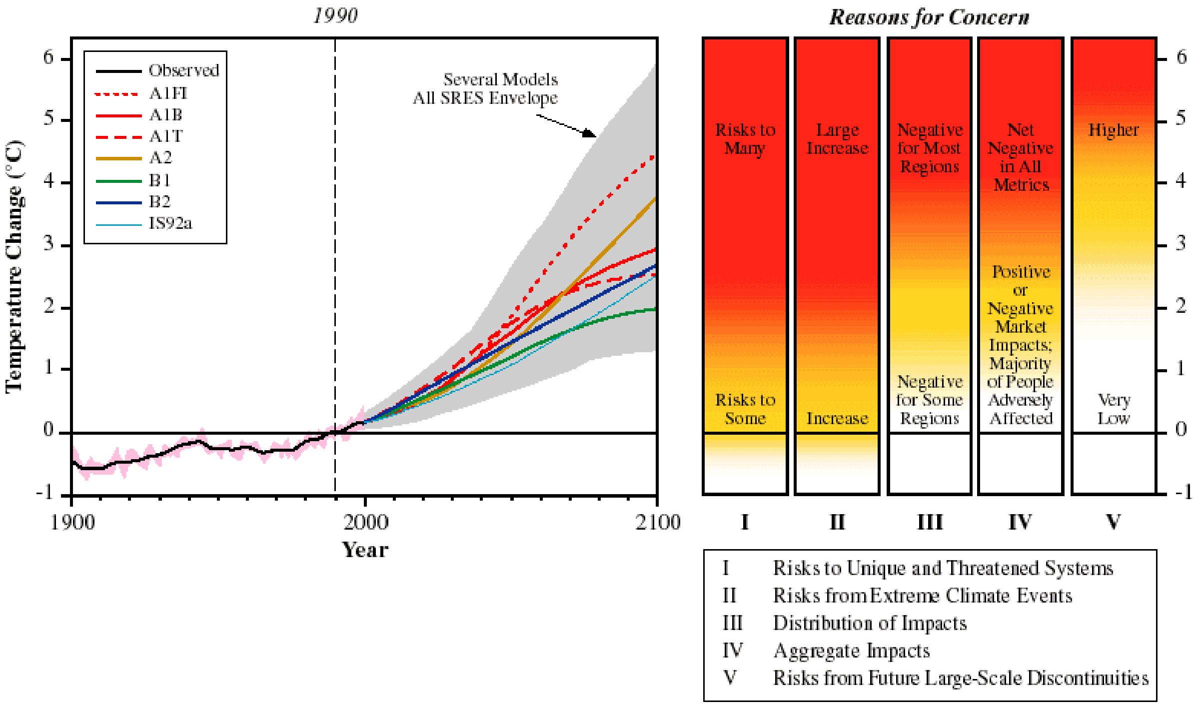
On the Indian subcontinent, Bangladesh and northeast India could face a number of diverse pressures: rising seas and storms inundating the Ganges delta region; a more variable monsoon, undermining the agricultural foundations that feed a quarter of a billion people; and changing patterns of river flow as climate change affects the Himalayan glaciers that feed the rivers, with corresponding international tensions across already volatile borders.

These are just examples; the possible human consequences of climate change are only just beginning to be seriously considered. A particularly complex consideration is that while most scientific studies have focused on the possible impacts of a warmer world, most human impacts may flow from the nature of a warming world, in which change—often hard to predict at the local level—may be the most difficult characteristic for societies to handle. Farming practices, water industries, and innumerable other social and infrastructural systems designed for the last century’s climate will not necessarily adapt easily to the accelerating change now projected, particularly as some of the underlying natural systems are also under pressure from global economic and population growth.

Such considerations inform the risk assessment–led approach to considering impacts. One form of this is illustrated in figure 2, in which the impacts of projected climate changes are grouped into five risk categories. This approach suggests that even under the most optimistic projections, some unique and threatened ecosystems will disappear and some regions will be exposed to adverse impacts. In the midrange, many unique systems may be at risk and the impact of extreme events will rise, with developing countries hurt the most; the impact on the aggregate global economy could still be modest. Change toward the upper end poses significant risks to all, and the risk of abrupt planetary-scale disruptions becomes significant.

To date, the debate between economists (who quantify specific, potentially measurable, and monetizeable impacts) and scientists (who focus on risk indices and scenarios) over impact has been largely a dialogue of the deaf. The next section sets out more formally a structure for thinking about these different dimensions.

Figure 2 Five risk indicators associated with projected global temperatures changes



Source: IPCC 2001c

- ***Economic Evaluation of Climate Change Impacts: Frameworks and Challenges***

How costly may climate change really be? This is a natural question for economists in particular to ask but an extraordinarily difficult one to answer. Continuing scientific uncertainties about the nature, timing, and severity of natural impacts are multiplied by many layers of uncertainty about how society will cope with growing impacts and how to quantify them. The impacts literature is dominated by natural scientists. Economists seek insights into the optimal trade-off between reducing impacts in lower-emission pathways and the presumed costs of reducing emissions. This section outlines the intellectual framework of quantification and sets out six challenges in evaluation.

Attempts by economists to quantify impacts in monetary terms have tended to concentrate on a few measurable dimensions, using either model simulations or comparative-static (cross-sectional) studies that compare indices such as land value and other indicators as a function of temperature. Since Mendelsohn, Nordhaus, and Shaw (1994), the “Ricardian” method of comparative-static estimates has been applied to other sectors, such as timber, energy, and water supply (see Mendelsohn and Williams 2004).

The essential foundation of such studies is that the explicitly climate-vulnerable sectors of the economy account for a relatively limited share of GDP. Ricardian approaches suggest that there are optimum temperatures for most sectors, which lie somewhat above the average temperatures typical in midlatitude regions. This drives the principal findings that climate damages are modest in midlatitude regions, adverse in low-latitude regions, and positive in high-latitude regions. Since midlatitude countries dominate world GDP, the net impact of climate change is modest across the century. Nordhaus and Boyer (2000) present the classic set of studies that argue this perspective. The Mendelsohn and Williams (2004) results support this in concluding that globally aggregated damages and benefits are comparable for the next several decades; damages start to dominate after about 2050 and get worse thereafter.

Table 2, drawn from a major review study on the social cost of carbon (Downing and others 2005), helps set such studies in perspective. As the authors note, more than 95 percent of the studies that seek to put a monetized value on climate impacts focus on only two out of the nine elements of the matrix—namely, the market and nonmarket costs associated with smooth projected change. Indeed, the Ricardian analyses, which compare the costs of two assumed climates, neglect the transitional costs of shifting systems from one climate to another (a climate that would itself still be changing). This is true of many of the studies cited above. Nordhaus' estimates try to quantify a wide range of measurable impacts, but he still has to resort to various assumptions by extrapolation that other impacts are correspondingly modest.

Table 2. Categorization of studies of the social cost of climate change

		Valuation uncertainties		
		Market (direct) value	Nonmarket (indirect use and options) value	Socially contingent costs, existence, and bequest value (a)
Nature of climate change considered	Mean climate	Global studies	Some global studies	None
	Climate variability and extremes	Regional studies, some allowance in global studies	Some local and regional studies	None
	System changes and singularities	Few sensitivity studies	None	None

Source: Adapted from Downing and others 2005; Jones and Yohe 2006.

a. Socially contingent costs are those that may be amplified by the inability of society to respond to impacts optimally, such as failures of governance or the frictions associated with migration or deeper disturbances. Existence value is that identified in environmental economics as the value that society accords to the existence of an environmental good, whether or not utilized. Bequest value can be understood as the explicit value of preserving options for future use.

Discounting. The long timescales of climate change make discounting over time a critical determinant of the present value of impact assessments. The discounting literature is enormous and has yielded consensus that market-based discount rates are not appropriate for evaluating very long-term issues like climate change. Indeed, it is now general practice to use discount rates for public policy evaluation that are well below market interest rates, particularly for longer-term endeavors; uncertainty around future economic growth rates lowers applicable rates further (see, for example, Weitzman 1998). The literature increasingly questions the form as well as the number used for discounting: while Heal's (1998) call for a logarithmic form has not been generally accepted, Groom and others (2003) conclude that the classical single exponential form is not tenable, and the British government itself has adopted a rate that declines over time (UK Treasury 2004). All these revisions tend to amplify the present value of climate change impacts, most of which occur in the longer term.

These revisions establish that the long-term cumulative impacts of climate change cannot be wholly discounted away in evaluating climate damages, as Downing and others (2005) note. The Stern report (Stern, 2007)adds another twist to the arguments. The ethical basis for discounting in public policy evaluation rests fundamentally on the belief that future generations will be better off. If impacts may be nonmarginal—particularly if they may be severe enough to prevent future generations from being better off in per capita terms—then the underlying basis for discounting is undermined. If climate change may have nonmarginal impacts, the discount rate needs to be endogenous—higher impacts are accompanied by lower discount rates and such scenarios are weighted more heavily.

A recent study (Ackerman and Finlayson, 2007) demonstrates unequivocally how the *combination* of discounting and impact assumptions determine the results of Nordhaus and Boyer (2000): their assumed discount rate weights the modest gains assumed in early decades far more than the expanding subsequent losses. Using the same model, but adopting an equity-based time preference and dropping the assumption that the initial warming in mid-latitudes boosts GDP, increases the present "social cost of carbon" by a factor of twenty.

Valuation over space: Contingent valuation, statistical life, and equity weightings. Similar scrutiny needs to be applied to evaluating transboundary impacts. Contingent valuation methods based on willingness to pay lead to valuation of mortality based on national Value of Statistical Life (VOSL). These values are heavily constrained by national income and can differ by a factor of more than 10 across countries, a disparity that led to bitter political disputes when applied by economists to evaluate impacts in the IPCC Second Assessment (IPCC 1995; for a contributing author's subsequent analysis of the issues see Tol, Fankhauser and Pearce 1999). In aggregate, there is a huge North-South asymmetry between the principal emitters and the most severely affected potential victims: it is the rich countries whose mitigation expenditures would be most affected by changes in estimated global damages, not the poor. Hence the case for using national VOSL (or other willingness-to-pay based measures) is unclear. A logical link can be maintained only by appeal to the argument that abatement expenditure in rich countries would displace foreign assistance for adaptation or other aid (an indirect opportunity cost argument). But there is no evidence that mitigation expenditure does or would displace foreign aid. Moreover, foreign adaptation assistance is likely to be a highly imperfect substitute for reduced climate variability (because of institutional constraints and the dynamic uncertainties documented below).

Equity weightings introduce a multiplier for VOSL or other willingness-to-pay-based impact measures in poorer countries to increase their weighting in global economic aggregation indices (Tol, Fankhauser and Pearce 1999; Groom and Koundouri, 2005) in an attempt to correct for the apparent inequities arising from such approaches. The basis and derivation for such weights is unclear, however, revealing some complex ethical issues underpinning global aggregation of damages that have yet to be resolved. Simply taking a purely egalitarian approach (for example, assuming a constant VOSL across humanity at the level of rich countries) vastly increases estimates of climate change impacts, but it, too, is riddled with inconsistencies.

Transitional impacts and adaptive capacity. The literature on the dynamic and "socially continent" aspects of impacts is extremely limited. A few points are clear, however.

Aggregating over space and time based on static comparisons may mask the bulk of social costs, which may be those associated with transitions and extremes: adaptation to a changed climate, predicted ex ante, may be very different from adaptation to a changing climate, with attendant changes in the distribution and scale of extremes. Both theory and recent experiences (such as Asia and New Orleans) suggest that what matters is the joint effect of climate with socioeconomic factors. Consequently, the scale of losses may be sensitive to the pre-existing conditions of the economy on which climate change impacts may fall.

Hallegatte, Hourcade and Dumas (2007) argue that impacts may be exacerbated by constraints on (a) reconstruction capabilities; (b) cost-sharing mechanisms, including insurance and international assistance; (c) local obstacles, including rigid agricultural practices; (d) knock-on economic impacts arising from depreciation of land- and weather-related capital stocks (through real estate and property ownership); and (e) ecological constraints. Drawing in part on the wider development literature on the economics of natural disasters (Benson and Clay 2004), Hallegatte and Hourcade (2005) present a model in which poor societies are unable to recover from one extreme climate event before the next disaster strikes, leaving such countries trapped in a cycle of underdevelopment.

Mechanisms for adaptation, compensation, and cost-sharing are inevitably weaker at the international level, though they are slowly developing (Gurenko 2006). This may increase the probability that adverse effects propagate across regions (including through migration), blurring any distinction between "winners" and "losers."

Uncertainty and the limits to adaptation. Adaptive capacity needs to be strengthened significantly. This is unquestionably true but incomplete, not least because of the uncertain nature of impacts (particularly extremes) combined with the demonstrated incapacity of societies to prepare adequately on the basis of risk warnings. The main impact of climate change may arise from the interplay between climate uncertainty and the constraints and sources of inertia in social and economic systems. The dilemma is neatly illustrated by the juxtaposition of two papers that appeared in *Climate Policy*. The first, Olsen (2006), is an agricultural model of the capacity of optimal adaptation to yield net benefits in Mali. The second, Butt, McCarl, and Kergna (2006), is a political economy study of the fact that a decade of international assistance efforts have made little headway in influencing practical policy in Uganda.

Three important factors constrain the capacity for preparatory adaptation: (a) uncertainty in regional climate predictions, probably an order of magnitude greater than that in global average predictions; (b) the masking effect of natural climate variability, which means that climate change signals may be undetected, ignored, or misinterpreted; and (c) the capital-intensive nature and inertia of adaptation strategies. Together these factors create a significant risk of maladaptation.

The first lesson that emerges from comparing optimal control models is that costs and responses can be very different under perfect foresight and decisionmaking under high uncertainty. Unfortunately, clairvoyant farmers—and perfect planners—are not a feature of the real world.

Risks, feedbacks, and surprises. These difficulties are amplified by the remaining elements in the risk matrix—namely, larger-scale risks and surprises in the climatic system, particularly when combined with inertia. Scientists studying the interaction between different components of the climate system and related natural systems express concern about various possible instabilities. The north Atlantic Ocean circulation is the best known but no means only example. The Hadley Centre in the United Kingdom projects that climate changes over Amazonia will lead to loss of the rainforest during this century. Other very long-term possibilities include the melting or collapse of the Greenland and West Antarctic Ice sheets (figure 3). The scale of threats posed by structural disruption is extremely difficult to evaluate but clearly should not be ignored in any quantification that claims to be comprehensive.

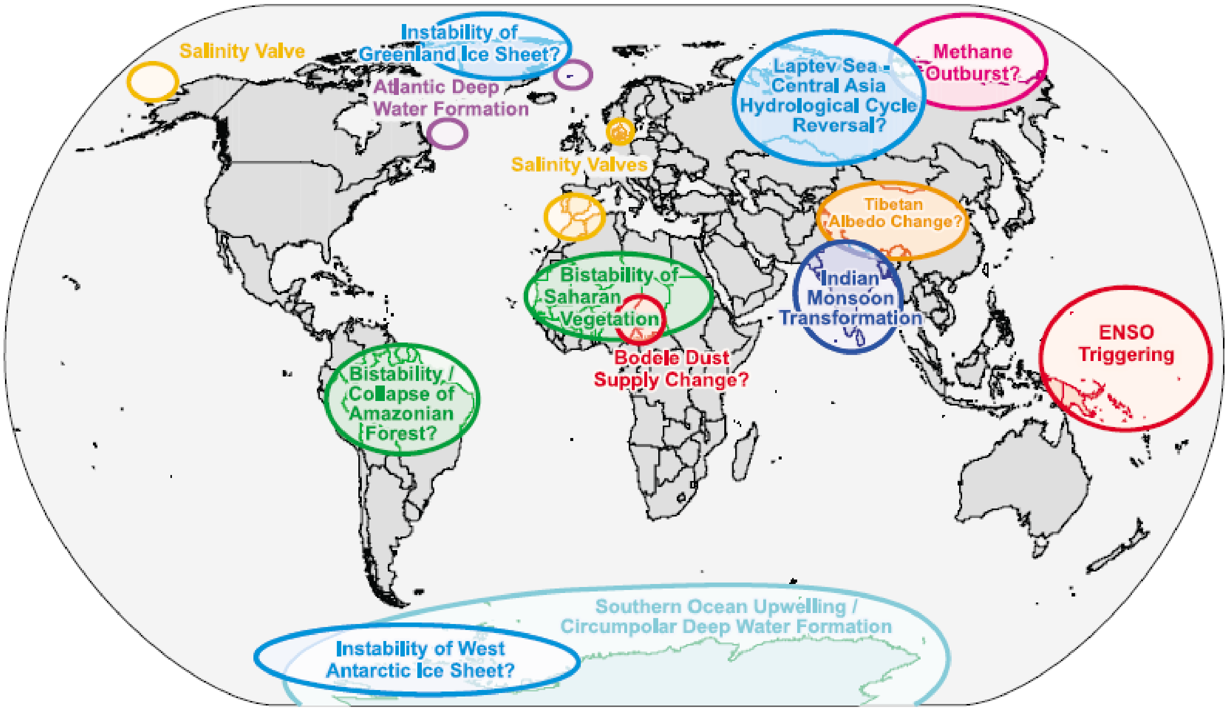


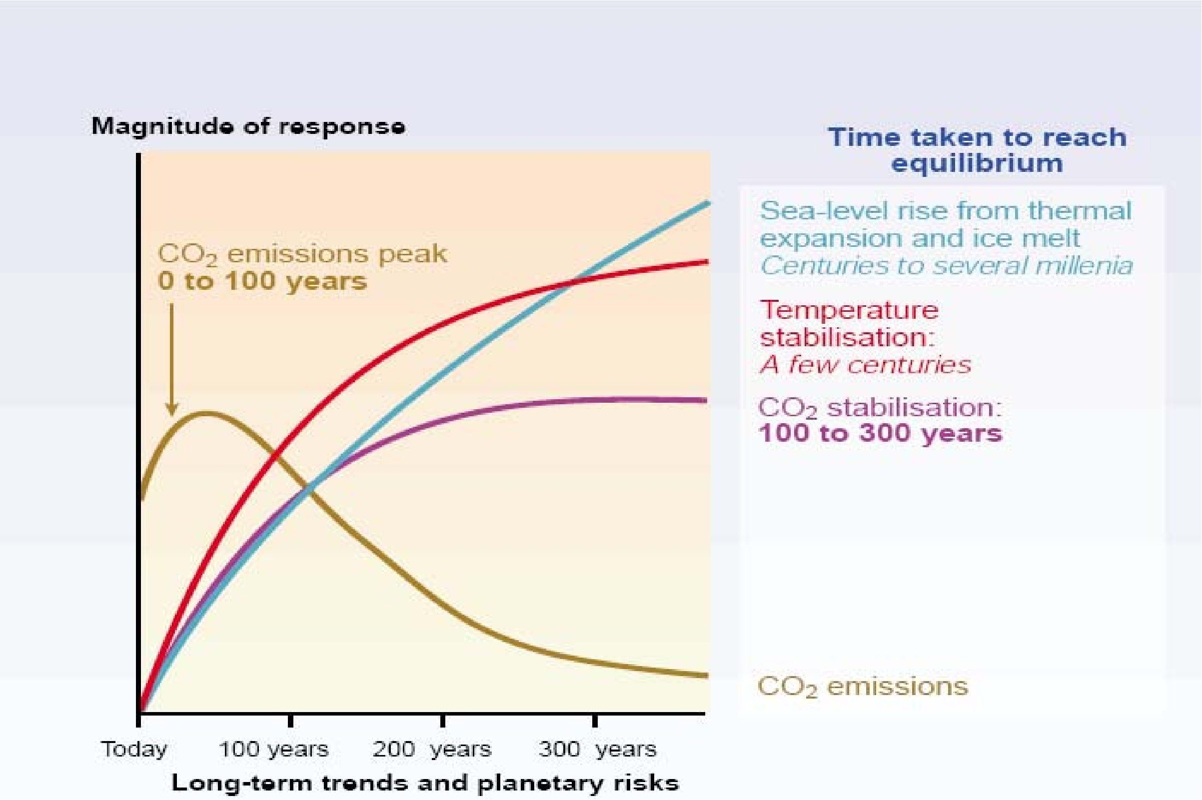
Figure 3 Potentially sensitive “switch-point” areas, in which local effects may trigger larger-scale changes [ENSO= El Niño-Southern Oscillatiion]
Source: Schellnhuber and Held 2002.

Feedbacks also concern scientists. Drying of the Amazonian rainforest system would feed more carbon back into the atmosphere. Thawing permafrost in the far north is likely to release pent-up methane (a potent greenhouse gas). Far larger amounts of methane are currently locked on the sea bed and could ultimately be released, though only over much longer time periods (centuries or millennia, if and as warming penetrates the ocean floors).

There are inherent uncertainties about such systems; the dynamics that keep them stable, and their limits, are not well understood. When it comes to such big questions about complex systems, uncertainty is endemic. But especially given the inertia in all these systems—including the inertia in economic systems discussed below—by the time limits are fully understood, they may be unavoidable. Several of the examples noted above—systemic changes in monsoon patterns, desertification of the Amazon, and slowdown of the thermohaline circulation—may be clearly identifiable only through observational data. But by the time changes can be observed in the data with sufficient statistical certainty to understand and project much further, it may be too late to prevent such transitions.

The very long term. A fundamental characteristic of the climate problem is the inertia involved. Atmospheric greenhouse gas concentrations will not stabilize until global greenhouse gas emissions are reduced to a small fraction of today's levels, which few expect before the end of the century. Even after the atmosphere stabilizes, other effects will continue to accumulate. Global temperatures will continue to rise for decades, as the oceans slowly adjust to the higher heat input. Sea levels will rise, as a result of both thermal expansion and ice melt—effects that will cumulate over hundreds (thermal expansion) to thousands (ice melt) of years. Over centuries, sea levels will rise many meters if and as the Greenland or West Antarctic ice sheets disintegrate (figure 4). Although these problems seem far away, there are economic reasons, discussed below, why choices over the next few decades will affect emissions and concentrations for decades beyond that and thus do much to determine the degree of commitment to a range of temperature, sea-level, and other kinds of risks and instabilities noted below.

Figure 4 Cumulative impacts of climate change over the long term



Source: IPCC 2001a

- ***Conclusions on Climate Impacts, Evaluation, and Adaptation***

The survey of issues of climate impacts, and the six specific challenges facing attempts to quantify impacts in economic terms, are sobering. Uncertainty is nothing new to economics and several economists (eg. Tol, 2003) have defended the broad cost-benefit approach whilst acknowledging the wide-ranging uncertainties. However, the specific concerns and debates are crucial to understand the limitations and likely implications.

Quantitative evaluation of impacts. Even the simple projections of smooth change raise profound issues about evaluation and aggregation over space and time. In addition, the full risk matrix requires some consideration of dynamic and "socially contingent" issues which depend upon the actual capacity of societies to prepare for and tackle climate-related changes. Societal constraints may affect the welfare consequences of impacts (or limit adaptation) in ways beyond the evaluation of direct market and nonmarket measures currently employed. Also, risks may arise from regionally variable (nontrend) changes within the broad envelope of projected climate variation including extreme events ("bounded risks"), and larger-scale system surprises.

There is no a priori ground for believing that these elements are insignificant compared with those economists have sought to quantify. This drives the conclusions of Downing and others (2005) that the social cost of carbon—the present value of damages associated with a tonne of carbon emissions—is characterized by huge uncertainties. They suggest that values could span a range from 1 to 1000£/tC, though they argue that the very low values in this range are unlikely.

The most recent and comprehensive effort, conducted in the Stern report (Stern, 2007), emphasizes the need for analysis that is explicitly stochastic, reflecting the wide range of scientific possibilities of both less and more damaging climate sensitivities and damage functions. It also argues for discount rates that reflect the fundamental principles of consequentialist ethics—and that correspondingly are endogenized to be consistent in the face of impacts that could challenge the underlying assumption that future generations will be better off.

Putting these two fundamental pillars together in a quantitative analysis leads the Stern report to close the apparent gulf between the scientific/precautionary approach and the cost-benefit approach. Their analysis concludes that climate change is indeed a problem of huge import and a fundamental threat to human development that requires urgent action. Stern's application of "balance-growth equivalent" methodology estimates the equivalent cost of climate change, left unchecked, to be potentially a double-digit percentage of gross world product.

The economics of impacts cannot provide a strictly objective answer to the problem of climate change, let alone one that is accepted as such by the most relevant parties. In the absence of this, the only ethically defensible approach to developing global responses has to be based on negotiations that seek to represent both emitters and victims. This though is equally problematic since many of the victims have not yet been borne.

Limits to adaptation. Early efforts to cost climate impacts were criticized on the grounds that they assumed little or no adaptation ("dumb farmers"). Since a substantial degree of climate change is already unavoidable, there is no question that far greater efforts are needed to help societies adapt to its likely impacts and that doing so has the potential to lower the cost of such impacts. But assuming that adaptation can radically reduce the costs of impacts is questionable, not least because of the fundamental nature of the uncertainties at the micro-level, where adaptation is actually relevant but uncertainties are greatest. In economic terms, it is by no means clear that replacing assumptions of "dumb farmers" (no adaptation) with assumptions of "clairvoyant farmers" (perfect adaptation) is more realistic.

The risks associated with uncertainties and irreversibilities are considerable and constrain the ability of adaptive measures to prevent adverse impacts. Moreover, climate change is not a discrete phenomenon with an identifiable end-point to which the world needs to adapt. To the contrary, the projected growth of global emissions means simply that it will be an ongoing and accelerating process of continual climatic change, without any identifiable prospect of stability, and growing risk of planetary-scale disruption. From all these perspectives, adaptation is likely to contain adverse impacts only if combined with serious moves toward slowing atmospheric change and ultimately stabilizing concentrations.

Climatic stability as an intrinsic good. Hallegatte, Hourcade and Dumas (2007) argue that from an economic standpoint, climate stability is a component in utility functions that should be explicitly represented; given loss aversion (one of the most stable findings in behavioral economics), there is an intrinsic value to avoiding an unstable climate. In economic terms, a stable climate thus has characteristics of an intrinsic good. Moreover, although it is poorer societies that may suffer most from an unstable climate, the decreasing marginal utility of income means that high-income populations and generations should be more willing to spend resources on climate protection. Climate stability is thus a “superior good,” which may influence some policy insights, including those relating to the cost-effective distribution of mitigation investments. This economic perspective reflects a more pragmatic view, which is becoming more widespread, that stabilizing the atmosphere, by reducing emissions, should be considered as one of the intrinsic goals of global development.

- ***Emissions and Development: An Empirical Overview***

Despite the emerging efforts to tackle the problem, global CO_2 emissions are widely projected to grow. If industrial countries fail to limit their emissions and energy-intensive and fossil fuel–driven energy systems remain a foundation of economic growth, it is hard to see rapid emissions growth in the rest of world being much curtailed, as other countries aspire to the same levels of economic development. Yet the link between wealth and emissions is weaker than generally supposed.

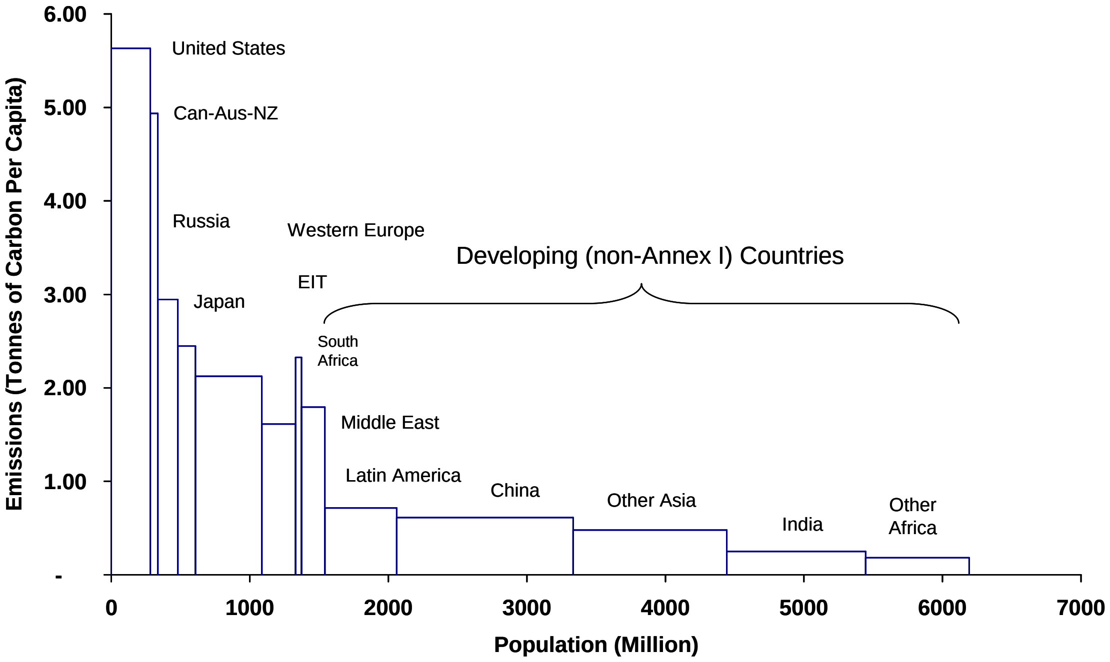
The literature on responding to climate change has frequently been characterized by inadequate attention to the factual base of the issue. Economic discourses based on supply and demand curves may assume away issues of deep-seated market imperfections, inertia, and equity. Political stances often ignore the fundamentally global nature of the problem. Both may ignore the scope for endogenous change in economic and technological systems.

- ***Four Facts about Emissions and Growth***

This section sets out four facts about the relation between global economic growth and increases in emissions. The following section then outlines four opportunities that arise in the context of considering lower-emitting development paths, as an empirical basis for the subsequent discussion of macroeconomics and policy responses.

Large disparities in emissions combined with population and economic growth create enormous potential for global increases in emissions if countries pursue existing models of development. Per capita emissions in the industrial countries are typically as much as 10 times the average in the more populous developing countries, particularly those in Africa and the Indian subcontinent (figure 5). The potential for global emissions growth is thus huge, even if leading countries start to embark on more serious efforts to reduce emissions.

Figure 5 Population and CO_2 emissions per capita, by region, 2000



Source: Grubb 2004b.
Note: Area of block represents annual emissions.

Recent debates have tended to lower populations projections for this century, in view of sharply declining birth rates. Most, however, still project that global population will expand by about 50 percent during the 21st century.[4]

Recent debates about the relation between CO_2 and GDP, projections focused on metrics of measurement,[5] and expectations of economic convergence versus a continued bimodal distribution of world per capita income levels (for example, Jones 1997; Quah 1993, 1996; Barro and Sal-i-Martin 1997; Riahi 2005). However none of these factors change the big picture: almost all scenarios involve considerable economic growth in developing countries that, in the absence of counteracting policies, will tend to raise their per capita emission levels closer to those of the industrial world.

Mainly as a result of these two forces, the vast majority of nonintervention scenarios in the peer-reviewed literature (as reviewed for the IPCC Fourth Assessment) result in global CO_2 emissions almost doubling by about midcentury and reaching two to four times current levels by 2100. These projections take the world far beyond the “doubled CO_2 concentrations” scenarios that were the traditional focus of climate change modeling.

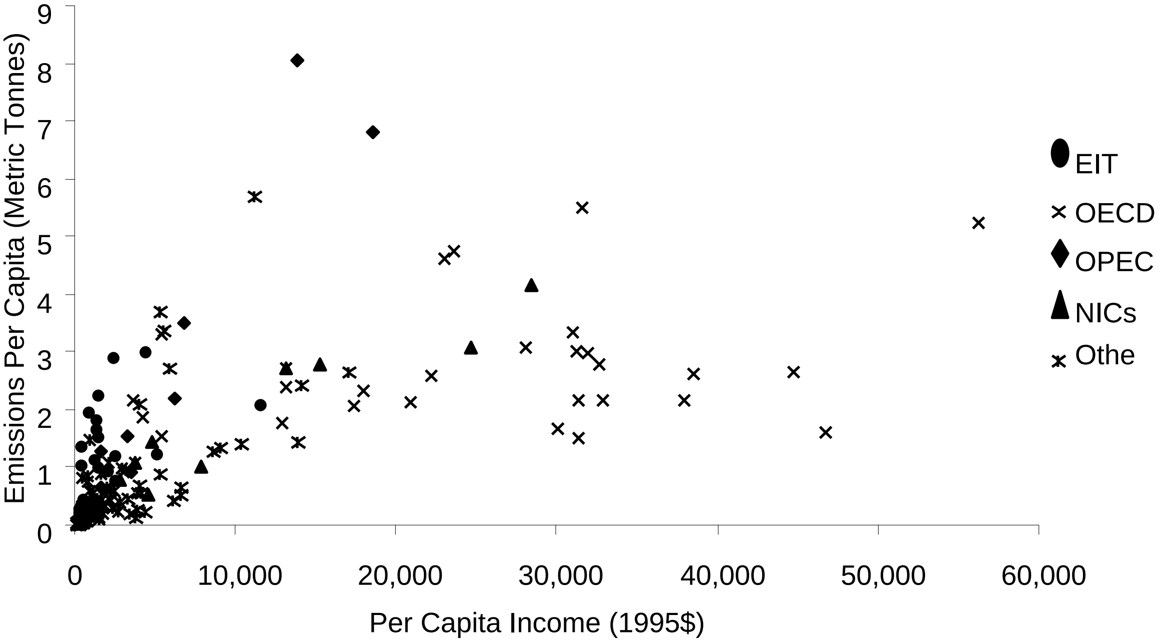


Figure 6. CO_2 emissions per capita, by country type
Source: Data are from World Resources Institute 2003[6].

Beyond the stage of basic industrialization, there are large differences in per capita emissions and huge variability in the relation between CO_2 and GDP. Currently, no country with income above about $10,000 per capita emits less than about 1.5 tC/cap (figure 6). This reflects the emissions inherent in building basic industrial and urban infrastructures—a fact that implies considerable growth in developing-country emissions.

There are wide variations among the richer countries. Per capita CO_2 emissions in the “new world” developed economies (North America, Australasia) (of 5–6 tC/cap) tend to be about twice the levels typical in “old world’ economies (Europe, Russia, Japan). Looked at more closely, the differences are even more extensive. This diversity provides a modest source of hope, even based on current patterns, because it implies a large degree of freedom over long-run emissions even in the absence of radical technological breakthroughs or major lifestyle changes.[7] A world in which most countries emit 1.5–2.5 tC/cap by the end of the century clearly has far lower climate risks than one in which they emit three times those levels.

The difference between these levels is not primarily a function of wealth. Rather, it depends on technology and infrastructure choices that affect the development, scale, and efficiency of buildings, industrial and transport systems, and supply systems (particularly electricity).

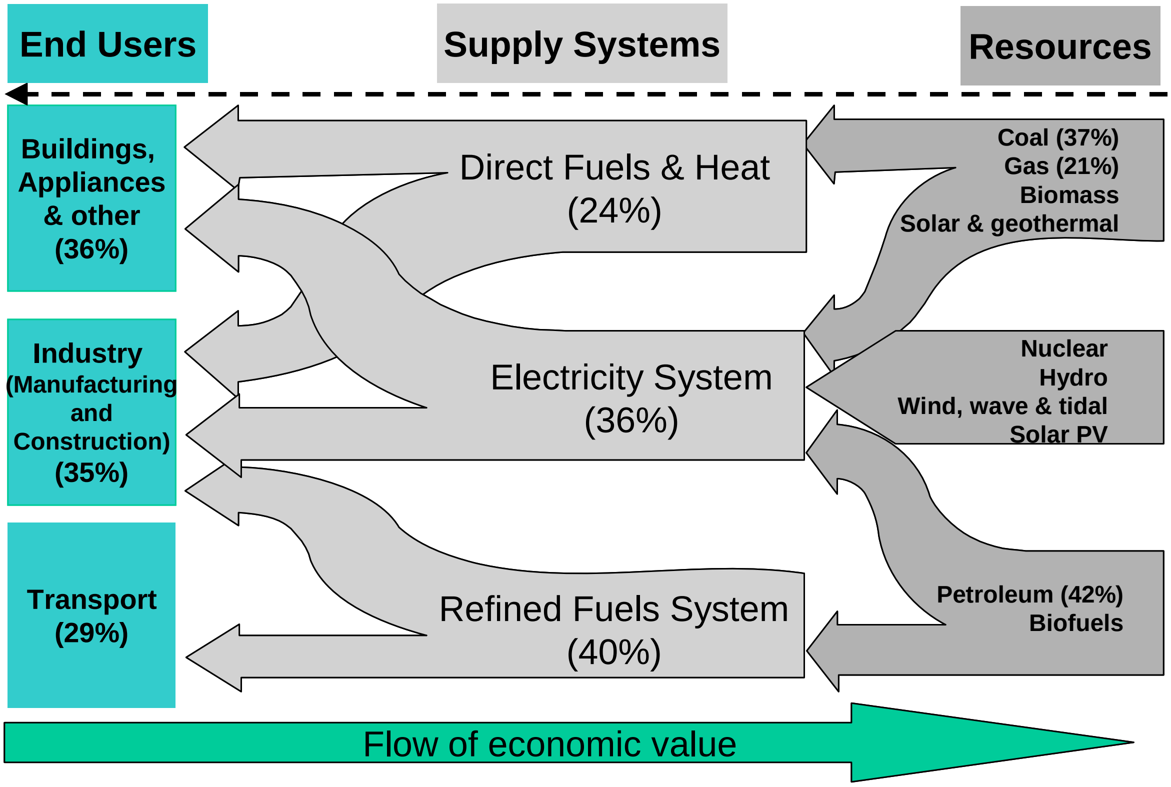
<chd>*Emissions arise from a wide diversity of activities, but many of them offer a wide array of technology options that affect the level of emissions.* The climate problem requires the world to reduce a number of different gases and sources of emissions in addition to fossil fuels;

greenhouse gases emanate not only from fossil fuels but also from agriculture, land use, and direct industrial-process emissions. For some developing countries, nonenergy sources (particularly deforestation and other land-use activities) dominate, and the desirability of addressing them is widely recognized. But the relative role of energy-related emissions tends to grow with development.

Even fossil fuel–related emissions result from several different systems, each of which involve fundamentally different processes. These processes are driven by energy demand in three main components (buildings, industry, and transport), supplied increasingly through three main systems (electricity, refined fuels, and direct fuel delivery) (figure 7).

Patterns of emission across regions (emission from industry, for example, are lower and transport higher in developed economies). Different sectors are also growing at different rates.

Figure 7 Main components of global energy system and CO_2 emissions

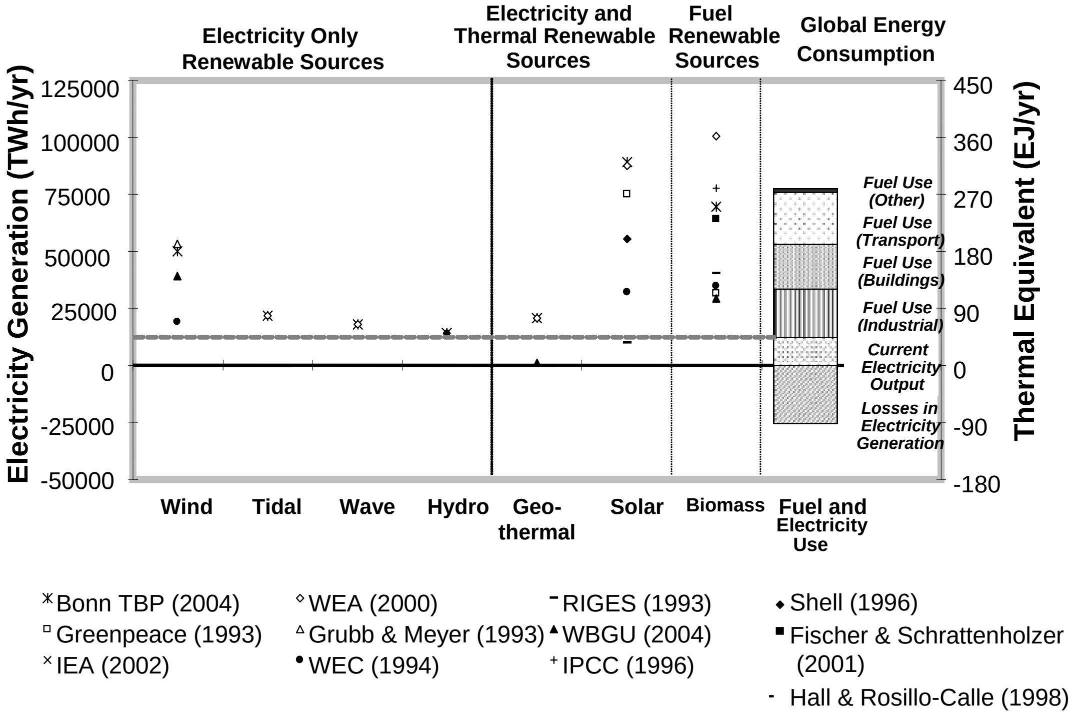


Source: Figures on resources from EIA 2002; figures on supply systems and end-use from IEA 2002.
Note: The data show the percentage of global energy-related CO_2 emissions associated with the different parts of the energy system. Some small flows that account for less than 1 percent of global energy flows (for example, electricity and natural gas contributions to transport) are not shown.

In most cases, the options for different technologies and systems are extensive. Buildings differ radically in the efficiency with which they consume energy. Urban planners are regularly faced with choices between road and rail investments. Electrical power is generated from a wide array of technologies.[8]

Even in terms of energy resources, most options, including renewable energy sources, are not seriously limited. Although constraints limit what is feasible, the estimated global potential for tidal, wave, and hydropower are comparable to the scale of global electricity consumption, while most estimates of practicable wind and solar resources are substantially greater still (figure 8). As with natural gas, key issues for delivery include the systems and the fact that (with the exceptions of direct solar heating and lighting and geothermal heating) all but one (biomass) produce primary electricity. Constraints concern the economics of matching sources and systems to demands. It is often said that countries will not leave their domestic energy resources (such as coal) in the ground. There is no fundamental reason why the same logic should not apply to the renewable energy resources that sweep most countries: the options developed are a matter of cost, technological capacity, and political choices.

Figure 8 Estimates of global renewable energy potential



Source: Neuhoff 2005[9].

The most important determinants of future emissions will be the combination of the patterns set by industrial countries and the capacity of developing countries to leapfrog t higher-income but lower-emitting patterns of development. Development economics has increasingly emphasized the scope of development choices and their dependence on institutional capacity in developing countries (Meier 2001). The same is likely to be true about emissions. Since one impact of weak institutions is that economies operate farther from the efficiency frontier, it cannot a priori be concluded that stronger institutions and resulting higher economic growth will result in higher emissions. Greater dependence on fossil fuels is not intrinsically good for development, and it carries numerous attendant problems, ranging from other environmental impacts to exposure to international fossil-fuel price variability. Institutional capacity to accelerate efficiency improvements and foster lower fossil-fuel paths could put countries on pathways that create lower emissions and are better for development.[10]

The concept of developing countries leapfrogging to more advanced conditions is not new, but it tends to have been confined to academic discussion far from the realities of the ongoing struggle for economic development. Leapfrogging does not represent a simplistic view of what could in theory be done, and it can no longer be relegated to the margins of the debate. It is a necessity that represents a set of specific opportunities, described in the next section.

- ***Four opportunities***

Four particular types of opportunity can be identified associated with moving development on to more environmentally sustainable paths.

Opportunities for enhancing energy and economic efficiency. There is a long-standing literature on the apparently favorable economics of improving energy efficiency (see, for example, IPCC (2007d). Global studies date back to Goldemberg (1988). Even in developed countries that made large strides during the 1980s and 1990s, considerable cost-effective potential remains.[11] Numerous World Bank studies have highlighted that the potential in developing countries tends to be even greater than in industrial countries.

Many factors explain the wastage; the literature on barriers to energy efficiency is enormous. One factor is the continuing degree of energy-sector subsidies, which are generally recognized to be macroeconomically detrimental.[12]

Reforming subsidies, or introducing stronger regulatory measures for energy efficiency, is not easy. In such conditions, it is not uncommon that additional issues can offer leverage to achieve reforms that would anyway be desirable. It is perfectly possible that climate change could help play such a role—blaming the medicine on the need to tackle emissions may be one factor in making it easier to swallow.

Co-benefits. Removal of fossil-fuel subsidies and stronger measures for energy efficiency may improve the internal efficiency of the energy sector. They may also yield wider "co-benefits" in the forestry, energy, and transport sectors. Energy is a source of multiple emissions. Higher energy consumption also means greater exposure to the impacts of price volatility in international fuel markets. Studies suggest that such co-benefits could justify a significant degree of measures that also reduce CO_2 emissions (see chapters 11 and 12 of IPCC 2007).

Leapfrogging in infrastructure. The most important single consideration in tackling emissions growth in developing countries is altering investments in new capital stock. Most of the sectors shown in Figure are characterized by inertia. Industrial equipment that consumes, generates, or processes energy has a lifetime that is measured in decades. The buildings that consume energy, the road and rail systems that determine transport demands, and the pipeline and port infrastructures required for direct fuel delivery can set infrastructure patterns for a century or more.

Much has been learned since rich countries started locking themselves into higher-emitting patterns of infrastructure. The wasteful nature of the United Kingdom's building stock remains one of greatest headaches for the government's energy policy. North America's exceptional energy intensity, and resulting dependence on oil imports, is to an important degree driven by choices in the transport sector made in the first half of the 20th century. Inefficient industrial equipment installed during those decades is often still operating, with continual cycles of refurbishment that rarely bring performance up to the standard of new plant (Alic, Mowery, and Rubin 2003). Leapfrogging in infrastructure—making choices at the leading edge for the long term—represents a huge opportunity.

Leapfrogging in technology. Some major developing countries could move to the frontier of technological developments in domestic investment and in capturing a growing share of the global market for energy-efficient and low–CO_2 technologies. Brazil's dominance in biofuel technology is now reaping large rewards. Technological development based on the large investment needs in key areas is a real opportunity, with solar photovoltaic (PV) technology perhaps the biggest prize of all, because of the almost unlimited quantity of this resource in most developing countries.

Time is not on our side. In energy use and supply, emission patterns will be set by how the world chooses to invest tens of trillions of dollars over the next few decades, investments that will have irreversible impacts throughout the century. The uncertainties surrounding the growth of global emissions and the extent to which trends depend on choices about the deployment of capital are underlined by the International Energy Agency's *World Energy Outlook* (2004), which estimates that about $16 trillion will be invested in energy supplies through 2030 (about $10 trillion of this in the power sector), divided roughly equally between industrial and developing countries. In their "reference" scenario, most of the generation investments are in carbon-intensive stock; the "alternative" scenario involves more rapid growth in less carbon-intensive investments. Although this is more expensive per unit, the scenario actually requires less capital investment overall, because of the increased efficiency of end use (even when the end-use investments are included). The choice of path out to 2030 will have profound implications for the structure of capital stock and its carbon intensity well into the second half of this century and even beyond.[13]

None of this should deflect attention from the need for industrial countries to set their emissions on a declining course. Indeed, as emphasized by a leading Chinese researcher (Zhou 2005), it will be much harder for developing countries to achieve progress if the world's industrial powerhouses do not simultaneously develop lower-carbon technologies, businesses, capacities, and institutional models. But a debate that ignores the crucial importance of emissions growth in developing countries is simply not a mature debate.

Moreover, ignoring the opportunities that are consistent with the need to reduce emissions would not be in the interests of developing countries themselves. The brake on embracing such opportunities appears to be partly political (the position in global negotiations that developing countries have no responsibility to act), partly institutional (the sheer difficulty of thinking long-term in the crush of development pressures), and partly motivated by fears of economic consequences.

• *Global Macroeconomic Dimensions of Atmospheric Stabilization*

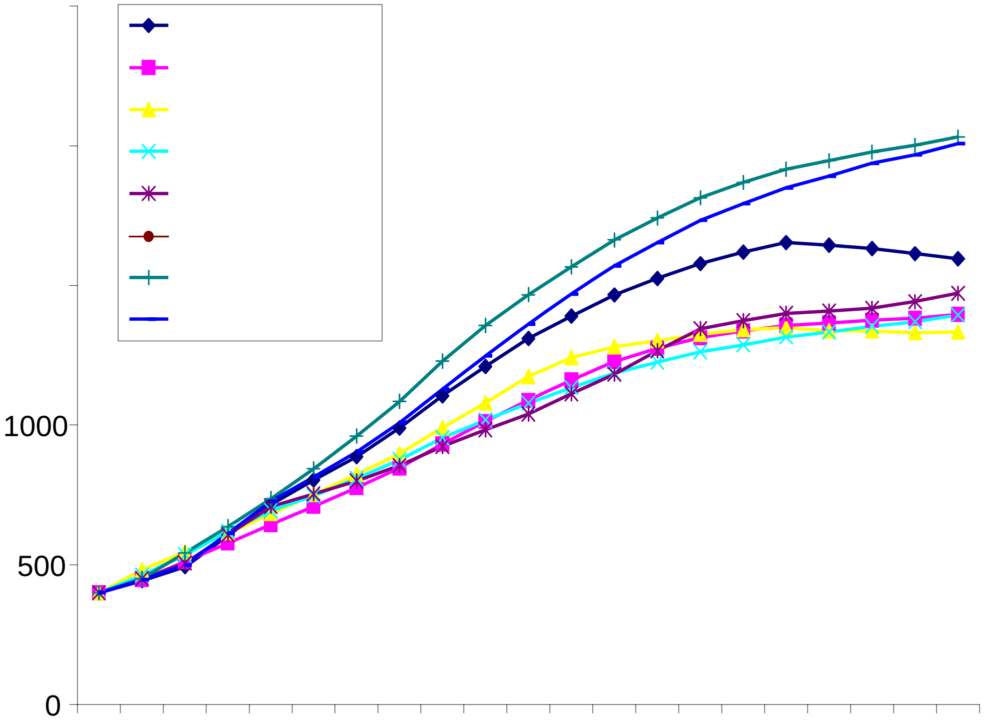
Achieving the scale of change required to stabilize concentrations will require strong policy measures. Most models represent "policy" in terms of the carbon price required to drive factor substitution toward low-carbon options, coupled with price elasticities to derive the impacts of higher prices on energy demand.

- ***Costs of Stabilization***

A recent set of modeling studies, the Innovation Modeling Comparison Project (IMCP), considers how such incentives may trigger technical change through various mechanisms (Edenhofer and others 2006). As chair of the IMCP, the author had access to the source data for the 10 diverse models involved in the study.[14] These models form the main basis for this subsection.

The carbon prices required to achieve stabilization span a wide range, both in absolute terms and in the time profile. For stabilization at 450 parts per million of CO2 (ppmCO2), in most of the IMCP models carbon prices rise to about \$100/tC (c. \$27/tCO2) plus or minus 50 percent by 2030. By 2050 carbon prices are in the range \$50–\$250/tC. After that, they diverge enormously, with some soaring, as allowable emissions shrink to low levels, and others rising more modestly. One model echoes the results of some simpler studies (for example, Anderson and Cavendish 2001) based on learning curves that suggest that carbon prices may peak around midcentury and then decline, as new low-carbon technology systems come to dominate. Note that some other models, that do not intrinsically include innovation responses to economic incentives, predict significantly higher carbon prices and GDP impacts (for comprehensive review see IPCC 2007d).

Figure 9. Baseline projections of undiscounted global energy system costs for stabilization at 450 ppmCO2 (IMCP studies)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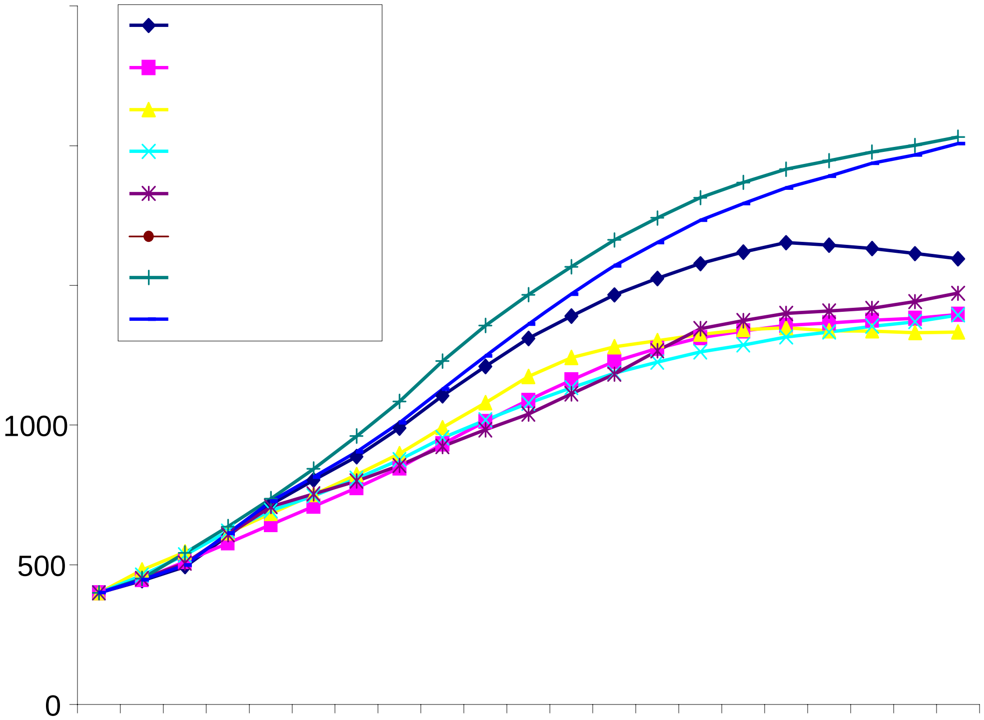
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Note. The models participating in the IMCP are all described in Edenhofer et al. (2006) and detailed in the individual papers of the associated Special Issue. The models span a range of basic economic methodologies and originate from diverse research centres in Europe, Japan and the US.

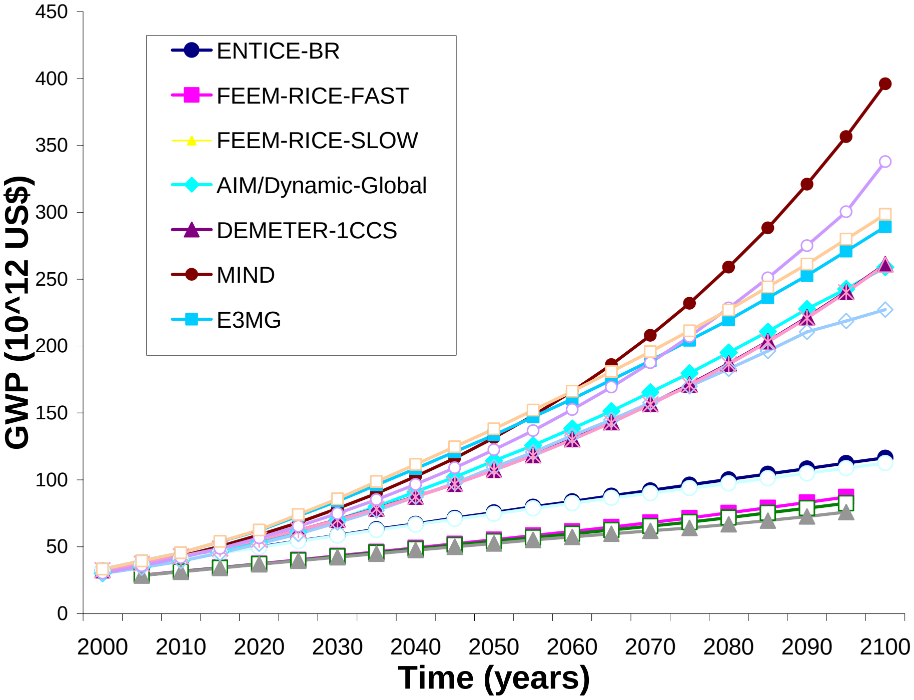
Rising carbon prices increase the costs of energy systems. Figure 9 shows the spread of impacts on energy system costs across seven of the participating models.[15] In the baseline case, with no CO_2 constraints, the cost of the global energy system rises from $400 billion a year to about $1 trillion a year by midcentury. Models estimating the costs of stabilization at 450 ppm fall into two main groups: models that predict that this rise increases energy-sector costs by midcentury by 50–100 percent and those that predict close to a tripling of energy system costs by midcentury. Interestingly, most models suggest that costs do not rise much beyond this during the second half of the century, with some showing a slight reversal, presumably because the ongoing decarbonization of the system means the carbon price (the marginal incentive) has a declining impact on actual energy-sector costs.

How do these costs affect the global economy? Figure 10(a) shows Gross World Product (or an equivalent proxy for global GDP) under the baseline projection and the (relative) impact on this measure of 450 ppm stabilization for each model in the IMCP.[16] Figure 10(b) shows the equivalent data normalized to an "average" baseline, which makes it easier to see relative impacts, together with principal reasons for the outliers.

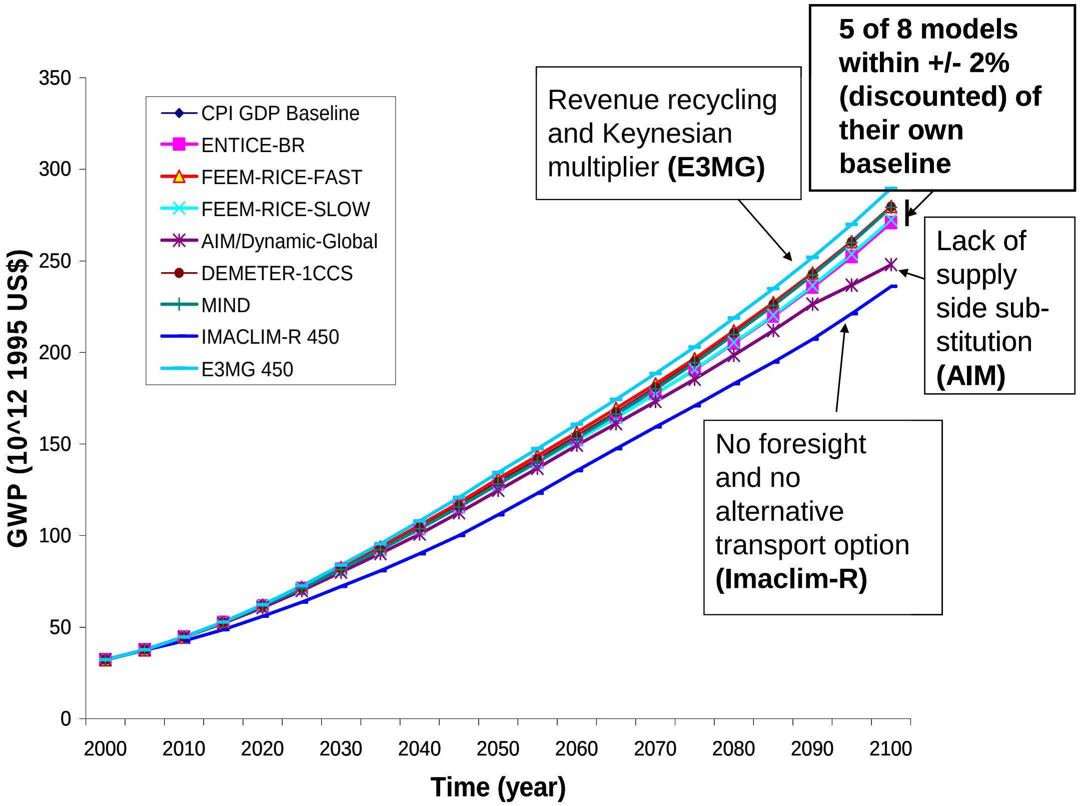
<Figures 10 about here>

Figure 10 Projections of Gross World Product and the impact of CO_2 stabilization at 450 ppmCO2 (IMCP studies). (a) absolute projections of different models; (b) economic impact of stabilization relative to a normalized baseline with indication of "outliers". See notes to Figure [9]

a



b



Revenue recycling and Keynesian multiplier **(E3MG)**

5 of 8 models within +/- 2% (discounted) of their own baseline

Lack of supply side sub-stitution **(AIM)**

No foresight and no alternative transport option **(Imaclim-R)**

There are intrinsic uncertainties around such modeling. In particular, the incorporation of endogenous technological change is fraught with complexity and hard to parametize.[17] Data thus need to be treated with caution. Several conclusions nevertheless flow from such analyses:

- The uncertainties in baseline projections of GDP swamp the uncertainties surrounding the cost of atmospheric stabilization itself. In other words, good policymaking that creates a strong macroeconomic framework is a far more important determinant of future welfare than the costs associated with stabilizing the atmosphere; to the extent that good macroeconomic management may go hand in hand with good environmental management, the two do not conflict.
- In most studies the costs of stabilization, even at low levels like 450 ppm CO_2, appear to be less than a year's forgone economic growth when the global response is optimized and a range of options is included. A closer examination of time profiles in the IMCP (Grubb, Carraro, and Schellnuber 2006) suggests that this conclusion is robust at least out to 2050 for all but one of the models, after which there is greater divergence across model estimates of forgone GDP, as the constraints bite even deeper and become more dependent on assumed technical progress.
- Some frameworks and assumptions generate outliers. Two models illustrate factors that could lead to a larger decline in GDP. One focuses on the investment in energy-saving capital as a mitigation option but does not include endogenous change in supply technologies, making it much harder to decouple economic growth from emissions. The other assumes there are no low-carbon options for the transport sector and that investment in infrastructure continues without foresight—actors simply react to the carbon prices they see. The result in this high-cost model is that the world gets trapped by inappropriate investment in high-carbon infrastructure during the first few decades of this century, making it very hard to then cut emissions back.
- In sharp contrast, two other studies suggest that reducing CO_2 emissions could boost GDP. In one study the negative costs originate from the Keynesian treatment of demand-side long-term growth. Because of increasing returns to production and employment, the recycling of carbon-tax revenues has the potential to boost output partly by reducing the cost of labor and hence boosting employment in developing countries. In the other model, accelerated development and diffusion of new technologies induced by climate policy has the potential to boost growth. This model captures the fact that the world underinvests in R&D; in certain parametizations the innovation needed to stabilize the atmosphere brings the world economy closer to an optimum level of innovation investment.[18]

The essential dynamic in all the optimizing models is that in both energy-sector and endogenous-growth models, the early decades are characterized by a switch in investment patterns. The associated GDP impacts are initially small, for a number of reasons. First, mitigation policies initially target low-cost, low-hanging fruit at low carbon prices, changing the trajectory of emissions without high costs. Second, the "learning investments" are in emerging low-carbon sectors; because these sectors are initially relatively small, the scale of learning investment is also limited. Finally, in the growth models, additional investment can boost GDP. In most—but not all—of the models, these factors are ultimately overtaken by the sustained increased costs of the energy system, but to widely varying degrees that depend largely on the degree of endogenous technological response. These dynamic mechanisms are not available in the highest-cost models, in which the costs are amplified by the inadequate foresight and lack of option-building.

This analysis leads to three key conclusions:

- The cost of tackling CO_2 emissions and moving a long way toward atmospheric stabilization can be contained to manageable levels that need not significantly impede economic development.
- Strong measures may be needed to drive the wholesale structural changes implied, with an appropriate mix of policies with timely and widespread participation. Inadequate action, too late or too narrowly spread, may significantly raise the costs.
- Along with the costs, there are opportunities associated with aligning macroeconomic development with lower emission pathways.

• ***Implications for Goals in Tackling Climate Change***

What are the implications of the huge uncertainties in quantifications of climate damages, set alongside such analyses of mitigation costs? The uncertainties seem to suggest that an optimum level cannot be set and emphasize the need for a sequential decision-making process. Yet there is a clear case for strong action now. Studies of global mitigation costs imply that mitigation has the potential to yield deep reductions, at costs much lower than that associated with leaving the problem unchecked, and that waiting will magnify costs on all fronts. In the context of infrastructural investment, there is a need to develop a sense of long-term goals.

The classic treatment of uncertainty (Weitzman 1974) suggests that in a context of high uncertainty about damage costs, the main policy instrument should be prices. This does not entirely address the challenge, however, which must include a sense of how much carbon-intensive infrastructure can be accommodated and the longer-term stabilization goals that might be appropriate. Figure 11 suggests that in a situation of high damage uncertainty, the other factor to consider is the point at which the costs of mitigation rise steeply. Almost all of the IMCP studies suggest that the costs of moving toward stabilization, for levels as low as 450 ppm CO_2, are modest (less than 1 percent GDP) up to about midcentury. These trajectories are accompanied by global CO_2 reductions to well below today's levels. This appears to be a reasonable planning target in considering infrastructure investment. It implies the need for radical change.

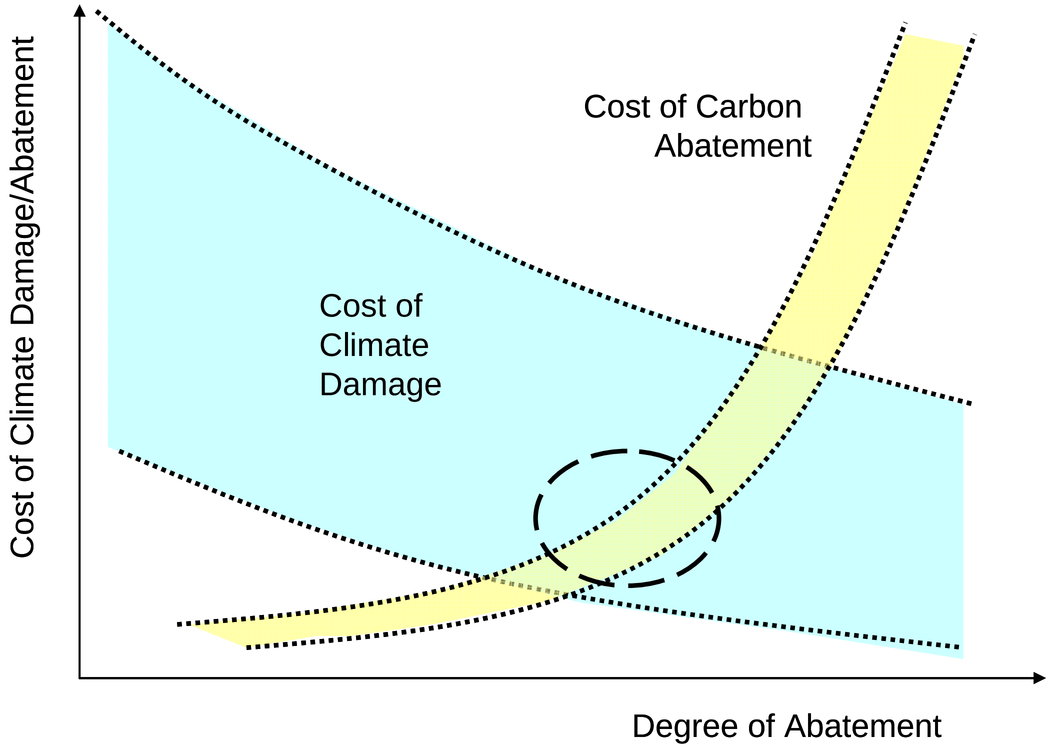


Figure 11 Abatement/tax levels under high uncertainty about cost of climate damages.

Note. The Figure illustrates schematically the cost-benefit tradeoff in the face of uncertainty and convexity. The 'cost of climate damage' declines as the degree of abatement (x-axis) increases, but is highly uncertain (as indicated by the wide vertical range – that is in fact still very much narrower than suggested by the discussion of Impacts earlier in this paper). The cost of abatement may be modest for small cuts, but both the cost and the uncertainty rises steeply for much more aggressive cutbacks. The dotted circle indicates that a rational tradeoff would be to pursue abatement to a level just before these costs start to rise sharply, whilst innovation policies seek to generate new options to bring down the cost of deeper emission cuts.

Source: Grubb and Newbery (forthcoming)

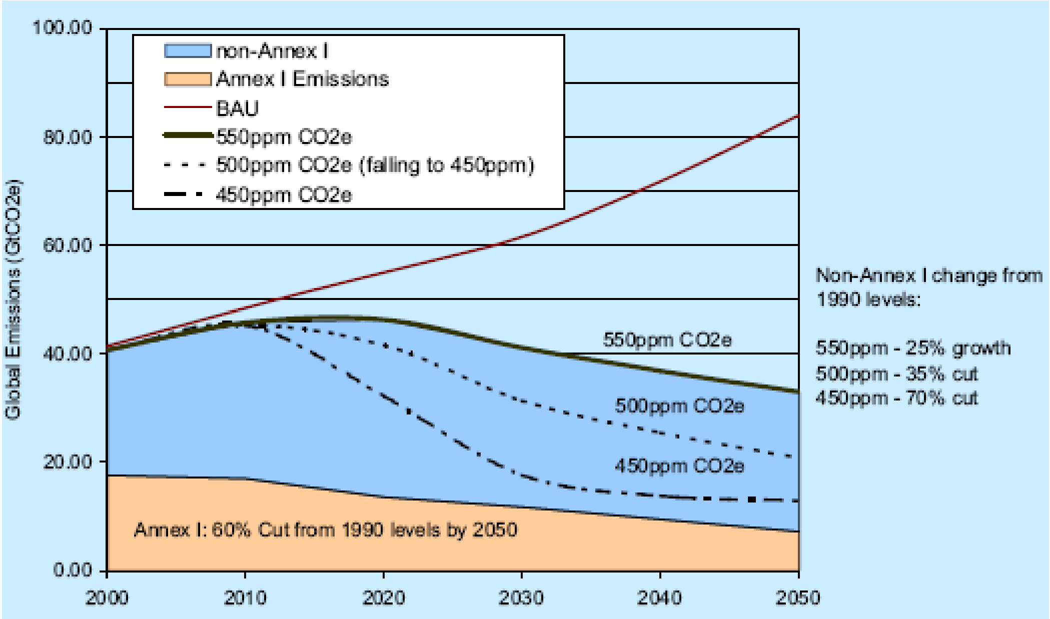


Figure 12Emissions reductions in developed and developing countries, where developed countries take responsibility for cuts equal to 60 percent of their 1990 emissions by 2050
Source: Stern (2007).

Figure 12 underlines this need by indicating separately for the industrialized countries (as listed in Annex I to the UNFCCC) and for developing countries the trajectories associated with the Stern Review's recommended range of 450–550 ppm CO_2e.[19]The figure indicates the developing-country trajectories if the industrial countries cut back by 60 percent below current levels by 2050; the Stern review also illustrates what happens if industrial countries cutback by 90 percent. Doing so gives developing countries a little extra headroom, but not much, particularly under 500–550 ppm CO_2e stabilization. This is because even a 60 percent cutback by industrial countries means that developing countries dominate emissions by 2050; additional industrial country cutbacks make less and less difference to the global total. CO_2 emissions are a global problem; to meet even 550 ppm, they need to be reduced below current levels by midcentury. Doing so will require that all significant emitting countries reduce emissions, a daunting task.

- ***Policy Instruments***

A great deal of theory has been written about optimal responses to climate change. One of the great empirical lessons from development economics over the past half century is that theory needs to be carefully grounded in realities if it is to lead to useful policy advice. The principal emphasis in this section is thus on the empirical structure of the mitigation problem.

- ***Types of Emitters***

From a policy perspective, sources of greenhouse gas emissions can be divided into two structural types of entity:

- Type 1 (large unitary) entities are principally capital-intensive firms for which energy or carbon forms a significant part of their cost base. This is typical of power generation and energy-intensive industries; it is also often applicable to forestry, where carbon costs could make a significant impact on the economics of the industry;
- Type 2 (small distributed entities) are individuals driving or occupying their homes, small businesses, and farmers, for whom energy and carbon costs represent a small fraction of their expenditure; innumerable other factors bear on their behavior.

Energy accounts for about two-thirds of global greenhouse gas emissions. Power generation accounts for about a third of energy-sector emissions; direct industrial use of energy for manufacturing processes accounts for about another 20 percent. With nonenergy emissions broadly divided between forestry and agriculture, this implies that each of the two fundamental types accounts for about half of global emissions.

The two types of entities differ in the likely significance of measures related to carbon prices, in the capacity of actors to analyze quantitatively consistent economic trade-offs, in typical time horizons, and in the significance of transaction costs and potential co-benefits of emissions limitations (table 3). In all these respects, it can be expected that measures related directly to carbon pricing may be more effective in relation to large unitary actors. However, these actors also tend to be most exposed to international competition arising from price differentials.

Table 3 Types of emitting entities for policy evaluation

	Type 1: Large centralized entities	Type 2: Small distributed entities
Typical sectors	Power generation, heavy industry and forestry	Transport, commercial, domestic, and agriculture
Direct significant of energy/ carbon prices in cost base	High	Low
Capacity of actors to evaluate options and trade-offs	High	Low
Typical investment horizon	Decades	A few years
Relative significance of transaction costs and behavioral characteristics	Low	High
Competitiveness exposure[a]	Medium to high	Low
Significance of co-benefits[b]	Low to medium	Medium to high

Source: Grubb and Newbery (Forthcoming)

a. Competitiveness exposure is complex and varied and depends on specific products, geography, and infrastructure. For example, power production will be not exposed at all for isolated production systems; extensive transmission interlinkages with neighboring power systems may make production in one region highly exposed.

b. Co-benefits may relate to local health (associated, for example, with domestic coal or biomass burning and vehicle emissions); congestion and energy security (transport); and various aspects of land use (for agriculture).

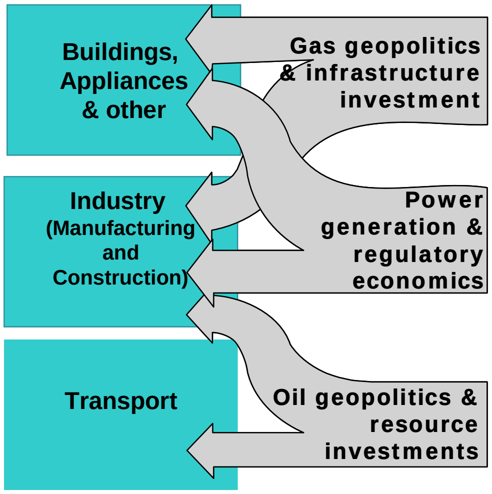
Distinguishing between the two types of entities underlines that climate change is not a problem for which there is a "one size fits all" solution. About half of emitting entities may be reasonably well behaved, in an economic sense, with a relatively high and rational responsiveness, for example, to price instruments. The other half may be much more problematic. For these diverse actors, encompassing almost the entire population, energy and carbon costs may be a trivial if irritating intrusion on their busy lives, and their capacity to manage them—or even to conceptually to link their behavior to energy costs or climate change—may be extremely limited.

- ***Classifying Economic Processes and Policy Instrument in the Energy Sector***

Three broad categories of economic processes are involved in moving to a low carbon economy. The first is factor substitution—that is, the substitution of low-carbon for higher-carbon activities, for given supply and demand curves, as determined by relative prices. Most economic studies, particularly those involving modeling, focus almost exclusively on this dimension; these analyses lead to the conclusion that the price of carbon is the main policy instrument.

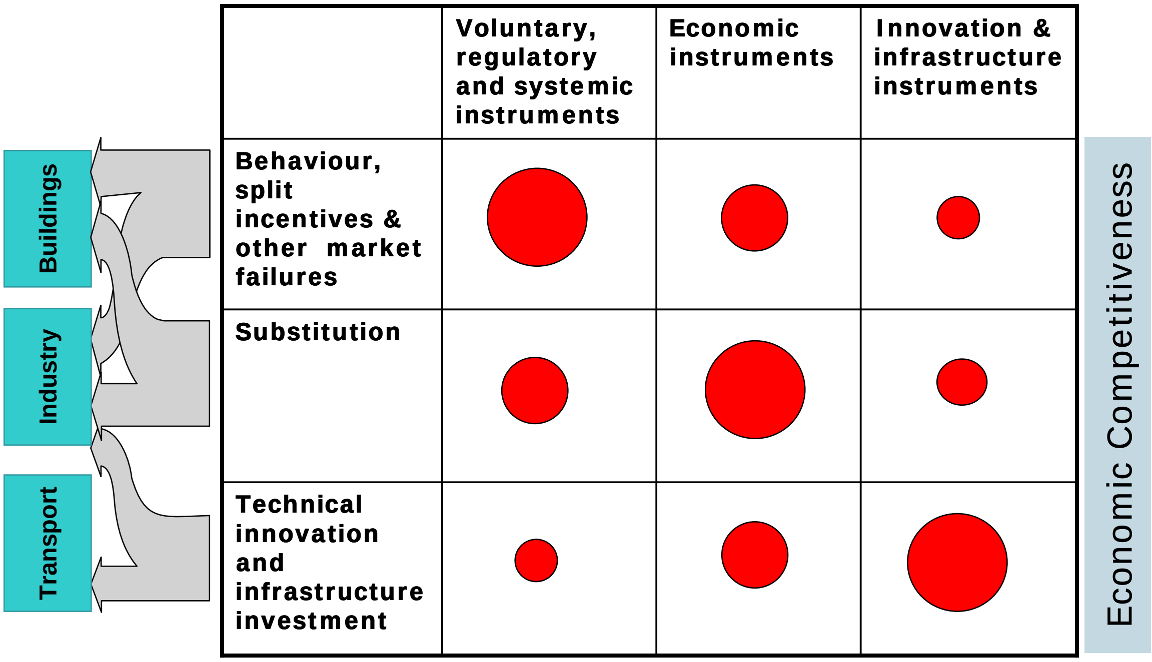
The long timescales and the numerous market failures associated with energy (considered further below) make two other broad categories important as well. The first is addressing market failures, barriers, and behavioral characteristics that lead to behavior that is, from a macroeconomic standpoint, nonoptimal for a given set of prices. The second is innovation and infrastructural changes that are concerned with changing the long-run production function of the economy—that is, the capacity to produce the same output for a given set of inputs and prices.

Addressing these other two processes implies the need for additional kinds of instruments. Figure13 maps the different economic components of emissions to their main structural characteristics economic processes; figure 14 maps these classes of economic processes against policy instruments.



Sector	**Dominant issues for energy-carbon management**
Direct fuels and buildings	Consumer & organisational behaviour, market barriers, co-benefits, buildings infrastructure
Power generation and heavy industry	Prices, regulatory structures, competitiveness and industrial innovation
Oil and transport	Consumer behaviour, vehicle innovation, energy security, transport infrastructure, resource investment

Figure13 Key characteristics of principal emitting sectors



	Voluntary, regulatory and systemic instruments	Economic instruments	Innovation & infrastructure instruments
Behaviour, split incentives & other market failures	●	●	●
Substitution	●	●	●
Technical innovation and infrastructure investment	●	●	●

Figure14 Schematic mapping of economic processes to policy instruments

Note: The relative importance of interactions is indicated by the size of each circle

This framing places factor substitution and carbon pricing at the center of a more complex matrix of economic processes and policies. Each of the three broad categories of processes tends to be associated with different kinds of policy responses. Various kinds of market failure (other than the pure carbon externality) affect energy use, perhaps predominantly in the way that consumers use energy in buildings (which, including the embodied emissions attributable to power consumption, account for more than a third of fossil-fuel emissions). These failures imply a need for active policies to promote energy efficiency that can take a wide range of forms, from product standards to negotiated agreements and many other more targeted interventions. Innovation and infrastructure represent two ways in which investments profoundly affect the long-run options and capacity to curtail CO_2 emissions, in ways that are unlikely to be adequately reflected purely through carbon price. Instruments for addressing these issues include standards, dedicated market supports, and direct government expenditure on R&D and infrastructure (such as public transport) that yield longer-term benefits.

Each class of instrument generally has some spillover effects on other economic processes (see figure 14). Price effects may also invoke behavioral changes over and above factor substitution. The literature on endogenous technological change is largely about the impact of price changes on innovation; spillovers from other policy instruments may be less important, but they exist.

- ***Implications for Developing-Country Policies***

A detailed elaboration of policies is beyond the scope of this article; many publications, including the IPCC Mitigation Reports, World Bank studies, and analyses by the International

Energy Agency, detail options and growing experience. This section has the more modest aim of examining some policy implications for developing countries.

Energy-efficiency measures. Improving energy efficiency is a global opportunity—but one with particular resonance for many developing countries. This is partly because of their greater relative exposure to the costs of energy imports but also because of the scale of opportunities. Measured at market exchange rates, most developing countries use three to four times as much energy per unit GDP as the OECD average (figure 15).Measured in purchasing power parity, the differences are much smaller, but these statistics embody only commercial energy, and energy intensity can easily rise in the earlier stages of development as more people connect to commercial energy. Increasing the efficiency with which they do so, leapfrogging to more advanced use of local resources, or both offer big opportunities.

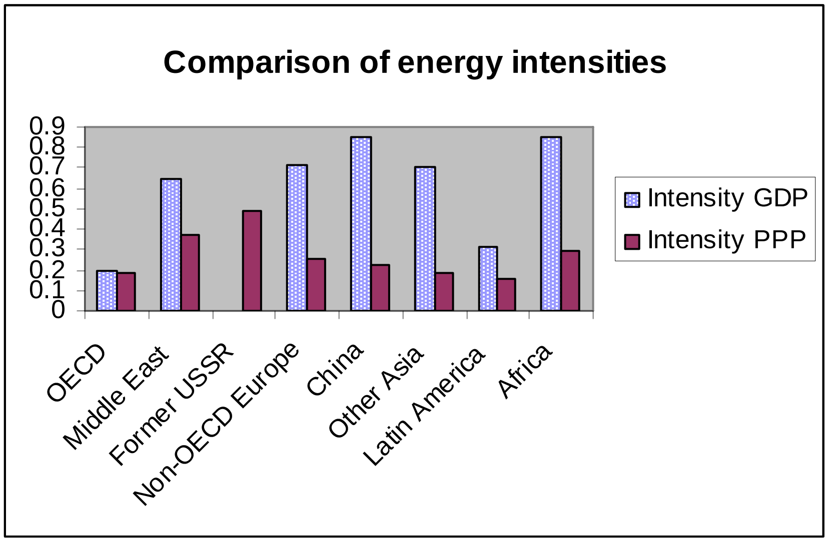


Figure 15 Energy use per unit of GDP, by region, 2002.

Source: Derived from IEA 2006.

Note: Data for the former Soviet Union at market exchange rates are off scale and omitted because of difficulties interpreting market exchange rates in these countries.

Many measures relating to energy efficiency—such as setting and enforcing energy-efficiency standards and legislation to ensure that adequate information on energy performance is available to consumers—depend purely on domestic policy. But in some cases, international mechanisms can help. Many World Bank programs have targeted energy efficiency.[20] The Clean Development Mechanism[21]is another source of potential finance, although the need for scale and demonstration of additional emission savings often makes it better suited to supply-side investments. Stronger action on energy efficiency helps enable—and improves responsiveness to—the central economic plank of policy, namely, energy and carbon pricing.

Energy and carbon pricing. While specific regulatory interventions can accelerate energy efficiency, there is no question that energy pricing is an important factor. Traditionally, many developing countries have subsidized energy. The drawbacks of doing so are well known:

inefficient use, poor infrastructure, inability to attract new investment, and a greater tax burden on the rest of the economy.

In addition, cross-sectional data suggest a long-run price elasticity of about -1.0—a figure that suggests that countries do not in the long run pay more for energy as a result of higher prices, because they end up making proportional reductions in the intensity with which they use energy (figure 16). This response is substantially greater than elasticities estimated from time series (typically less than 0.5). The difference probably reflects a range of economic processes associated with price rises and spillover of higher prices into provoking other policy responses (in infrastructure investment and building standards, for example) that also reduce energy intensity.

<Figure 16 about here>

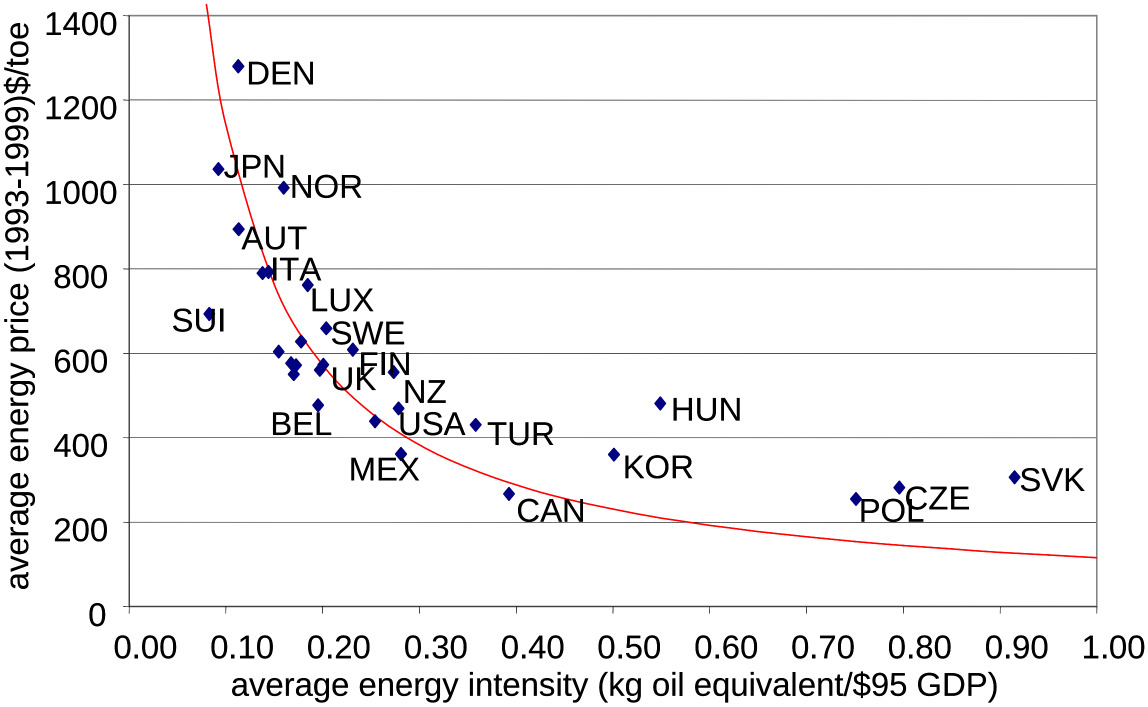


Figure 16 Relation between energy price and energy intensity in selected countries

Source: Newbery 2003.

Despite decades of economic advice to remove energy subsidies, many countries still provide them. These subsidies often reflect the entrenched interests of those who have historically benefited from subsidized energy. Since policy tends to arise from coalitions of interests, concern about environment and climate change may be a useful additional factor encouraging countries to remove inappropriate subsidies.

Going beyond this to implement explicit carbon pricing—either through taxes or emissions trading—may be hard for developing countries to contemplate, but there are serious reasons why they may wish to do so. In addition to the role of carbon pricing as an essential tool in tackling climate change (and the role of energy taxes more generally as a way of reducing exposure to international energy markets), such taxes raise revenue in ways that may well be less distortionary than other taxes (such as labor taxes). Indeed, the boost to GDP from CO_2 found in the E3MG model arises directly through this mechanism, particularly in developing countries, where high rates of unemployment mean that lowering labor-related taxes yields a proportionately greater economic benefit.

The experience in the European Emissions Trading Scheme (Grubb and Neuhoff 2006) demonstrates unequivocally that emissions trading increases the profitability of power generators. In developing countries this may be a useful way of raising resources in a sector in which investment is crucial to future development.

Infrastructure and innovation. The most compelling case for developing-country action is the sheer pace of investment in carbon-intensive infrastructure. The International Energy Agency's *World Energy Outlook* projects that \$11–\$17 trillion will be invested in energy infrastructure out to 2030. Much of this investment will be in equipment designed to last much longer. The planned lifetime emissions from new coal plant projected to be constructed during this period amount to more than 200Gt CO_2 —almost 40 percent more than the total emissions from all sources in the previous quarter century and almost a third of the total allowable CO_2 emissions for the century that would be consistent with stabilizing at 550 ppm CO_2e, the upper limit of ranges considered in the Stern review (figure 17). If the climate problem turns out to be even more severe, there is a high risk that much of this capital investment may become "stranded assets," as the need to tighten CO_2 controls becomes overwhelming.

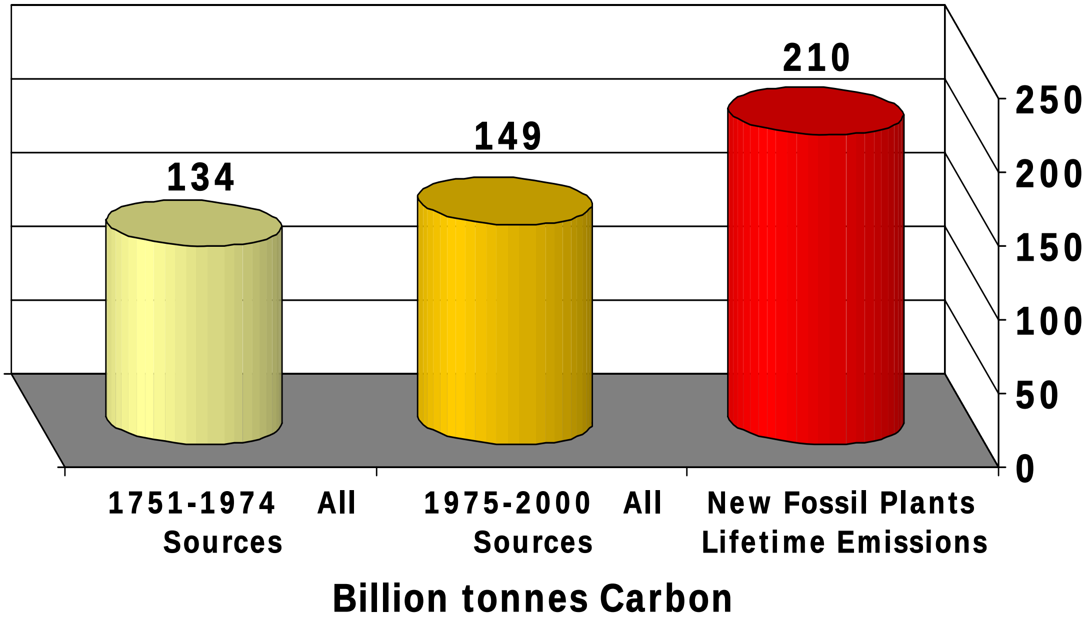


Figure 17 Historic lifetime emissions and expected emissions from coal power plants projected for construction, 2003–30

Source: www.e3g.org.

Coal power plants are not the only kind of infrastructure under construction. The choice between road and rail investment, for example, has even longer-term implications. The study by

Crassous, Hourcade and Sassi (2006) underlines the potential costs of pursuing investments in carbon-intensive transport infrastructure if low-carbon vehicles do not become available at scale. New buildings will last many decades or even centuries; the costs of retrofitting insulation measures are much higher than installing low-carbon buildings in the first place. Of course, many countries are still investing in infrastructure, but the sheer pace of construction in developing countries places a special need for them to consider the long-run implications of investment—and for the international community to consider ways of helping decarbonize the process of economic development globally, with particular attention to long-lived infrastructure.

One of the most generic findings of the literature on ‘sustainable development’ is that goals of environmental protection and development are closely interrelated (eg. Swart, Robinson and Cohen, 2003). Long term emissions depend upon wide social and macroeconomic choices about development paths, for example in terms of assimilating new and more efficient technologies; whilst the ability to address both environment and development objectives draw upon a common basis of institutional capacity. At a more concrete level, in the course of development the key to an effective integrated response to climate change is to combine all three kinds of policies identified (improving market efficiency, carbon pricing, and infrastructure and innovation policy), at both the national and international level. Only such broad-ranging responses, implemented urgently, offer much hope of tackling this most daunting of global challenges.

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- ***Notes***

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1. The first half of this section draws heavily on Grubb (2004a). Many of the source data are from IPCC (2001a, b, c). The IPCC is currently engaged in its Fourth Assessment (IPCC forthcoming), which will update such analyses.

2. The IPCC Third Assessment (IPCC 2001e) detailed observations, trends, and projections. The Working Group II assessed observed and projected impacts. The Fourth Assessment will present enhanced data on impacts and projections, including at the regional level.

3. For discussion of these and innumerable other cases, see the IPCC [2007], the most extensive of the three Working Group reports, with 20 chapters of regional and sectoral assessments.

4 Out of 115 population scenarios collated recently by IIASA (International Institute for Applied Systems Analysis) for the IPCC (Lutz and Sanderson 2001; UN 2005; World Bank 2005; U.S. Census Bureau 2005), the majority project population in the second half of the century to be moderately stable, at about 9–10 billion people. Only one scenario involves global population declining below 5 billion by the end of the century.

5. An extensive debate has focused on the use of purchasing power parity (PPP) versus market exchange rates (MER) and assumptions about economic convergence. While the choice of GDP denominator would

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not be expected to have a first-order impact on projections of a physical quantity such as emissions (Holtsmark and Alfsen 2004a, 2004b), it may have second-order impacts as a result of structural effects. Nordhaus (2005) concludes that the "jury is still out" and recommends a hybrid treatment using PPP base-year calibration with MER growth rates. Dixon and Rimmer (2005) present evidence that PPP treatments could lower emission projections as a result of differential structural effects and associated sectoral emission intensities and elasticities.

[6] EIT=Economies in Transition, OECD= Organisation for Economic Co-operation and Development, OPEC= Organisation of the Petroleum Exporting Countries, NICs= Newly Industrialised Countries.

7. According to Lecocq (2006), "The econometric evidence is mixed. If cross-country data show the predicted relationship (albeit with controversies: country-level analysis shows a relatively weak relationship between levels of GDP and emissions), econometric analysis does not support an optimistic interpretation of the hypothesis that 'the problem will take care of itself' with economic growth.… but the pessimistic interpretation, that growth and CO2 emissions would be irrevocably related, is not supported by the data either. Case studies confirm that there are major degrees of flexibility."

8. Pacala and Socolow (2004) frame the debate in terms of "technology wedges" that could each deliver savings of 1 Gigatonne of Carbon (GtC) a year by midcentury. They list 15 possible wedges.

[9] RIGES= Renewables-Intensive Global Energy Scenario, TBP= Thematic Background Papers, WBGU= Wissenschaftliche Beirat der Bundesregierung Globale Umweltveränderungen(German Advisory Council on Global Change), WEA= World Energy Assessment, WEC= World Energy Council.

10. Chapter 12 of IPCC (2007) covers these issues in depth.

11. The United Kingdom improved its national energy productivity (the ratio of GDP to energy consumption) by more than 20 percent during the 1990s, but the government's Performance Innovation Unit still estimated the potential net value of additional energy savings to the U.K. economy in 2000 at more than £2 billion a year (PIU, 2002).

12. Larsen and Shah (1992) estimate that subsidies for energy totaled more than $230 billion a year.

13. Ulph and Ulph (1997, pp/ 648) note that "information acquisition and irreversibility could make a significant difference to policy advice," but models of irreversibility effects (Pindyck 2000; Kolstad 1996, 1996b) appear to have treated carbon- and noncarbon-intensive investments asymmetrically, assuming that only noncarbon-intensive investments to be irreversible. In practice, both embody considerable inertia: every major investment has irreversible consequences. The dominant net irreversibility is the carbon in the atmosphere and associated damages. Uncertainty about impacts (relative to best estimates) consequently increase the attractiveness of low-carbon paths to a degree that depends on the potential damages, risks, and degrees of irreversibility.

14. Some other models span an ever wider range; IPCC 2007 contains a comprehensive review.

15. The other three are IMCP models that are sufficiently aggregated that they do not report energy system costs. The exact coverage of "energy-system costs" may differ somewhat across models and cannot always be readily separated, so the numbers need to be treated with caution.

16. Three of the models represent only the energy sector and are therefore not included in the GDP data.

17. For a set of studies of more classical global energy-economy models that also cover non–CO2 gases, see the EMF studies (http://www.stanford.edu/group/EMF/).).

18. The model was designed to show how effective technical change can be in reducing stabilization costs if appropriate policies and investments are undertaken and crowding out effects are limited. When these particular features of technical change dynamics are switched off, as they are in the FEEM-RICE SLOW model, costs become positive and consistent with those estimated by the other models.

[19] CO2e means "equivalent" ie. Including non-CO2 emissions in terms of their "carbon equivalent" impact. The range 450–550 ppm CO_2e corresponds to roughly 400–475 ppm CO_2 only.

20. Total World Bank commitments on energy efficiency and renewable resources have expanded rapidly, to $680 million in 2005.

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[21] The CDM allows investments in emission-reducing projects in developing countries to generate 'certified emission reduction units', that may be used by industrialised country investors in those projects to contribute towards compliance with their commitments under national legislation (eg. EU ETS) and international (Kyoto) agreements that set emission limits.