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RICHARD T. ELY LECTURE

The Economics of Climate Change

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Greenhouse gas (GHG) emissions are externalities and represent the biggest market failure the world has seen. We all produce emissions, people around the world are already suffering from past emissions, and current emissions will have potentially catastrophic impacts in the future. Thus, these emissions are not ordinary, localized externalities. Risk on a global scale is at the core of the issue. These basic features of the problem must shape the economic analysis we bring to bear; failure to do this will, and has, produced approaches to policy that are profoundly misleading and indeed dangerous.

The purpose of this lecture is to set out what I think is an appropriate way to examine the economics of climate change, given the unique scientific and economic challenges posed, and to suggest implications for emissions targets, policy instruments, and global action. The subject is complex and very wide-ranging. It is a subject of vital importance but one in which the economics is fairly young. A central challenge is to provide the economic tools necessary as quickly as possible, because policy decisions are both urgent and moving quickly—particularly following the recent United Nations Framework Convention on Climate Change (UNFCCC) meetings in Bali in December 2007. The relevant decisions can be greatly improved if we bring the best economic analyses and judgements to the table in real time.

A brief description of the scientific processes linking climate change to GHG emissions will help us to understand how they should shape the economic analysis. First, people, through their consumption and production decisions, emit GHGs. Carbon dioxide is especially important, accounting for around three-quarters of the human-generated global warming effect; other relevant GHGs include methane, nitrous oxide, and hydrofluorocarbons (HFCs). Second, these flows accumulate into stocks of GHGs in the atmosphere. It is overall stocks of GHGs that matter, and not their place of origin. The rate at which stock accumulation occurs depends on the "carbon cycle," including the earth's absorptive capabilities and other feedback effects. Third, the stock of GHGs in the atmosphere traps heat and results in global warming: how much depends on "climate sensitivity." Fourth, the process of global warming results in climate change. Fifth, climate change affects people, species, and plants in a variety of complex ways, most notably via water in some shape or form: storms, floods, droughts, sea-level rise. These changes will potentially transform the physical and human geography of the planet, affecting where and how we live our lives. Each of these five links involves considerable uncertainty. The absorption-stock accumulation, climate-sensitivity, and warming-climate change links all involve time lags.

The key issues in terms of impacts are not simply or mainly about global warming as such—they concern climate change more broadly. Understanding these changes requires

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specific analysis of how climate will be affected regionally. Levels and variabilities of rainfall depend on the functioning of weather and climate for the world as a whole. As discussed below, temperature increases of 4–5°C on average for the world would involve radical and dangerous changes for the whole planet, with widely differing, often extreme, local impacts. Further, the challenge, in large measure, is one of dealing with the consequences of *change* and not only of comparing long-run equilibria. Under business as usual (BAU), over the next two centuries we are likely to see change at a rate that is fast-forward in historical time and on a scale that the world has not seen for tens of millions of years.

This very brief and oversimplified description of the science carries key lessons for economics. The scientific evidence on the potential risks is now overwhelming, as demonstrated in the recent Intergoverrnmental Panel on Climate Change (IPCC) Fourth Assessment Report, or AR4 (IPCC 2007). Like most of those here today, I am not a climate scientist. As economists, our task is to take the science, particularly its analysis of risks, and think about its implications for policy. Only by taking the extraordinary position that the scientific evidence shows that the risks are definitely negligible should economists advocate doing nothing now. The science clearly shows that the probability and frequency of floods, storms, droughts, and so on, is likely to continue to grow with cumulative emissions, and that the magnitude of some of these impacts could be catastrophic.

While an understanding of the greenhouse effect dates from the nineteenth century,[1] in the last decade, and particularly in the last few years, the science has fortunately started to give us greater guidance on some of the possible probability distributions linking emissions and stocks to possible warming and climate change, thus allowing us to bring to the table analytical tools on economic policy toward risk.

The brief description of the science above tells us that GHG emissions are an externality which is different from our usual examples in four key ways: (a) it is global in its origins and impacts; (b) some of the effects are very long term and governed by a flow-stock process; (c) there is a great deal of uncertainty in most steps of the scientific chain; and (d) the effects are potentially very large and many may be irreversible. Thus, it follows that the economic analysis must place at its core: (i) the economics of risk and uncertainty; (ii) the links between economics and ethics (there are major potential policy trade-offs both within and between generations), as well as notions of responsibilities and rights in relation to others and the environment; and (iii) the role of international economic policy. Further, the potential magnitude of impacts means that, for much of the analysis, we have to compare strategies that can have radically different development paths for the world. We cannot, therefore, rely only on the methods of marginal analysis. Here, I attempt to sketch briefly an analysis that brings these three parts of economics to center stage. It is rather surprising, indeed worrying, that much previous analysis of practical policy has relegated some or all of these three key pieces of economics to the sidelines.

The Structure of the Argument.—The structure of the argument on stabilization is crucial, and we begin by setting that out before going into analytical detail. The choice of a stabilization target shapes much of the rest of policy analysis and discussion, because it carries strong implications for the permissible flow of emissions, and thus for emissions reductions targets. The reduction targets, in turn, shape the pricing and technology policies.

Understanding the risks from different strategies is basic to an understanding of policy. Many articulated policies for risk reduction work in terms of targets, usually expressed in terms of emission flows, stabilization levels, or average temperature increases. The last of these has the advantage that it is (apparently) easier for the general public to understand. The problem is that this apparent ease conceals crucial elements that matter greatly to social and economic outcomes—it is the effects on storms, floods, droughts, and sea-level rise that are of particular importance, and a heavy focus on temperature can obscure this. Further, and crucially, temperature outcomes are highly stochastic and cannot be targeted directly. Emissions can be

[1] Joseph Fourier recognized in the 1820s (Fourier 1827) that the atmosphere was trapping heat; three decades later, John Tyndall (1861) identified the types of gases responsible for the trapping; and at the end of the century, Svante Arrhenius (1896) gave calculations of the possible effects of doubling GHGs.

more easily controlled by policy. However, it is the stocks that shape the warming. Thus, there are arguments for and against each of the three dimensions. We shall opt for stock targets, on the basis that they are closest to the phenomenon that drives climate change and the most easily expressed in one number.

An alternative focus for policy is the price of GHGs rather than quantities. In a perfectly understood nonstochastic world, standard duality theory says that price and quantity tools are essentially mirror images and can be used interchangeably. However, where risk and uncertainty are important and knowledge is highly imperfect, we have to consider the relative merits of each. For the most part, we ignore the difference between risk and uncertainty here (where the latter is used strictly in the Knightian sense of unknown probabilities), but it is a very important issue (Claude Henry 2006; Stern 2007, 38–39) and a key topic for further research.

We begin by setting out some of the major risks from climate change, and argue that these risks point to the need for both stock and flow targets, guided by an assessment of the costs involved in achieving them. Long-term stabilization (or stock) targets are associated with a range of potential flow paths, although the stock target exerts a very powerful influence on their shape. The choice of a particular flow path would be influenced by the expected pattern of costs over time. The target flow paths can then be associated with a path for marginal costs of abatement, if we think of efficient policy designed to keep flows to the levels on the path, in particular by using a price for carbon set at the marginal abatement cost (MAC). Essentially, the economics of risk points to the need for stock and flow quantity targets and the economics of costs and efficiency to a price mechanism to achieve the targets.

A policy that tries to start with a price for marginal GHG damages has two major problems: (a) the price estimate is highly sensitive to ethical and structural assumptions on the future; and (b) there is a risk of major losses from higher stocks than anticipated, since the damages rise steeply with stocks and many are irreversible.

Formal modelling of damages can supplement the argument in three ways. First, it can provide indicative estimates of overall damages to guide strategic risk analysis. Second, it can provide estimates of marginal damage costs of GHGs, for comparison with MACs. Third, and most important in my view, it can help to clarify key trade-offs and the overall logic and key elements of an argument.

A useful analogy is the role of Computable General Equilibrium Models (CGMs) in discussions of trade policy. These have much more robust foundations than aggregative models on the economics of climate change, yet their quantitative results are very sensitive to assumptions, and they leave out so much that is important to policy. Thus, most economists would not elevate them to the main plank of an argument on trade policy. That policy would usually be better founded on an understanding of economic theory and of economic history, together with country studies and particular studies of the context and issues in question.

However, as the Stern Review stressed, such analysis has very serious weaknesses and must not be taken too literally. It is generally forced to aggregate into a single good, and in so doing misses a great deal of the crucial detail of impacts—on different dimensions and in different locations—which should guide risk analysis. It is forced to make assumptions about rates and structures of growth over many centuries. Further, it will be sensitive to the specification of ethical frameworks and parameters. Thus its estimates of marginal social costs of damages provide a very weak foundation for policy. This type of modelling does have an important supplementary place in an analysis, but all too often it has been applied naively and transformed into the central plank of an argument.

Our analysis of risks and targets points to the need for aggregate GHG stabilization targets of below 550 parts per million (ppm) carbon dioxide equivalent (CO_2e), arguably substantially below. This corresponds to cuts in global emissions flows of at least 30 percent, and probably around 50 percent, by 2050. These cuts may seem large in the context of (we hope) a growing world economy, but are not ambitious in relation to the risks we run by exceeding 550ppm CO_2e. And, given the avoided risks, the costs of around 1 percent of world GDP per annum (see Section IB below) of achieving this stabilization should be regarded as relatively low. The carbon price required to achieve these reductions (up to, say, 2030) would be around, or in excess of, $30 per ton of CO_2.

This paper incorporates many important elements of the Stern Review, published on the Web in October/November 2006 (see http://www.sternreview.org.uk, including Postscript) and in book form (Stern 2007) a year ago, but goes beyond it in many important ways—in relation to subsequent policy discussions, new evidence and analysis, and discussions in the economics literature.

There are four further parts to this paper. The second part focuses on risks and how to reduce them, and on costs of abatement. The third part examines formal modelling and damage assessment. The fourth part examines policy, and in particular the role of different policy instruments. The final part outlines what I see as the central elements of a global deal or framework for collaborative policy and discusses how that deal can be built and sustained.

I. Stabilization of Stocks of Greenhouse Gases I: Risks and Costs

A. *Risks and Targets*

The relation between the stock of GHGs in the atmosphere and the resulting temperature increase is at the heart of any risk analysis. The preceding link in the chain, the way the carbon cycle governs the process relating emissions to changes in stocks, and the subsequent link, from global average temperature to regional and local climate change, are full of risk as well. But the stock-temperature relationship is the clearest way to begin, as it anchors everything else. Broadly conceived, it is about "climate sensitivity"—in terms of modelling, this is indicated by the expected eventual temperature increase from a doubling of GHG stocks.[2]

There are now a number of general circulation models (GCMs—also known as global climate models) that have been built to describe the links from emissions to climate change. The large ones work with a very large number of geographic cells, consume computer time extremely heavily, and can be run only on some of the world's biggest computers. Nevertheless, particularly if combined with appropriate linking to a large number of other machines, they can be run many times for different possible parameter choices. Such exercises yield Monte Carlo estimates of probability distributions of outcomes. A discussion of various methods and models may be found in Malte Meinshausen (2006) and in Chapter 1 of the Stern Review.

Figure 1 and Table 1 are drawn from the models of the UK's Hadley Centre. The work of the Hadley Center was a particular focus of models for the Stern Review for a number of reasons. First, it is one of the world's finest climate science groups, with a very large computing capacity. Second, it was close by and the staff were extremely accessible and helpful. Third, its probability distributions are fairly cautious, balanced, and "middle of the road" (Meinshausen 2006); this judgement is sustained by a comparison of their results with the subsequently published AR4 (IPCC 2007).

Figure 1 and Table 1 present estimated probabilities for eventual temperature increases (which take time to be established) relative to preindustrial times (around 1850), were the world to stabilize at the given concentration of GHGs in the atmosphere measured in ppm CO_2e. Figure 1 portrays 90 percent confidence intervals—the solid horizontal bars—for temperature increases. The lower bound (fifth percentile) is derived from the IPCC Third Assessment Report, or TAR (Tom Wigley and Sarah Raper 2001; IPCC 2001a, b)[3] and the upper bound is from the Hadley Center (Hadley Center 2005; James M. Murphy et al. 2004). The dotted bars cover the range of the 11 studies examined by Meinshausen (2006). The bar for 550ppm CO_2e (with a 90 percent interval of 1.5°C to 5.3°C) approximately represents the possible range for "climate sensitivity."

Concentrations are currently around 430ppm CO_2e (Stern Review, Figure 1.1 (Stern 2007, 5)—Kyoto GHGs), and are rising at around 2.5ppm CO_2e per annum. This rate appears to be accelerating, particularly as a result of the very rapid growth of emissions in China. On fairly conservative estimates (International Energy

[2] Climate modellers tend to define "doubling" in relation to preindustrial times. The relationship from stock to temperature increase is approximately logarithmic, so that doubling from other stock levels would be likely to yield a similar increase.

[3] The TAR was without probabilities but Wigley and Raper produced distributions based on it. The Stern Review blended the TAR and Hadley because the former was based on international discussion, but the latter was more recent. The Stern Review used lower climate sensitivities than Hadley, although the IPCC's more recent AR4 (IPCC 2007) is closer to those used by Hadley.

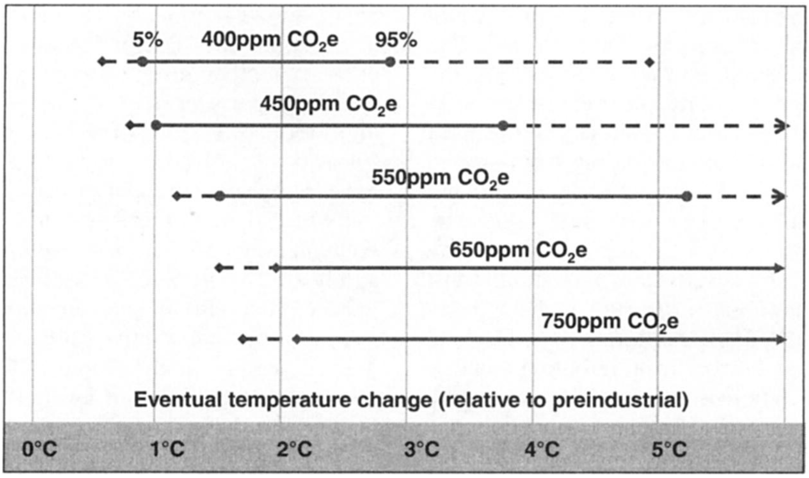

FIGURE 1. STABILIZATION AND EVENTUAL CHANGE IN TEMPERATURE

Source: Stern Review, Table 1.1 (Stern 2007, 16); Meinshausen 2006; Wigley and Raper 2001; Murphy et al. 2004.

TABLE 1—LIKELIHOOD (IN PERCENTAGE) OF EXCEEDING A TEMPERATURE INCREASE AT EQUILIBRIUM

Stabilization level (in ppm CO_2e)	2°C	3°C	4°C	5°C	6°C	7°C
450	78	18	3	1	0	0
500	96	44	11	3	1	0
550	99	69	24	7	2	1
650	100	94	58	24	9	4
750	100	99	82	47	22	9

Source: Stern Review Box 8.1 (Stern 2007, 220) with some added information.

Agency (IEA) 2007), China's energy-related emissions are likely to double by 2030, taking overall emissions from 6–7 to 12–15 gigatons (Gt). There seems little doubt that, under BAU, the annual increments to stocks would average somewhere well above 3ppm CO_2e, perhaps 4 or more, over the next century. That is likely to take us to around, or well beyond, 750ppm CO_2e by the end of the century. If we manage to stabilize there, that would give us around a 50–50 chance of a stabilization temperature increase above 5°C. This is a high probability of a disastrous transformation of the planet (see below).[4] The issue is still more worrying than that of dealing with very large damages with very low probability.

Further, we should emphasize that key positive feedback from the carbon cycle—such as release of methane from the permafrost, the collapse of the Amazon, and thus the destruction of a key carbon sink, and reduction in the absorptive capacity of the oceans—has been omitted from the projected concentration increases quoted here. It is possible that stocks could become even harder to stabilize than this description suggests.

[4] To avoid excessive length of discussion, we focus on 5°C, because it is an extremely dangerous increase and because its probability of occurrence under BAU is far from small. In a full analysis, one could and should look at the full range of possible concentrations and associated probability distributions for temperature increases.

We do not really know what the world would look like at 5°C above preindustrial times. The most recent warm period was around 3 million years ago when the world experienced temperatures 2–3°C higher than today (Eystein Jansen et al. 2007, 440). Humans (dating from around 100,000 years or so) have not experienced anything that high. Around 10,000–12,000 years ago, temperatures were around 5°C lower than today, and ice sheets came down to latitudes just north of London and just south of New York. As the ice melted and sea levels rose, England separated from the continent, rerouting much of the river flow. These magnitudes of temperature changes transform the planet.

At an increase of 5°C, most of the world's ice and snow would disappear, including major ice sheets and, probably, the snows and glaciers of the Himalayas. This would eventually lead to sea-level rises of 10 meters or more, and would thoroughly disrupt the flows of the major rivers from the Himalayas, which serve countries comprising around half of the world's population. There would be severe torrents in the rainy season and dry rivers in the dry season. The world would probably lose more than half its species. Storms, floods, and droughts would probably be much more intense than they are today.

Further tipping points could be passed, which together with accentuated positive feedbacks could lead to "runaway" further temperature increase. The last time temperature was in the region of 5°C above preindustrial times was in the Eocene period around 35–55 million years ago. Swampy forests covered much of the world and there were alligators near the North Pole. Such changes would fundamentally alter where and how different species, including humans, could live. Human life would probably become difficult or impossible in many regions that are currently heavily populated, thus necessitating large population movements, possibly or probably on a huge scale. History tells us that large movements of population often bring major conflict. And many of the changes would take place over 100–200 years rather than thousands or millions of years.

While there is no way that we can be precise about the magnitude of the effects associated with temperature increases of this size, it does seem reasonable to suppose that they would, in all likelihood, be disastrous. We cannot obtain plausible predictions by extrapolating from "cross-sectional" (Robert Mendelsohn et al. 2000, 557) comparisons of regions with current temperature differences of around 5°C—comparisons between, say, Massachusetts and Florida miss the point. Nor, given the nonlinearities involved, can we extrapolate from lower temperature increases (say 2°C) concerning which there is more evidence. Most people contemplating 5°C increases and upward would surely attach a very substantial weight on keeping the probability of such outcomes down.

From this perspective, an examination of Table 1 suggests that 550ppm CO_2e is an upper limit to the stabilization levels that should be contemplated. This level is nevertheless rather dangerous, with a 7 percent probability of being above 5°C and a 24 percent probability of being above 4°C. The move to 650ppm CO_2e gives a leap in probability of being above 4°C to 58 percent, and of being above 5°C to 24 percent. Further, we should remember that the Hadley Center probabilities are moderately conservative—one highly computationally intensive Monte Carlo estimate of climate sensitivity found a 4.2 percent probability of temperatures exceeding 8°C (David Stainforth et al. 2005). A concentration in the region of 550ppm CO_2e is clearly itself a fairly dangerous place to be and the danger posed by even higher concentrations looks unambiguously unacceptable. For this reason, I find it remarkable that some economists continue to argue that stabilization levels around 650ppm CO_2e or even higher are preferable to 550ppm, or even optimal (William D. Nordhaus 2007a, 166; Mendelsohn 2007, 95). It is important to be clear that the "climate policy ramp" (Nordhaus 2007b, 687) advocated by some economists involves a real possibility of devastating climatic changes.

In thinking about targets for stabilization, we have to think about more than the eventual stocks. We must also consider where we start; costs of stabilization; and possibilities of reversal, or backing out, if we subsequently find ourselves in or approaching very dangerous territory. The costs of stabilization depend strongly on where we start. Starting at 430ppm CO_2e, stabilizing at 550ppm CO_2e or below would likely cost around 1 percent of world GDP with good policy and timely decision making (see Section IB); for stabilization at 450ppm CO_2e, it might cost 3 or 4 times as much (possibly more). With bad policy, costs could be still higher. Note that the comparison of costs between 450ppm and 550ppm CO_2e illustrates the cost of delay[5]—waiting for 30 years before strong action would take us to around 530ppm CO_2e, from which point the cost of stabilizing at 550ppm CO_2e would likely be similar to stabilizing at 450ppm CO_2e starting from now. Under most reasonable assumptions on growth and discounting, a flow of 1 percent of GDP for 50–100 years starting now would be seen as much less costly than a flow for a similar period of 4 percent or so of GDP, starting 30 years later.

It can be argued that, at some future point, we might be able to turn to geoengineering, for example, firing particles into the atmosphere to keep out solar energy, analogous to the effect of major volcanic eruptions in the past. There are, however, substantial dangers associated with initiating other effects we do not understand. We might well be replacing one severe risk with another; however, extreme circumstances could require an extreme response. And there are difficult issues of global governance—would it be right for just one country, or group of countries, to do this? It seems much more sensible, at acceptable cost, to avoid getting into this position.

The above is basically the risk-management economics of climate change. For an expenditure of around 1 percent (between −1 percent and 3 percent) of world GDP (see Section IB), we could keep concentration levels well below 550ppm CO_2e and ideally below 500ppm CO_2e. While leaving the world vulnerable, this would avoid the reckless risks implied by the higher stabilization concentrations (e.g., 650ppm CO_2e) advocated by some economists. Thinking about the information basis for this argument also points to caution. If (as is unlikely) the risks of high concentrations turn out to be low and we have taken action, we would still have purchased a cleaner, more biodiverse, and more attractive world, at modest cost. If our actions are weak and the central scientific estimates are correct, we will be in very dangerous circumstances from which it may be impossible, or very costly, to recover.

[5] There would be some negatives (more inflexible equipment in place) and some positives (more technical knowledge).

B. *Costs of Abatement and Prices of GHGs*

To this point, our discussion of targets has focused on those for the stabilization of stocks. We must now ask about implications for emissions paths and how much, with good policy, they would cost. We have already anticipated part of the broad answer—around 1 percent of world GDP per annum to get below 550ppm CO_2e—but we must look at the argument in a little more detail.

Figure 2 illustrates possible paths for stabilization at 550ppm CO_2e (thin line), 500ppm CO_2e (dotted) and 450ppm CO_2e (dot-dashed); the solid line is BAU. There are many paths for stabilization at a given level—see, for example, Stern Review Figure 8.2 (Stern 2007, 226)—but all of them are a similar shape to those shown (if a path peaks later it has to fall faster). And if the carbon cycle weakens, the cuts would have to be larger to achieve stabilization at a given level—see Stern Review Figure 8.1 (Stern 2007, 222). Broadly speaking, however, a path stabilizing at 550ppm CO_2e or below will have to show emissions peaking in the next 20 years. For lower stabilization levels, the peak will have to be sooner. The magnitudes of the implied reductions between 2000 and 2050 are around 30 percent for 550ppm CO_2e, 50 percent for 500ppm CO_2e, and 70 percent for 450ppm CO_2e. Cuts relative to BAU are indicated in the figure.

Figure 3 shows that, to achieve these cuts in emissions, it will be necessary to take action across the board and not in just two or three sectors such as power and transport. For the world as a whole, energy emissions represent around two-thirds of the total, and nonenergy around one-third. Land use change, mainly deforestation and degradation of forests, accounts for nearly 20 percent of the total. Given that the world economy is likely to be perhaps three times bigger in mid-century than it is now, absolute cuts of around 50 percent would require cuts of 80–85 percent in emissions per unit of output. Further, since emissions from some sectors (in particular agriculture) will be difficult to cut back to anything like this extent, and since richer countries should make much bigger proportional reductions than poor countries (see Section IV), richer countries will need to have close-to-zero emissions in power (electricity) and transport by 2050. Close-to-zero emissions in power are indeed possible and this would enable

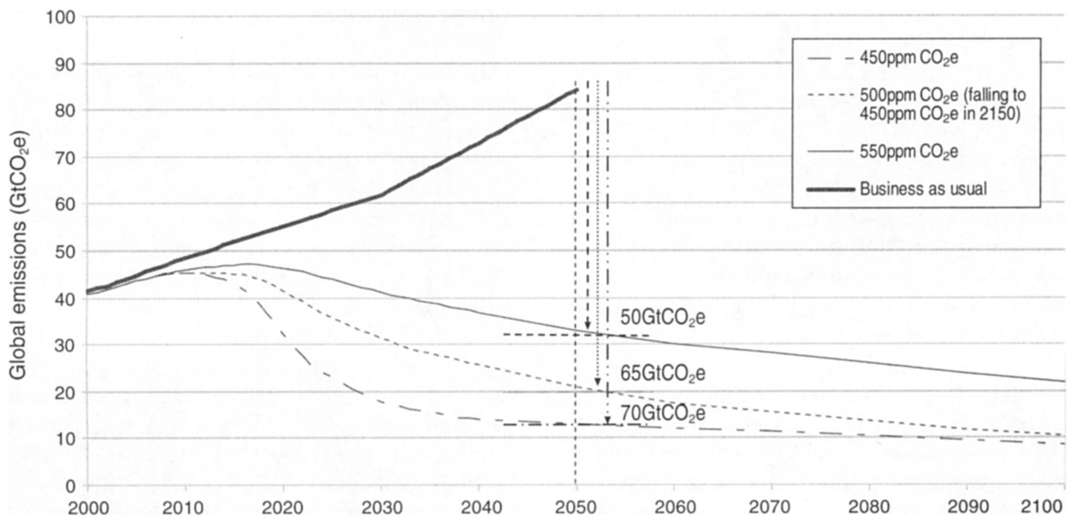

FIGURE 2. BAU AND STABILIZATION TRAJECTORIES FOR 450–550PPM CO_2e

Source: Stern Review, Figure 8.4 (Stern 2007, 233).

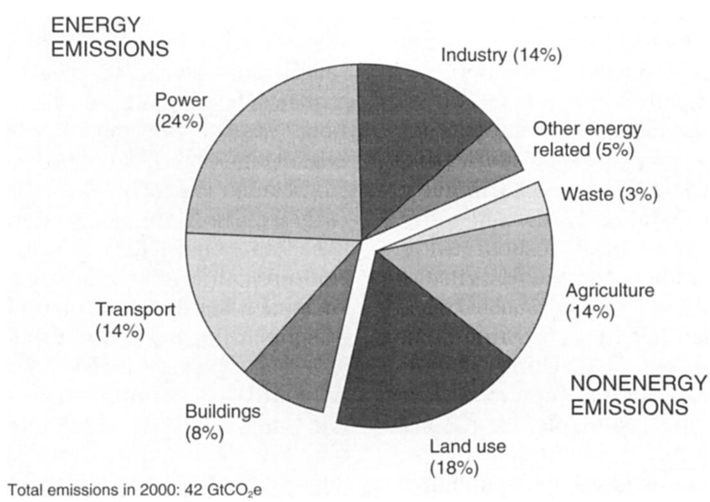

FIGURE 3. REDUCING EMISSIONS REQUIRES ACTION ACROSS MANY SECTORS

Source: Stern 2007, 196.

close-to-zero emissions for much of transport. This would, however, require radical changes to the source and use of energy, including much greater energy efficiency. Achieving the necessary reductions would also require an end to deforestation. The totality of such reductions would, however, not result in a radical change in way of life to the extent of that brought by electricity, rail, automobiles, or the Internet.

On the path for stabilization there would be different options for cutting emissions that would be more prominent at different times. In the earlier periods, there would be greater scope for energy efficiency and halting deforestation, and with technical progress there will be, and already are, strong roles for different technologies in power and transport.

Various different options for abatement were discussed in Chapter 9 of the Stern Review.[6] McKinsey has recently carried out a more detailed study (Per-Anders Enkvist, Tomas Nauclér, and Jerker Rosander 2007)—see Figure 4. There are several important lessons from this type of curve. First, there are many options for reducing emissions that have negative cost; that is, they save money. Second, there is a whole range of options and each should be explored in detail—for example, the costs associated with combating deforestation in the McKinsey curve are, in my view, far too high.[7] Third, the emissions savings from any one option will depend on what it replaces. Fourth, given the broad range of options, policy is very important—bad policy will lead to the uptake of more expensive options. Fifth, technical progress will be important and should be promoted so that the range of options is widened and costs are reduced. Finally, and of special importance, starting now in a strong way and with clear signals will allow more time for planned choices, discovery of options, and exploration of the renewal periods and timings for equipment. This is the measured, lower-cost approach. Going more slowly and then moving in haste when and if the science is confirmed still more strongly, is likely to be the expensive option.

Very importantly for policy, this type of figure gives us an understanding of where carbon prices (or GHG prices more generally) should be. By 2030, cuts at the world level would have to be of the order of 20 Gt CO_2e (see Figure 2) for stabilization at 550ppm CO_2e. This suggests a CO_2 price of around €30 per ton.[8]

A fairly clear idea of where the carbon price should be from the point of view of necessary abatement is of great help both to policymakers and to investors. It also provides the opportunity to check against estimates of the marginal social cost of carbon (SCC) reflecting the future damage of an incremental emission. The levels quoted here for the MAC are consistent with ranges for the SCC indicated in the Stern Review along an abatement path for 550ppm CO_2e stabilization.

However, the SCC is very slippery numerically since it is so sensitive to assumptions about model structure, including future emission paths, carbon cycles, climate sensitivity, future technologies, *and* ethical approaches to valuation over the centuries to come. The SCC at time t is the expectation of the integral[9] over τ from t onward of:

- the marginal social utility of consumption at τ (embodying ethical values and a particular path)

  × the impact on consumption at τ of all relevant preceding temperature changes (and resultant climate change)

  × the impact on a relevant temperature increase of increases in preceding carbon stocks

  × the impact on all relevant stocks of an increase in carbon emissions at t, where "impact" in the above is to be interpreted as a partial derivative.

Given this sensitivity, it is remarkable how carelessly the SCC is often quoted—it is quite common, for example, for people to quote an SCC without even referring to a reference emissions path, to say nothing of all the other relevant assumptions that matter greatly.

Thus, the SCC is a very weak foundation for policy. The target approach and the calculation of the associated MAC is more attractive from the point of view both of policy toward risk and of clarity of conclusions. It is also important, however, to check prices derived from the MAC against SCC calculations and to keep policy under revision, as further information and discovery arrives. Some notion of the SCC is also useful in examining the emissions savings from,

[6] Illustrative MAC curves were provided in the Stern Review, Figures 9.1 (Stern 2007, 243) and 9.2 (Stern 2007, 249).

[7] Erin C. Myers (2007, 9–12) reviews the literature and highlights the outlier status of the McKinsey deforestation estimate; see also the discussion in Section IV.

[8] This is not the place to speculate about euro-dollar exchange rates over two or three decades.

[9] This sketch of the calculation assumes the simple objective of the maximization of the integral of expected utility.

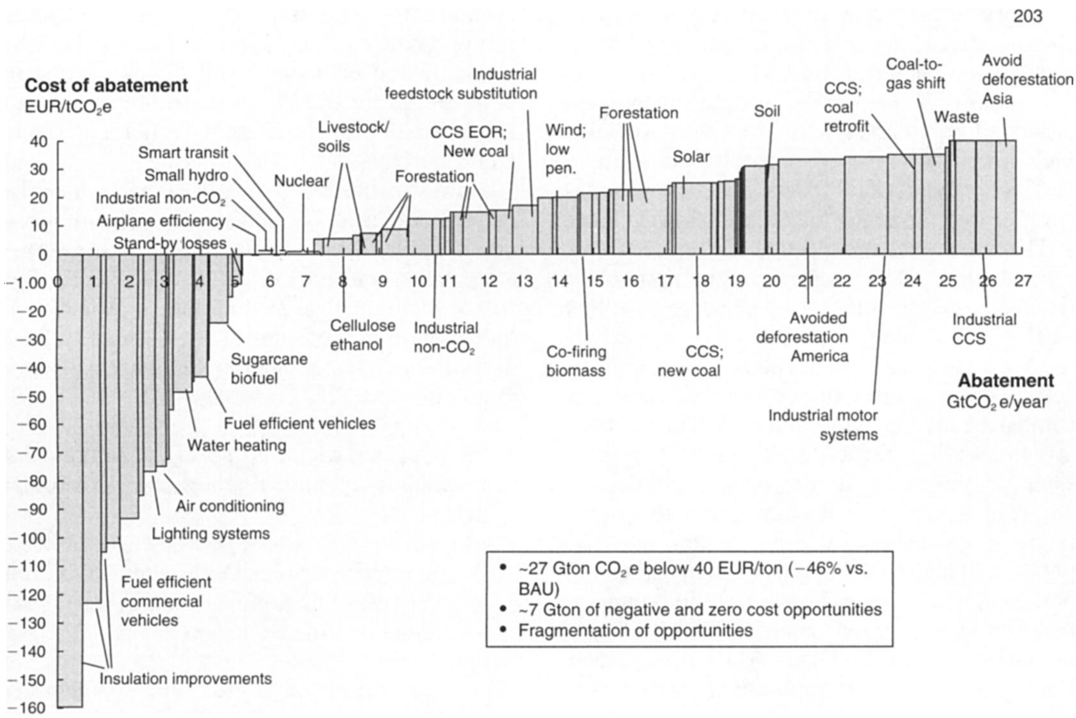

FIGURE 4. MCKINSEY BOTTOM-UP APPROACH TO ABATEMENT COSTS

Source: Enkvist et al. 2007, 38.

for example, transport programs or policies. If the MAC and SCC were thought to be in very different ball parks for an anticipated path, it would suggest strongly that policy revision is necessary.

Prices for abatement should be at a level that supports carbon capture and storage (CCS) for coal. Without CCS for coal it will be difficult (and more costly) to achieve the necessary cuts, given that many countries will rely heavily on coal for power generation for the next 30 or 40 years (IEA 2006; 2007). China and India (Expert Committee on Integrated Energy Policy (ECIEP) 2006), for example, will be using coal for around 80 percent of their electricity plants for the next 30 years or so—for the simple reasons that coal is cheap and available within their own borders; that they are familiar with the technologies; and that the plants can be erected quickly. Speed is of great importance for them, as the costs of electricity outages are very high.

The Stern Review (Chapter 10) also looked at top-down macro modelling of costs of emissions reductions (see also Terry Barker, Mahvash Saeed Qureshi, and Jonathan Köhler 2006). Both the bottom-up (Chapter 9) and the top-down (Chapter 10) studies produced numbers in similar ranges—around 1 percent of world GDP. There is, of course, considerable uncertainty. Bad policy or delayed decisions could give higher numbers. Stronger technical progress could give lower numbers. Assumptions about substitutability between different goods and options matter, too. Since the Stern Review was published, there have been a number of new studies, both bottom-up and top-down. Significant examples of the former are those from McKinsey (Enkvist, Nauclér, and Rosander 2007) and the IEA (2007), both of which indicated costs either in the region we suggested, or somewhat lower. Similar conclusions are drawn in the AR4 (IPCC 2007).

It is very important to recognize that costs of 1 percent of GDP do not necessarily slow medium- or long-term growth rates. They are like a one-off 1 percent increase in prices from "doing energy" in different ways. Further, there is a real possibility that incentives to discovery could generate a Schumpeterian burst of growth—on such possibilities see recent work by Philippe Aghion (2007). The scale of markets for new technologies will be very large (IEA 2006); see also Samuel Fankhauser, Friedel Sehlleier, and Stern (2007) for an assessment of investment and employment opportunities, which are likely to be positive.[10]

Finally, reducing GHGs can bring strong benefits elsewhere. Cleaner energy can provide greater energy security and energy access. It can give reductions in local air pollution. Cleaner transport policies can increase life expectancy. Combating deforestation can protect watersheds, sustain biodiversity, and promote local livelihoods. Taking these associated benefits into account would reduce cost estimates further.

In summary, looking back after a year, we would suggest that subsequent evidence and analysis have confirmed the range of our cost estimates for stabilization, or indicated that they may be on the high side. Good policy and timely decision making are, however, crucial to keeping costs down. And we would emphasize that taking a clear view now of a stabilization goal allows for a measured and careful adjustment, allowing for the replacement cycles of capital goods. To wait and see, or to rely on a "climate policy ramp," risks not only excessive and dangerous levels of stocks but also much more costly abatement if, as is likely, there is a subsequent realization that the response has been delayed and inadequate.

II. Stabilization of Stocks of Greenhouse Gases II: Modelling and Evaluation of Damages

A. *Introduction*

The previous section looked directly at the risks from GHGs, and at the costs of action to reduce emissions, and thus risks. This is the kind of judgement that people take when considering various forms of insurance, or design of buildings or infrastructure, or new medical treatments. They try to be as clear as possible on consequences and costs, bearing in mind that both are stochastic and that risk is of the essence, while also being aware that it will often be difficult to put a price or money values on consequences and risks.

It is also informative, however, to try to produce, using aggregate models, quantitative estimates of avoided damages in order to compare with costs. For climate change, that quantification may be possible for some dimensions, for some locations, for some time periods, and for some ranges of temperature increases.[11] However, the avoidance of planet-transforming change by keeping down risks of 5°C and above is at the heart of the argument here and it is extremely difficult to provide plausible aggregate numbers for the effects and overall damages of temperatures so far out of experience, particularly when nonlinearities may be of great importance. Nevertheless, formal modelling is central to the tools of our trade and the exercises do have value in bringing out the logic of some important trade-offs.

In making valuations of consequences, we have to face very difficult analytical and ethical issues. How does one value the transformation of the planet, the consequences of radical changes in ways of life, and big movements of population and associated conflict? Our standard cost-benefit analysis (CBA) tools do not give us much guidance. I have invested a lot of effort (e.g., Jean P. Drèze and Stern 1987, 1990), as have many others, in developing these tools, and have some understanding of what they are and where they can be applied. They are largely marginal methods, providing tools for analysis of big changes in, say, one or two markets as a result of a program. But when we are considering major strategic decisions for the world as a whole, with huge dynamic uncertainties and feedbacks, the potential contribution of an approach to decision making based on marginal methods is very limited. Rational decision making has to go back to the first principles from which the marginal

[10] These assessments refer to the potential shifts of the demand side of labor markets—outcomes depend, of course, on market structures.

[11] See, for example, Chapters 1, 3, 4 and 5 of the Stern Review.

methods of CBA are derived. This is not at all to use a different theory. On the contrary, it is to maintain the theory and to avoid a gross misapplication of the special (i.e., marginal) case.

The centrality of nonmarginal changes and of risk means either using the risk-analysis approach of Section IA, or using aggregate modelling with a social welfare function to compare consequences. Both have their role, but for the reasons given I would see the former as the main plank of the argument. The latter has a valuable supplementary role which we now investigate.

In setting out a social welfare function to evaluate damages and costs, the valuation of consequences on different dimensions—social, health, conflict, and so on—will be extremely difficult. I do not go into these issues. I focus on one issue that has, understandably, received considerable attention in discussion of the Stern Review—how to value benefits accruing to different people at different times. There are unavoidable ethical issues. They are the subject of Section IIB. In Section IIC we examine some of the challenges, results, and sensitivities of formal modelling, and comment on new evidence and discussions concerning the Stern Review's damage estimates after one year.

B. *Ethics*

Discounting.—Much of the discussion of ethics in relation to the Stern Review has been focused on discounting. Sometimes, simplistic approaches to discounting conceal or obscure the underlying structural and ethical logic by shoehorning the issues into a simple discount rate specified entirely externally to the problem. However, careful use of theory and concepts is crucial. Some have argued that "the discount rate of the Stern model" is too low in relation to market rates of return. This argument has generally been thoroughly confused for a whole set of reasons. It arises from inappropriate application of a marginal method to a strongly nonmarginal context, failure to apply modern public economics, ignorance of the multi-good nature of this problem, and, in some cases, ignorance of the difference between a social discount rate and a pure time discount rate. Given this pervasive confusion about the basic theory of discounting, it seems worthwhile to clarify briefly the logic of discounting as applied to climate change and relate it to some simple empirical data.

Let us start with the definition of a discount rate in policy evaluations. It is simply the proportionate rate of fall of the value of the numeraire used in the policy evaluation. In the simple case, with aggregate consumption as the numeraire, we have a social discount factor or SDF, $\lambda(t)$, which measures the social value of a unit of consumption at time t relative to a unit at time zero. The social discount rate, or SDR, is then $-\dot{\lambda}/\lambda$.

A number of general conclusions follow immediately from these basic definitions. First, the SDF and the SDR depend on a given reference path for future growth in consumption and will be different for different paths. Second, the discount rate will vary over time. Third, with uncertainty, there will be a different discount rate for each possible sequence of outcomes. Fourth, there will be a different discount rate for different choices of numeraire. In imperfect economies, the social value of a unit of private consumption may be different from the social value of a unit of private investment, which may be different from the social value of a unit of public investment. And the rates of changes of these values may be different too.

A further key element for understanding discount rates is the notion of optimality of investments and decisions. For each capital good, if resources can be allocated without constraint between consuming the good in question and its use in accumulation, we have, for that good, the result that the social rate of return on investment (the marginal productivity of this type of good at shadow prices), the SRI, should be equal to the SDR in terms of that good (i.e., with that good as numeraire). This is intuitively clear and in optimal growth theory is a standard first-order condition. But where there are constraints on this optimization, as there usually will be in imperfect economies, this condition that the SRI equal the SDR is not generally applicable. Drèze and Stern (1987, 1990), for example, show how opportunity costs, and thus shadow prices and shadow rates of return, depend on which alternative use a unit of resource comes from. Further, in such economies it will not generally be true that the private rate of return on investment (PRI) will be equal to the SRI. And similarly, private discount rates (PDRs) can diverge from SDRs. Such divergences can arise from all forms of market imperfections, including externalities. In this case we have the additional complication that key players, future generations, are not directly represented. Thus, in the general case:

$$PDR \neq SDR \neq SRI \neq PRI.$$

Before looking into discount rates along a given path, we should remind ourselves that the most basic mistake here is to use a marginal concept (discount rates) around a current path for strategic choices and comparisons among paths. Policy on climate change means choosing among paths with very different growth patterns for a whole collection of capital goods, including those relating to natural endowments. Thus, it is simply wrong to look at rates as currently observed, or in historical terms, which refer to existing paths. A choice among paths means also choosing the implied set of discount rates associated with the paths (Stern 2007, 27–31; for more on this issue see Cameron Hepburn 2006). This is simply another way of expressing the old idea that the shadow prices or marginal values depend on where you are. It is absolutely fundamental here for this very nonmarginal set of choices to recognize that the social discount rates are endogenous, not exogenous. They are determined by ethical values, which have to be discussed explicitly, and by the paths that result from climate change and investment choices.

Let us suppose, however, that we go past this problem and look at discount rates around a given path, or path of choice. What can we learn from observed rates in markets? Rates at which households can borrow and lend, usually for periods of no longer than three or four decades, give a reading on their private discount rates or PDRs (assuming they equate their discount rate with their market rate, with some appropriate treatment of uncertainty). But as this borrowing and lending takes place through private decisions made by individuals acting in a market, this does not necessarily answer the relevant question in the context of climate change decisions by a society—namely, how do we, acting together, evaluate our responsibilities to future generations over very long periods?

Rates of return on investment generally reflect private rates of return narrowly measured. They take no account of externalities, which are of the essence for this discussion. Thus, even if we think we can observe some private rates of discount for some households, and some private rates of return for some firms, we do not have a reading on the concept at issue here, the social discount rates for the key goods. Thus, observations on the PRIs and PDRs have only limited usefulness. And note that the problems that prevent the equalities in this chain, such as missing markets, unrepresented consumers, imperfect information, uncertainty, production, and consumption externalities are all absolutely central for policy toward the problem of climate change. We come back again to a basic conclusion: the notions of ethics, with the choice of paths, together determine endogenously the discount rates. There is no market-determined rate that we can read off to sidestep an ethical discussion.

It must surely, then, be clear that it is a serious mistake to argue that the SDR should be anchored by importing one of the many private rates of return on the markets (or a rate from government manuals, or a rate from outside empirical studies). Yet it is a mistake that many in the literature have made. Nordhaus (2007b, 690) and Martin L. Weitzman (2007b), for example, substitute a market investment return of 6 percent for the SDR, thus producing a relatively high 6 percent rate of discount on future consumption. This mistakenly equates the PRI to the SRI and the SRI to the SDR. Such an approach is entirely inappropriate given the type of nonmarginal choices at issue and the risk structure of the problem, and in light of developments in modern public economics, which encompasses social cost-benefit analysis and which takes account of many imperfections in the economy, including unrepresented consumers, imperfect information, the absence of first-best taxes, and so on.

If, despite these difficulties, we nevertheless insist on looking to markets for a benchmark rate of discount, then what do we find? In the United Kingdom and United States, we find (relatively) "riskless," indexed lending rates on government bonds centered around 1.5 percent over very long periods. For private very long-run rates of return on equities, we find rates centered around 6 or 7 percent (Rajnish Mehra and Edward C. Prescott 2003, 892; Kenneth J. Arrow et al. 2004, 156; Sree Kochugovindan and Roland Nilsson 2007a, 64; 2007b, 71). Given that it is social discount rates that are at issue, and also that actions to reduce carbon are likely to be financed via the diversion of resources from consumption (via pricing) rather than from investment, it is the long-run riskless rates associated with consumer decisions that have more relevance than those for the investment-related equities. Thus, even if one were to endorse the approach of importing a discount rate from markets, when one uses the rate of return closer (but not equivalent) to the relevant concept—the risk-free rate—it is far from clear that one would obtain a rate of discount on future consumption as high as the 6 percent advocated by Nordhaus (2007b, 690).

Weitzman (2007c) has recently produced an interesting insight into the difference between the riskless rate and equity returns in terms of perceived high weights in the downside tail of equity returns—the implication being that the perceived equivalent return on equities, allowing for risk, is close to the lower riskless rates. In this context Weitzman (2007a, b), has also suggested encapsulating risk and uncertainty in some contexts into discount rates. In my view, however, it is far more transparent to treat risk directly through the approach to social welfare under uncertainty than to squash it into a single parameter that tries to reduce the problem to one of certainty.

Suppose, however, that we persisted with the argument that it is better to invest at 6–7 percent and then spend money on overcoming the problems of climate change later rather than spending money now on these problems. The multi-good nature of the problem, together with the irreversibilities from GHG accumulation and climate change, tell us that we would be making an additional mistake. The price of environmental goods will likely have gone up very sharply, so that our returns from the standard types of investment will buy us much less in reducing environmental damage than resources allocated now (see also Section I on the costs of delay).[12] This reflects the result that if environmental services are declining as stocks of the environment are depleted, then the SDR with that good as numeraire will be negative. On this, see the interesting work by Michael Hoel and Thomas Sterner (2007), Sterner and U. Martin Persson (2007) and Roger Guesnerie (2004), and also the Stern Review (Stern 2007, 60). Environmental services are also likely to be income elastic, which will further reduce the implied SDR.

Finally, we underline an unhappily common mistake—namely confusing the pure time discount rate (PTDR) with the SDR. With a very simple single good structure and consumption at time t having social value $u(c)e^{-\delta t}$, we have the SDF, λ, as $u'(c)e^{-\delta t}$.[13] Its proportionate rate of fall (the SDR) is $\eta(\dot{c}/c) + \delta$, where η is the elasticity of the social marginal utility of consumption with respect to consumption.[14] Often η is taken to be a constant. In this very simple case, we can now see the difference between the SDR and the PTDR. The PTDR is the rate of fall of the value of a unit of consumption, *simply because it is in the future*, quite separately from the levels of consumption enjoyed at the time. Here, the PTDR is δ. For example with $\delta = 0$, $\eta = 1.5$, and $\dot{c}/c = 2.5$ percent, we have a social discount rate of 3.75 percent, in excess of the UK government's test discount rate (Her Majesty's Treasury 2003), notwithstanding a PTDR of zero. It is η and the growth rate that capture the idea that we should discount the consumption of future generations on the basis that they are likely to be richer than ourselves. This reason for discounting is, and should be, part of most models, including those of the Stern Review. We shall show in the next subsection that the cost, in terms of climate changes, of weak or delayed action in the formal models is much greater than that of timely and stronger action, in terms of abatement expenditure, over a range of parameter values for η.

A δ of 2 percent (3 percent)—as endorsed by many commentators such as Nordhaus (2007b)

[12] The issue is still more complex in this context, as delays in action result in environmental damage along the way, as well as increasing the cost of achieving a given stabilization level. On balance, the extra intertemporal complexity is likely to strengthen this paper's argument in this case.

[13] The SDF is the marginal utility of consumption at time t (and we normalize the SDF to one for $t = 0$). If we consider a changing population $N(t)$, and replace $u(c)$ by $Nu(c)$ where c is C/N and C is total consumption at time t, the partial derivative with respect to C is $u'(c)$.

[14] Unfortunately, some, including Nordhaus (2007b) and Weitzman (2007b), have been tempted to think that a value for the PTDR can be "backed out" from this expression by equating the SDR with some market rate of return. For example, with a market investment return of 6 percent, consumption growth of 2 percent, and $\eta = 2$, one "infers" that $\delta = 2$ percent. Thus, the fallacy that the SDR can be anchored by some market rate of return leads to a second fallacy, namely that society's PTDR can be "revealed" from market behavior (instead of requiring explicit specification on ethical grounds).

and Weitzman (2007b)—implies that the utility of a person born in 1995 (1985) would be "worth" (have a social weight) roughly half that of a person born in 1960. This type of discrimination seems very hard to justify as an ethical proposition and would be unappealing to many. Indeed, the ethical proposition that δ should be very small or zero has appealed to a long line of illustrious economists including Frank P. Ramsey (1928, 543), Arthur Cecil Pigou (1932, 24–5), Roy F. Harrod (1948, 37–40), Robert M. Solow (1974, 9), James A. Mirrlees (Mirrlees and Stern 1972), and Amartya Sen (Sudhir Anand and Sen 2000). I have heard only one ethical argument for positive δ (Wilfred Beckerman and Hepburn 2007; Simon Dietz, Hepburn, and Stern 2008) that has some traction—namely a temporal interpretation of the idea that one will have stronger fellow feelings for those closer to us (such as family or clan) relative to those more distant. This is often explained in terms of functionality for survival of groups. However, this type of reasoning from evolutionary biology does not have much relevance when we are thinking about the survival of the planet as a whole.

For these reasons, the Stern Review followed the tradition established by the economists cited above, adopting and arguing strongly for a δ that exceeds zero only in order to account for the possibility of some exogenous event that would render future welfare calculations irrelevant—the exogenous extinction of humanity (for discussion of this interpretation of δ, see, e.g., David Pearce and David Ulph (1995) and David Newbery (1992)). On this basis, the Review adopted a δ of 0.1 percent (although even this value for δ appears to be quite large in relation to this interpretation, implying a probability of exogenous extinction of around 10 percent in 100 years). For a project or program, the probability of exogenous extinction could be substantially higher, and this is reflected in some cost-benefit manuals or approaches; in our case, however, we are considering humanity as a whole.

My overall assessment of the discussion of discounting in the context of climate change is that it is disappointing. All too often it has failed to come to grips with the basic concepts, with the key nonmarginal and uncertainty elements at the core of the issue, and with the theories of social cost-benefit analysis and modern public economics of the last 30 or 40 years.

Distributional Judgements.—Having seen the implausibility of importing a discount rate from outside the model to sidestep ethical judgements, let us turn to the ethics relating to the distribution of consumption or income, at least in its very narrow form of η within the narrower cases (as in the models that follow) where the social objective is the expectation of the integral of $\sum_i u(c_i)e^{-\delta t}$ (Stern 2007, 50–54).[15] Thinking about η is, of course, thinking about value judgements—it is a prescriptive and not a descriptive exercise. But that does not mean that η is arbitrary; we can, and should, ask about *"thought experiments"* and observations that might inform a choice of η. In so doing we must remember that η plays three roles, guiding (a) intratemporal distribution, (b) intertemporal distribution, and (c) attitudes to risks. We look at the relevance of empirical data for each of the three in turn.

Intratemporal Distribution: Let us begin with a thought experiment concerning direct consumption transfers in a very simple context. If A has k times the consumption of B, the social value of a unit of consumption to B is k^{η} times that to A for constant η. For example, for $k = 5$ and $\eta = 2$, the relative value is 25 and a transfer from A to B would be socially worthwhile even if up to 96 percent were lost along the way (the so-called "leaky bucket"—Arthur M. Okun (1975)). While I might not regard that position as unacceptable, to take just one example, it appears inconsistent with many attitudes to transfers. In this sense, many would consider an η of 2 to be very egalitarian. With $\eta = 1$, the 96 percent in the example above becomes 80 percent because the unit to B is worth five times that to A. Some might regard even this position as rather egalitarian.

Value judgements are, of course, precisely that and there will be many different positions. They will inevitably be important in this context—they must be discussed explicitly and the implications of different values should be examined. Examples follow of what we find when we turn to empirical evidence and try to obtain implied values (the "inverse optimum" approach). Empirical evidence can inform, but

[15] The summation is across individuals existing at time t and c_i is the consumption of individual i.

not settle, discussions about value judgements—for further exploration see Dietz, Hepburn, and Stern (2008). In using such evidence, we must constantly bear in mind two key issues. First, we must ask about the relevance of individual decisions for the societal decisions about the problem at hand—here social decisions by the world community now, bearing in mind consequences for future generations. And, second, if we infer values from decisions, we must ask whether we have modelled well the decision processes, the objectives, and the perceived structure of the problem as seen by the decision maker.

Anthony B. Atkinson and Andrea Brandolini (2007) have produced an interesting set of examples on empirical income distributions and actual transfer schemes in relation to welfare weights.[16] They conclude that constancy of η across a range of increases is difficult to "square with" the way that many transfer schemes occur in practice; in addition, there are many examples where policies appear inconsistent with η greater than one. For example, given the current income distribution in the United States, an η of two would imply that a redistribution from the fifth-richest decile to the second-poorest decile would be welfare-improving even if only 7 percent of the transfer reached the recipient; for a transfer from the richest decile to the second-poorest, virtually any redistribution would be welfare-improving regardless of loss along the way, so long as the recipient received some benefit (Atkinson and Brandolini 2007, 14). Of course, interpretation of actual intratemporal tax and transfer schemes will depend on many assumptions about the structure of incentives[17] and policymaking procedures. Perhaps people think that tax-transfer disincentives are very strong and they oppose transfers for these reasons. Or notions of rights and duties may influence them. The upshot is that empirical estimates of implied welfare weights can give a wide range of η, including η below one and even as little as zero.

It is striking that there are some, such as Nordhaus (2007b) and Weitzman (2007b), who appear to argue for high η (equal to 2 or 3) in intertemporal analysis yet do not bring out how this is potentially inconsistent with standard cost-benefit analysis treatments of intragenerational distribution (which effectively assume $\eta = 0$) or with some intratemporal tax and transfer policies.

Intertemporal Distribution: In discussions of η in an intertemporal framework, there has been much focus on implied saving rates. Some (Partha Dasgupta 2007, 6; Nordhaus 2007b, 694–96), following arguments in Kenneth J. Arrow (1995, 12–17), have criticized the relatively high weight placed by the Stern Review on the consumption of future generations (whether via η or δ) by arguing that the Review's parameter choices can, in certain scenarios, imply implausibly high optimal savings rates. As is clearly explained in the Review (Stern 2007, 54), with $\delta = 0$, output proportional to capital, and no technical progress, the optimal savings rate is $1/\eta$. With η close to one, this would lead to very high optimal savings rates. At the same time, the Review also states clearly (Stern 2007, 54) that this result is highly dependent on model assumptions.

Brad DeLong, in a short blog entry (DeLong 2006), points out this flaw in the Dasgupta-Nordhaus position and argues that technical progress would greatly reduce the optimal savings rate. Mirrlees and Stern (1972) presented a more fully developed argument. Using a standard one-good, infinite-horizon Ramsey growth model, constant returns to scale, and a Cobb-Douglas production function, they show that under one specification—with constant population, a competitive share of capital equal to 0.375, and 3 percent exogenous technological progress—the optimal consumption path for $\eta = 2$ and $\delta = 0$ involves a savings rate, s, between 0.19 and 0.29 (or 0.23 if constrained to a constant s). This is far below the 0.5 that would be optimal with $\eta = 2$ and $\delta = 0$ in the simpler case of output proportional to capital and no technical progress.

Just as with intragenerational values, the approach of the "inverse optimum" or implied social values does not take us very far in this context. We cannot really interpret actual saving decisions as revealing the collective view

[16] The welfare weight on an individual with consumption c is taken here as the social marginal utility of consumption at that level. To keep things simple, we assume that this depends only on the individual's consumption and not on her preceding consumption or the consumption of others.

[17] See, for example, Stern (1976), who shows how sensitive tax calculations are to assumptions about substitutability between goods and leisure.

of how society acting together should see its responsibilities to the future in terms of distributional values—too much depends on assumptions about how decisions are made in a society and on how the participants perceive the workings of the future economy. Observed aggregate savings rates are sums of individual decisions, each taken from a narrow perspective. This is not the same thing as a society trying to work out responsible and ethical collective action—the crucial issue for climate change.

Attitudes to Risks: "Guidance" on η from analyses of risk and uncertainty is even less informative. We can interpret η as the parameter of relative risk aversion in the context of an expected utility model of individual behavior. However, the expected utility model is unreliable as a description of attitudes to risk. Further, we see a whole range of behavior, from the acceptance of "unfair risks" in gambling (similar to $\eta < 0$) to extreme risk aversion in insurance (very high η). And even if behavior were somewhat more "rational" in the narrow sense of conforming to the expected utility hypothesis, it would still be unclear how sound a basis it would be for the specification of a prescriptive value for use in this context.

From this very brief discussion of empirical information, which might help us to think about η in a prescriptive context, our conclusion is that there is very little to guide us.[18] Again, we are pushed back to the standard moral philosopher's approach of trying to think through simple examples, i.e., the thought experiment. It has the great virtue of facing the issues directly—it is transparent and clear.

What do we conclude about ethics and discounting in this context when we clear the various confusions out of the way? The answer is fairly simple. First, we must address the ethics directly. There is no simple market information from intertemporal choices or otherwise that can give us the answers. Second, if we express the problem in standard welfare economic terms, i.e., portray the objective as an expectation of an integral of social utility, we cannot use marginal approximations to changes in welfare since we are comparing strategies that yield very different paths. Third, within this framework we may focus the discussion on elasticities of marginal social utility η and pure time discount rates δ, but in so doing we must recognize the ethical narrowness of this approach. Fourth, direct ethical discussion of η and δ suggests a broad range for η, although the consequences for simple transfers suggest that many would regard η in excess of 2 as unacceptably egalitarian; on the other hand, there appears to be little in the way of ethical arguments to support δ much above zero. Fifth, within a marginal analysis framework, the relevant concept for discounting here is the SDR. In the narrow η–δ context, with η of 1 to 2, very low δ, and growth at 1.5–2.5 percent,[19] we find an SDR of 1.5–5 percent, which is close to ranges for long-run consumer real borrowing rates and (at least in the UK) government discount rates for program evaluations.

C. *Formal Modelling*

Aggregate models have been popular in the economics of climate change. They attempt to integrate the science of climate change, as expressed, for example, via GCMs, with economic modelling and are termed integrated assessment models, or IAMs.

As I have argued, it is very hard to believe that models where radically different paths have to be compared, where time periods of hundreds of years must be considered, where risk and uncertainty are of the essence, and where many crucial economic, social, and scientific features are poorly understood, can be used as the main quantitative plank in a policy argument. Thus, IAMs, while imposing some discipline on some aspects of the argument, risk either confusing the issues or throwing out crucial features of the problem.

A related but different point is their use, when modelling of costs of abatement is integrated with modelling of damages from emissions, as vehicles for optimization analysis. In

[18] Thirty years ago (Stern 1977), I examined all three of these methods with no particularly strong conclusions, other than that the results covered a broad range.

[19] In Section IIC we consider η in this range. Higher growth rates are not examined in detail. The modelling would have to take account of a changed path of emissions with earlier damages. With risk distributions appropriate to current knowledge, our preliminary findings suggest that estimated damages from climate change are likely to be well above the cost of action to drastically reduce those risks.

this respect, they are still less credible. Those of us schooled in the optimal tax and optimal growth analysis of the 1960s, 1970s, and 1980s learned just how sensitive model results can be to simple structural assumptions, such as the form of preferences, production, or technical progress, even before parameter values are introduced (Atkinson and Joseph Stiglitz 1976, 1980; Angus Deaton and Stern 1986).

The models portrayed here should be seen as helpful supplements exploring some serious logical and modelling issues related to the estimation of damages from BAU and their comparison with alternative paths. We shall see, not surprisingly, that the key assumptions influencing damage estimates concern risk and ethics. It is surprising, however, that these two issues did not occupy until recently the absolutely central position that the logic of the analysis demands. The result is that—given the recent evidence on emissions, carbon cycles, and climate change sensitivity—most of the studies prior to a year or two ago grossly underestimated damages from BAU.

The PAGE[20] model was chosen for the work of the Stern Review first, because, in contrast with a large majority of preceding work, it places risk and uncertainty at center stage. It provides for a Monte Carlo analysis of explicit distributions of a large number of parameter values. Second, Chris Hope, its originator, chose the parameters and their distributions to straddle a range of climate models, IAMs, and economic models in the literature. Third, Chris Hope kindly made the model available and was very generous with his advice. The model was described extensively in Chapter 6 of the Stern Review as well as by Hope (2006a, b) and Dietz et al. (2007a, b).

Key assumptions on the form of the models and of the parameters in these models may be grouped into two broad headings: the *structural* elements that shape the estimated consequences of different kinds of emissions strategies, and the *ethical* elements that shape the evaluations of different outcomes. Of the structural elements in this approach, four are crucial: the emission flows; the functioning of the carbon cycle linking flows to stocks; the climate sensitivity linking stocks to temperature; and the damages from temperature, via climate change. Of the ethical elements, the following are crucial: the type of ethical values considered (including the role of rights and obligations); the type of outcomes introduced into evaluation functions (including separate goods or services such as environment, health, and standard elements of consumption); the functional forms used to capture evaluations; and the parameters within those functional forms, including those covering intra- and intergenerational values. The ethical discussion should not be shoehorned into a narrow focus on just one or two parameters such as η and δ; the ethical issues and their interactions with a model structure designed to reflect a range of uncertainties are much broader and deeper.

Stern Review Damages and Sensitivity.—The Stern Review base case had damages from BAU relative to no climate change of around 10 percent of consumption per annum measured in terms of the Balanced Growth Equivalent, or BGE (see Mirrlees and Stern 1972). Here, the BGE for any given path is calculated from the expected social utility integral of that path by asking "what initial consumption level, growing at a given growth rate and without uncertainty, would give this expected social utility integral?" The difference between the BGEs with and without climate change can be thought of as the premium, in terms of a percentage of annual consumption, that society might be willing to pay to do away with the risk and uncertainties associated with dangerous climate change. Essentially, the BAU provides a calibration in terms of consumption (useful since "expected integrated utils" are hard to interpret) for the expected utility integral: it summarizes an average over time, space, and possible outcomes.

Table 2 presents some of the results of the PAGE model. The parameter η was discussed in Section IIB and is the elasticity of the social marginal utility of consumption where the integrand for expected social utility is the sum over i of $N_i u(C_i/N_i)e^{-\delta t}$, and where C_i and N_i are consumption and population in region i. In the model, γ is the exponent of a power function linking temperature T to damage through the function AT^{γ} (Stern 2007, 660—the damages vary by region). Table 2 provides BGE differences (in percent) across paths without and with climate change, with a 5–95 percent confidence interval in brackets. We think of increases in γ

[20] PAGE 2002, Policy Analysis of the Greenhouse Effect 2002 Integrated Assessment Model, see Hope (2006a, b).

TABLE 2—SENSITIVITY OF TOTAL COST OF CLIMATE CHANGE TO KEY MODEL ASSUMPTIONS
(*Definitions in text*)

Damage function exponent (γ)	Consumption elasticity of social marginal utility (η) 1	1.5	2
2	10.4 (2.2–22.8)	6.0 (1.7–14.1)	3.3 (0.9–7.8)
2.5	16.5 (3.2–37.8)	10.0 (2.3–24.5)	5.2 (1.1–13.2)
3	33.3 (4.5–73.0)	29.3 (3.0–57.2)	29.1 (1.7–35.1)

Note: Units are percentage losses in the BGE relative to no climate change (see text for discussion).

Source: Dietz et al. 2007b.

as capturing increases in the structural risks,[21] and of increases in η as capturing increases in aversion to inequality and risk.

Intuitively, we can think of γ as combining both the relation between temperature and damages, and the distribution of temperatures arising from a certain emission path. These are, of course, distinct effects, but both an increase in γ and a broader distribution for the temperature (in particular more weight in the upper tail, either from a weakening in the carbon cycle or from higher climate sensitivity) has the effect of producing a higher probability of large damages. The effects are treated separately in the Review (Chapter 6 and the Technical Annex to Postscript), where many more sensitivity results are given. These two processes (damages and temperature distributions) can and should be modelled separately, but here we keep the discussion and presentation as simple as possible.

While we shall discuss results in terms of the sensitivity of estimated damages with and without climate change, we must emphasize that stabilization at 550ppm CO_2e removes around 90 percent[22] of the damages (Stern 2007, 333), so that we are essentially comparing two strategies, namely BAU and stability below 550ppm CO_2e. *A key broad lesson from this type of modelling is that the costs of stabilizing below 550ppm CO_2e are generally far lower than the costs of the damages from climate change that would thereby be avoided.* While the measurement of estimated damages may vary, this key lesson is robust to parameter changes.

In this type of modeling, results are highly sensitive to assumptions on both structural risks and ethics, suggesting that great care should be exercised in choosing the key parameters. We can illustrate the importance of these two issues in terms of both computations in the model and of general results. Replacing all random variables in the PAGE model by their modes brings down the central case of damages from BAU from 10–11 percent to 3–4 percent.[23] Thus, it is wrong to argue, as Dasgupta (2007) and Nordhaus (2007b) have, that the Chapter 6 results of the Stern Review arise solely from assumptions related to ethics, in particular the use of $\eta = 1$ and, at least in the view of Nordhaus, a low δ. *Both* risks *and* ethics are crucial to any serious assessment of policy toward climate change and, in particular, assessment of damages from BAU.

A formal result is provided in Box 1, which shows that for any given set of structural risks and a utility function, pure time discounting (a key element in the ethics) can be set so that the estimated damages are as small as we please. Further, for any given pure time discounting, risks and utility can be set such that damages are as big as we please.

Recently, in a series of papers (Weitzman 2007a, b), Marty Weitzman has argued that when we consider how the various different

[21] To keep things simple, the results in the table have γ fixed—that is, nonstochastic. The Monte Carlo probabilities are therefore generated by the variations in the many other parameters. In the Postscript to the Review (Stern 2007, 658–71), stochastic γ is presented. The base case of γ fixed and equal to 2 in Table 2 corresponds closely to the base case for stochastic γ in Chapter 6 of the Review and the Technical Annex to Postscript.

[22] Measured in terms of BGE.

[23] See Dietz et al. (2007a, c). The drop from replacing all random variables by their means is smaller but still substantial.

ROLE FOR BOTH RISK AND ETHICS

- Write expected utility integral as $\int_0^\infty g(t)f(t)\ dt$, where $g(t) = E[\hat{u}(c)]$, and $\hat{u}$ is the welfare difference without and with climate change; $f(t)$ is the pure time discount factor. $g(t)$ will depend on model structure, policies/path, and shape of $u(c)$. It is possible that $g(t)$ is infinite for some finite T (see Weitzman 2007a).

- For any given $g(t)$, we can construct $f(t)$ so that $\int_0^\infty g(t)f(t)\ dt < \varepsilon$ for any $\varepsilon > 0$, i.e., there are arbitrarily small losses from climate change. An example is $f(t) \equiv (1/g(t))e^{-\delta t}$ with $\delta > 1/\varepsilon$.

- For any given $f(t)$, we can construct $g(t)$ so that there are infinite losses from climate change, i.e., $\int_0^\infty g(t)f(t)\ dt = \infty$. An example is $g(t) \equiv 1/f(t)$.

- Clearly, both ethical values and risk play key roles.

BOX 1

probability distributions (particularly of climate sensitivity) that might arise in different models can or should be combined, there is a convincing case for strong weights in the tails of overall temperature and damage distributions. These can lead to divergent (i.e., infinite) estimates of expected damages. His arguments are powerful and persuasive, underlining strongly the crucial role of risk in this story and raising questions on the use of the expected utility approach.

It is interesting to note that divergence of integrals can occur in three ways in this expected utility integral: first, via uncertainty, as Weitzman emphasizes; second, via intragenerational distribution (for example, this can occur for the Pareto distribution of income, Christian Kleiber and Samuel Kotz 2003, 59–106); and third, via integration over time. Indeed, for $\eta = 1$ and $\delta = 0$, with positive growth the time integral is on the borderline of convergence (Stern 2007, 58). Thus, for $\eta = 1$ and $\delta = 0.1$ percent, the bulk of the changes (in terms of the expected utility integral)—over 90 percent—occur after 2200. For $\eta = 2$, the proportion is around 10 percent and for $\eta = 1.5$ around 30 percent. For some (e.g., William Cline 2007), this is an argument for η higher than one, and I have some sympathy with this view.

Claude Henry (2006; Stern 2007, 38–39) has argued that our lack of knowledge on which of the probability distributions to use for temperature and damages is an example of Knightian uncertainty, and he shows, using recent mathematics on how the von Neumann–Morgenstern axioms might be modified, how strong weights are likely to be (or should be) attached to the worst outcomes. We might see his approach, together with that of Marty Weitzman, as a mathematical embodiment of the precautionary principle.

Other forms of sensitivity are summarized only briefly here—see the Stern Review for more details. We comment on some specifics of a weakening carbon cycle on the structural side; and pure time preference, intragenerational issues, and a narrower view of dimensions of damage on the ethical side. The Stern Review had a "base climate scenario" (Stern 2007, 175) which ruled out a weakening carbon cycle and included only very moderate positive natural feedbacks. These are known to be possibilities, but are not sufficiently well understood to enable calibration for most modelling purposes. A "high-climate scenario" (Stern 2007, 175) introduced increased changes for the carbon cycle, covering plant and soil respiration and possible methane emissions from thawing permafrost, but these effects as modelled now look fairly small in relation to current scientific concerns. This added a 4 percent extra BGE loss from BAU relative to no climate change. We also experimented with higher climate sensitivity—see Box 6.2 of the Review (Stern 2007, 179)—although we did not publish results. It seems now that the "high +" scenario discussed there may be of real relevance.

The PAGE model used in the Review includes some damage estimates from nonmarket effects such as health. If these are removed, the base-case damage estimates drop from 10 percent to 5 percent. Unsurprisingly, results are sensitive to pure time discounting. A pure time discount rate of 1 percent implies, under the extinction view of discounting, only a 60 percent chance of the world surviving the next 50 years, which most would regard as a very pessimistic number. Nevertheless, as the Review's Technical Annex to Postscript shows, even with $\delta = 1$ percent, damages from BAU are likely to be higher than the costs of a mitigation strategy that removes the bulk of the risks.

We did not carry out an examination in the model of intragenerational issues in any detail, but comparisons with other studies suggested that these could add around a quarter or more to loss estimates (for η around 1), in this case another 4–5 percent. Starting with the base case of BGE losses of 10–11 percent, these variations (−5 percent for a narrower view of damages, +4 percent for higher climate response, +4 or 5 percent for intragenerational issues) gave us the range of 5–20 percent losses per annum from BAU that has been widely quoted. These are averages in three senses: over time, over space, and over possible outcomes.

In Chapter 13 of the Review, different methods for looking at stabilization are examined, starting with the bottom-up or risk-evaluation approach of Chapters 1, 3, 4, and 5 (and Section I). The discussion of the top-down damage modelling approach, used in this section of the paper and in Chapter 6 of the Review, explains that the 10–11 percent BAU base-case damage costs are reduced to around 1 percent for stabilization at 550ppm CO_2e (Stern 2007, 333) i.e., the cost saving from avoided damages of stabilizing at 550ppm CO_2e is 9–10 percent. When compared with costs of stabilization at 550ppm CO_2e of around 1 percent of world consumption or GDP[24] (see Section IB above), this saving from action represents a very good return. Even if damages avoided are only 3–4 percent of world consumption or GDP, stabilizing below 550ppm CO_2e is still a good deal. The basic statement that the costs of strong and timely action are much less than the costs of weak and delayed action is very robust. Let us underline again, however, that the Review gives stronger weight in terms of space and emphasis to the bottom-up risk evaluation approach than to the top-down aggregate modelling approach.

Comparison with Other Modelling of Damages.—Much of the earlier literature on climate modelling found damage results that were lower than the results in the Stern Review.[25] Much of this earlier work underestimates BAU emission flows (see below), suppresses or only lightly touches on risk, takes an extraordinarily low view of damages from temperature increases, and embodies very high pure time discounting with little explicit ethical discussion as to why (see Section IIB).

As Figure 5 shows, Richard S. J. Tol (2002) and Nordhaus (Nordhaus and Joseph G. Boyer 2000) essentially suppress uncertainty about climate sensitivity by using point estimates and not spreads.[26] There are some minor attempts to "add on" risk, but it is not given the central role demanded by the science and the economics. The range covered by PAGE is cautious on climate sensitivity, using only triangular distributions for its parameters—its *full* spread from all Monte Carlo runs is within the IPCC AR4 "*likely*" (66 percent confidence interval) range. The Meinshausen (2006) spread covers the 90 percent confidence interval for the full range of models he surveys, some of which go far higher.

Figure 6 summarizes results by Mendelsohn (Mendelsohn et al. 2000) and Tol (2002) with astonishingly low damages of 0–2 percent of GDP from temperature increases as high as 5–6°C. The Nordhaus and PAGE (Christopher Hope 2006a) damages in terms of output are fairly close together, although arguably much too small in relation to the possible implications of 5–6°C temperature increases.

These early models have given rise to a powerful and unjustified bias against strong and timely action on climate change. The question

24 Over time, 1 percent of consumption and 1 percent of GDP are broadly equivalent.

25 A valuable review can be found in Geoffrey Heal (2007).

26 Their models (FUND for Tol and DICE/RICE for Nordhaus) can, however, be used for Monte Carlo studies.

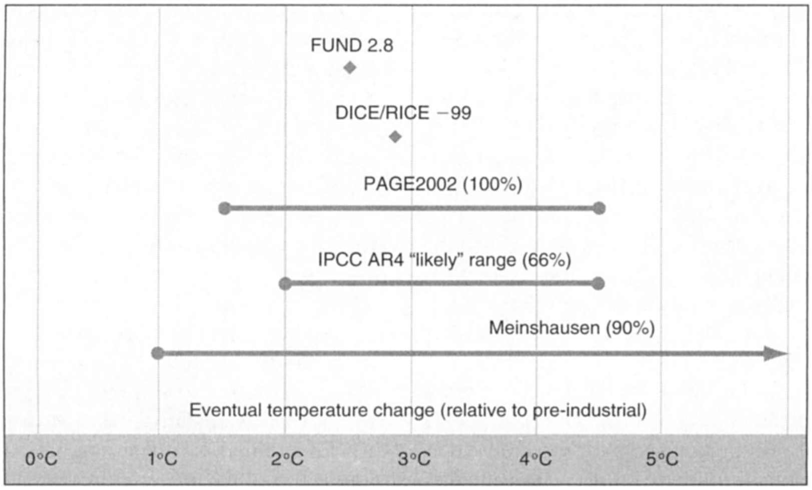

Figure 5. Estimates of Climate Sensitivity from IAMs Compared to GCMs

Sources: Tol 2002; Nordhaus and Boyer 2000; Hope 2006a; 2006b; IPCC 2007; Meinshausen 2006.

is not so much why the Stern Review's modelling obtained high damages under BAU, as why the earlier literature made assumptions that give such low results.

D. *Damages and Sensitivity, One Year On from the Review*

Looking back, I think the Review was too cautious on all four of the key structural elements: (a) emissions growth, (b) carbon cycle, (c) climate sensitivity, and (d) damages from a given temperature.

(a) The work of Ross Garnaut and his Commission, working for the new Australian government on climate change, is revisiting the emissions scenarios in the IPCC Special Report on Emissions Scenarios or SRES (IPCC 2000). In its Chapter 6 model (Stern 2007, 173–88), the Stern Review used the second highest of the four scenarios (called A2). Garnaut is now suggesting that the highest of the four, A1F1, is likely to be the best description of BAU (Garnaut 2007). Key among the reasons is the growth rates of the developing world, particularly China and India, and their continued strong emphasis on coal (ECIEP 2006).

(b) The carbon cycle is likely to weaken as a result of, for example, the possible collapse of the Amazon forest at temperature increases of above 3–4°C, or the decreasing absorptive capacity of the oceans. Further, a thawing of the permafrost is likely to result in strong methane release.

(c) The climate sensitivity assumed in the Review is likely to be conservative (as argued in Section I).

(d) The damages from given temperature increases assumed in the Stern Review seem very low. The Review's mean damage loss (based on estimates in the economic literature) from 5°C was around 5 percent of GDP (Stern 2007, 180). As argued in Section I, a temperature increase of 5°C would most likely result in massive movements of population and large-scale conflict.

Considering these structural factors together, the modelling of the Stern Review probably underestimated significantly the risks of high damages from BAU, perhaps by 50 percent or more if one compares the first two rows of Table 2. Much of the earlier literature grossly underestimated the risks.

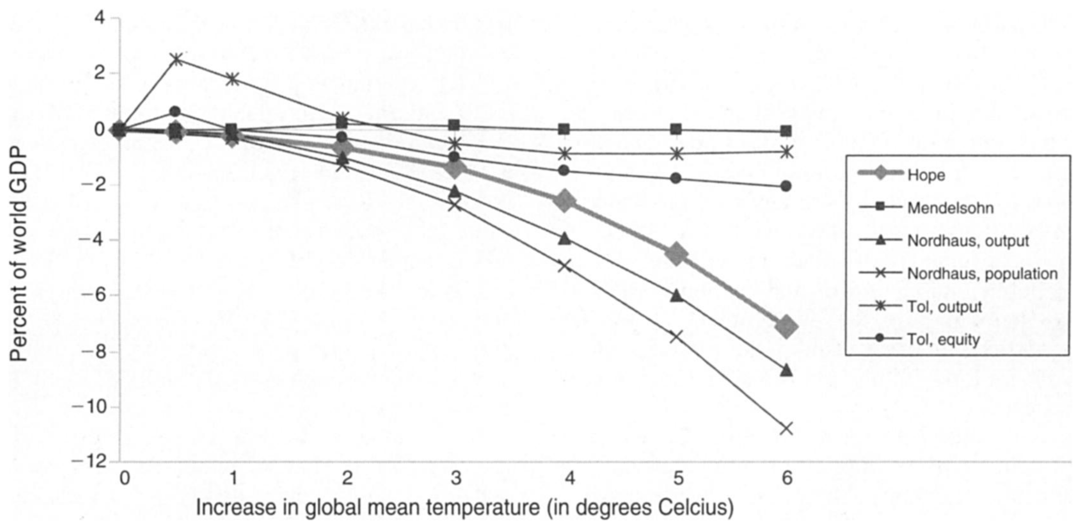

FIGURE 6. THE MODELLED DAMAGES FROM CLIMATE CHANGE WITH INCREASING GLOBAL TEMPERATURES

Source: Dietz et al. 2007a.

Looking at both γ and η, with the benefit of hindsight, my inclination would be to place the base case from which sensitivity analysis is undertaken farther down the diagonal of Table 2—that is, with higher γ and higher η. As indicated in Section IIB, the "weight in the far future" from $\eta = 1$ and $\delta = 0.1$ percent suggests that there is a case for raising η, although it remains true that many would see the implications of $\eta = 2$ for intragenerational distribution as very egalitarian. In a sense, moving down the $(\eta - \gamma)$ diagonal is taking on board the positions of two commentators on the Review—Weitzman (2007a, b) argued for greater emphasis on risk and uncertainty, and Dasgupta (2007) for more egalitarian values than those captured by $\eta = 1$.

In summary, one year on from the Stern Review, with the benefit of new scientific evidence and valuable economic discussions, my views would have been modified as follows. First, the case has been strengthened that the bottom-up, disaggregated, less formal, risk-evaluation approach is preferable to aggregate modelling in investigating the case for action. The latter is particularly weak in relation to formal optimization. Second, within aggregate modelling, we have learned still more clearly that the key issues are ethics and risks and that we have to look at them together to form a serious view on damages. Third, our own modelling probably underestimated the risks from BAU. Fourth, the reasons that some earlier studies have lower damage estimates than the Stern Review are twofold: they badly underestimate all four of the elements just described, and in many cases their approach to pure time discounting discriminates, unjustifiably in my view, very strongly against future generations.

III. Policy Instruments

At the heart of good policy will be a price for GHGs—this is a classic and sound approach to externalities and is crucial for an incentive structure both to reduce GHG emissions and to keep costs of abatement down. Indeed, in a world without any other imperfections, it would be a sufficient instrument for optimal policy. But it will not be enough in our world, given the risks, urgency, inertia in decision making, difficulty of providing clear and credible future price signals in an international framework, market imperfections, unrepresented consumers, and serious concerns about equity. A second plank of policy will have to embrace technology and accelerate its development. Third, policy should take account of information and transactions costs, particularly in relation to energy efficiency. Fourth, it should provide an international framework to help with combating deforestation, which is subject to a number of market failures. And fifth, policy should have a strong international focus, to promote collaboration, take account of equity, and reduce global costs.

Careful analytical investigation by economists of policies on climate change involves the whole range of the tools of our trade, including the economics of risk and uncertainty, innovation and technology, development and growth, international trade and investment, financial markets, legal issues, ethics and welfare, as well as public and environmental economics. It will no doubt require the development of further analytical methods. And it necessitates close collaboration with scientists and other social scientists.

Our focus here in this very brief discussion of policy will be on price-oriented mechanisms and on technology, but we should also note a sixth key element that is often overlooked in discussions of economic policy, namely how preferences change as a result of public discussion. This was an integral part of John Stuart Mill's (Mill 1972 [1861], 262) perception of democracy and policy formation (see also the discussion in Chapter 9 of Stern, Jean-Jacques Dethier, and F. Halsey Rogers 2005). In this context, it involves a change in public understanding of responsible behavior. Thus, people will spend time on separating out different elements of waste for recycling, or they will drive more carefully, not only because there may be a financial incentive for recycling or penalties for bad driving, but also because they have a view of responsible behavior.

Pricing an externality can be done in a number of ways. First, there is carbon taxation; second, carbon trading on the basis of trade in rights to emit which are allocated or auctioned; and third, implicit pricing via regulations and standards which insist on constraints on actions or technologies which involve extra cost but which imply reductions in emissions. Each of the three has different advantages and disadvantages and all three are likely to be used. Understanding the pros and cons, where the different mechanisms can and should be used, and how to deal with problems of overlaps, are all very important issues. We have the space to look briefly only at a few of the relevant considerations.

Taxes have the advantage of being implementable by individual governments without international agreement. All taxes are contentious but those on recognized "bads" such as tobacco, alcohol, or carbon emissions may be less so than others and allow the balance of taxes to adjust away from other taxes such as income or VAT; alternative uses of revenue are possible too, including those related to climate change. We should beware, though, of arguments about double dividends: environmental taxes have dead-weight losses in addition to their beneficial effects in addressing externalities. Taxes on GHGs would require measurement of GHGs, just as in trading, but taxes on petroleum products, coal, or other fossil fuels can act as fairly good approximations, avoiding direct emission measurement, which can be relatively costly to small enterprises.

As discussed in Section IA, where the world is perfect other than in relation to the tax in question, quantity controls and price measurements can have dual and essentially identical effects. Where there is risk, uncertainty, and imperfections in this market and in other parts of the economy, there will be price uncertainty, quantity uncertainty, or both, depending on the policies chosen and the nature of the uncertainty. Both price certainty and quantity certainty are important: firms would like clear and simple price signals for decision making; quantity overshooting on emissions is dangerous. With learning and readjustment of policy (although not so frequently as to confuse structures and issues), the difference in effects between a tax-orientated policy and a quantity/carbon-trading policy may not be so large. Given where we start, however, in my view the danger of overshooting emissions targets is of great significance.

Tradable quotas, the second method of establishing a price for GHGs, have the advantage of providing greater certainty about quantities of emissions than taxes. The European Union Emissions Trading Scheme (EUETS) has shown that a big part of the economy can be covered (currently around one half of European emissions) with relatively low administrative burdens by focusing on major emitting industries, such as power.

By starting with allocations that are not paid for and moving to auctions, trading can build acceptance by industry because it allows for a less dramatic adjustment. Free allocations based on historical emissions do have important problems, however: they are likely to slow adjustment since immediate profit pressures are lower; they can give competitive advantages to incumbent firms that may succeed in getting large quota allocations, thus reducing competition and promoting rent-seeking; and they forego public revenue. Thus, moving to auctioning over time has strong advantages and should be a clear and transparent policy.

An aspect of quotas and trading that is crucial is their potential role in international efficiency and collaboration. Developing countries (see next section) have a strong and understandable sense of injustice. They see rich countries having first relied on fossil fuels for their development, and thus being largely responsible for the existing stocks of GHGs, then telling them to find another, and possibly more costly, route to development. They feel least responsible for the position we are in, yet they will be hit earliest and hardest.

International trading provides for lower costs, from the usual arguments about international trade, and provides an incentive for poor countries to participate. These arguments on cost and collaboration are central to my view that there should be a very substantial focus on carbon trading in the policy of rich countries, with openness to international trade, backed by strong rich country targets for reductions, in order to maintain prices at levels that will give incentives both for reduction at home and purchase abroad. Rich and poor country targets will be discussed in the next section.

Price volatility is sometimes said to be a problem with quotas and trading, and the EUETS is cited as an example. But that scheme provided some basic simple lessons that have been learned: in its first stage (2005–2007), giving away too many quotas collapsed the price. Quotas have been allocated with greater rigor and stringency in the second phase (2008–2012) and the price for that phase is currently above €20 per ton, already approaching the type of range indicated as necessary. Volatility can be reduced by (a) clarity, (b) firmness of quotas, and (c) broader and deeper markets—greater trading across sectors, periods, and countries. Particular measures for dealing with volatility should be analyzed in relation to, or after, these broader more market-friendly approaches. And care should be taken not to restrict international trade as a result; for example, differences in caps on prices in different regions might, because of attempts to arbitrage where prices are different but fixed, make open trade difficult or impossible.

Further, difficulties arise in trading with countries that are not taking strong measures, price-based or otherwise, against climate change. There is, in principle, a case for levying appropriate border taxes on goods from countries that do not otherwise embody a carbon price. A system analogous to the operation of the border procedures for VAT could be envisaged. My own view is that this should be a last resort. There are many searching for arguments on protection that might climb on the bandwagon. The best way forward is to build international collaboration with a positive and constructive approach.

Regulation and standards can give greater certainty to industry. This can accelerate responses and allow the exploitation of economies of scale: lead-free petrol and catalytic converters are probably good examples. Misguided regulation, on the other hand, could reduce emissions in very costly ways. Again urgency points to a role for regulation/standards, and careful economic analysis can keep costs down. In thinking about these costs, however, we should remark that there are a number of examples in the history of the motor industry where innovations on safety or pollution were resisted by industry on cost grounds, only for compliance costs to turn out to be much lower than manufacturer predictions; for Environmental Protection Agency (EPA) vehicle emission control programs, industry stakeholders predicted price changes to consumers that exceeded actual changes by ratios ranging from 2:1 to 6:1 (John F. Anderson and Todd Sherwood 2002).

While taxation, trading, and regulation will all have roles to play, it is important to think carefully about how they might interact. For example, if taxation and carbon trading overlap, there are likely to be problems in establishing a clear and uniform price for carbon, leading to confused signals and inefficiency. And strong regulatory targets such as renewables percentages could, without care, result in low demand on carbon markets.

Our discussion of technology will be very brief, but in my view, policy in this area will be of great importance—we cannot simply leave the correction of externalities to carbon markets or taxation. There is a standard argument on knowledge and technology which sees ideas and experience as having positive externalities. Figure 7 shows that experience is indeed important in the electricity industry—it seems that in a

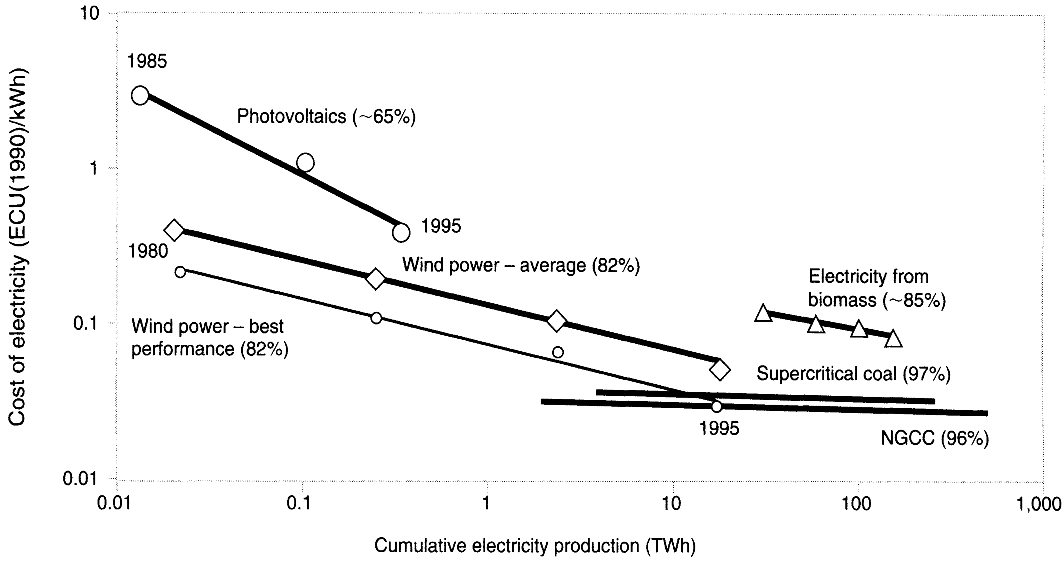

Figure 7. Cost of Electricity for Different Technologies

Note: The number in brackets indicates speed of learning: 65 percent means that unit costs are 65 percent of the previous level after a doubling of production.

Source: Stern 2007, 254.

number of "less mature" technologies costs can fall quite sharply with cumulative experience. Further, the rate of fall is different for different technologies. This tells us that public support for deployment—such as feed-in tariffs, which may be different for different technologies—has a strong foundation. Care with applying such incentives is necessary to avoid the dangers of bureaucrats trying to pick private sector technological "winners."

Research and development (R&D) in basic technologies also require public support. It is remarkable how much public support for R&D in energy has fallen since the early 1980s (see Figure 8). Part of this was probably due to low energy prices,[27] but nevertheless the now-recognized urgency of developing low carbon technologies requires a strong reversal of this trend. Private and public sector R&D on energy have moved closely together and this is an area where public-private partnership to enhance both private and social returns, and to cover different risks, will be crucial. Fortunately, the last few years have seen a number of exciting and promising developments, such as in materials and technologies, other than silicon, for photovoltaics.

The international aspects of technology are crucial too. We all gain from reduced emissions if others adopt cleaner technologies quickly. Thus, a balance of private return to innovation, for example through patents, and rapid sharing must be found. This should be part of a global deal or framework to which we now turn.

IV. A Global Deal

Climate change is global in its origins and in its impacts. An effective response must therefore be organized globally and must involve international understanding and collaboration. Collaboration, if it is to be established and sustained, must be underpinned by a shared appreciation that the methods adopted are: *effective* (on the scale required); *efficient* (they keep costs down); and *equitable* (responsibilities and costs are allocated in ways that take account of wealth, ability, and historical responsibility). The incentive structures must be such that solutions are incentive-compatible. And country-by-country political support must be built, as this is what will sustain policies over time.

[27] Extensive privatization has probably played a role as well. For example, the UK's nationalized National Coal Board and Central Electricity Generation Board had R&D departments of international distinction.

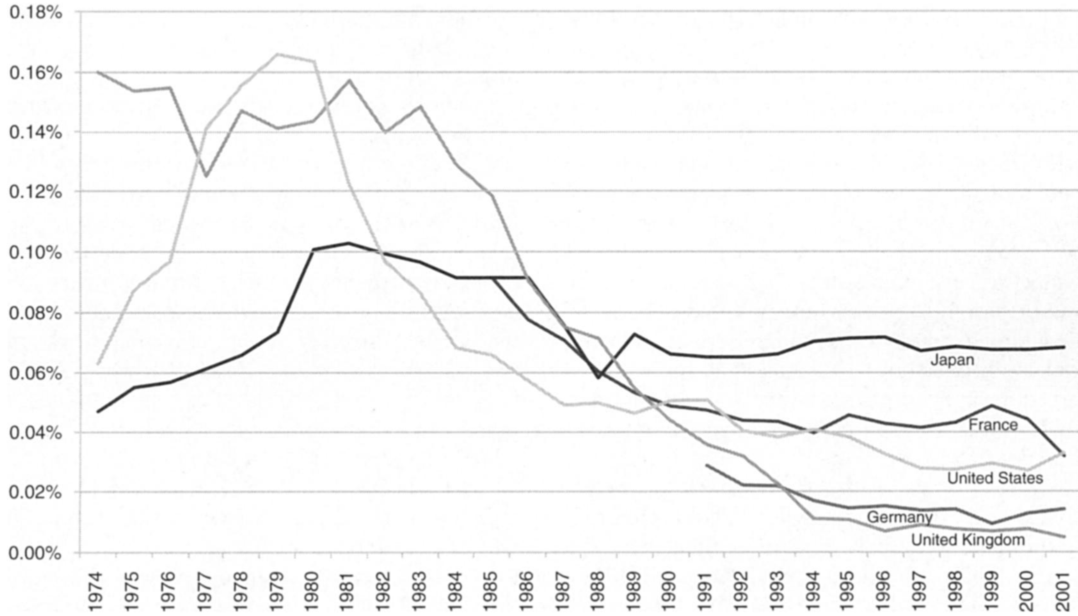

FIGURE 8. PUBLIC ENERGY R&D INVESTMENTS AS A SHARE OF GDP

Source: Stern 2007, 401.

Public support for action will be founded not only on recognition of the magnitude of the problem, but also on the realization that it is possible to construct collaborative policies that are effective, efficient, and equitable. It is a great responsibility of economists to help design those policies. And they must do so urgently—the international discussion is moving quickly and key decisions will be taken over the next few years.

The following is my own attempt to describe the outline of a possible global deal based on the preceding analysis and on my own intensive experience over the last two years of involvement in public discussion, taking account of the recent UNFCCC meetings at Bali last month. Let us begin with overall reductions targets and the allocation of responsibilities across countries. Our earlier discussion of trading, technologies, and deforestation will then allow us to see quickly the broad structure of a global deal. Let us be clear at the outset that this should not be seen in the overly formal way of a WTO discussion, founded in legal structures, with compliance driven by sanctions, and where no one is bound until the full deal is agreed. This is much more a framework in which each country, or group of countries, can assess its own responsibilities and targets with some knowledge of where the rest of the world is going and how it can interact.

On targets—a key element of *effectiveness*, or action on an appropriate scale—we should be clear how far the international discussion has already moved. The G8–G5 summit chaired by Germany in Heiligendamm in June 2007 declared a world target of 50 percent reductions by 2050. As sometimes happens in international communiqués, not all details (such as base date and levels of agreement among attendees) were clear; but it was a significant marker nonetheless. And it is broadly consistent with the type of stabilization range, around 500ppm CO_2e for example, discussed in Section I. In what follows, unless otherwise stated, emissions reductions will be measured from 1990, covering all GHGs (in the six-gas Kyoto sense) and emissions sources. The Heiligendamm 50 percent target is for the world as whole and it is generally agreed (see below) that, in the spirit of the Kyoto language of "common but differentiated treatment," the richer countries should take responsibility for reductions bigger than the average. In what follows, we shall think of rich country reductions as including those discharged by purchases on international markets.

At Bali in December 2007, three countries, Costa Rica, New Zealand, and Norway, declared targets of 100 percent reductions by 2050, i.e., "going carbon-neutral." The latter two are highly likely to need international purchases to get there. Note, too, that reductions of more than 100 percent are possible—many in developing countries would regard targets for rich countries above 100 percent as appropriate, given past history—and that such reductions that would almost inevitably involve international purchase.

California has a target of 80 percent reductions by 2050. France has its "Facteur Quatre": dividing by 4, or 75 percent reductions, by 2050 (Stern 2007, 516). The United Kingdom has a 60 percent target but the Prime Minister Gordon Brown indicated in November 2007 that this could be raised to 80 percent (Brown 2007). Australia, under the new government elected at the end of November 2007, has now signed Kyoto and has a target of 60 percent (Kevin Rudd 2007); 80 percent is under consideration after the Garnaut Review is published next summer.

Targets for 2050 seem far away but the long lifetime of many investments means that early decisions are needed to reach them. Intermediate targets are also being set. At the European Spring Council, 20–30 percent targets were set for 2020; Germany has set 40 percent targets by 2020. The European Council also set targets for renewables and CCS for 2020 and beyond, but it is the overall emissions targets, and their achievement, which are crucial. How they are achieved country by country will vary and must take account of economic as well as environmental, social, and political considerations. At Bali, many were pressing for rich countries to accept 25–40 percent cuts by 2020. That is indeed in the right range for rich country cuts of 80 percent by 2050 and is now at least an initial 2020 benchmark. Overall, in discussions of global and rich country targets, ranges consistent with the criteria of effectiveness and equity are now the basic benchmarks, and many key commitments have been made. Delivery on targets at reasonable cost—essentially *efficiency*—is, of course, crucial and a challenge. Policies that could support this constituted the subject of Section III and should be at the heart of a global deal.

Let us investigate equity in a little more detail. The history of flows and their relation to future stabilization targets should, in my view, be central to a discussion of equity. All too often, equity is seen solely or largely in terms of the relative level of future flows (for example, per capita convergence by 2050). A few numbers and a little basic arithmetic will help to understand the issues. Currently, global emission flows are around 40–45 Gt CO_2e. With a world population of around 6 billion, that means average global per capita emissions are around 7 tons. Given that the world population in 2050 will be around 9 billion, in order to achieve 50 percent reductions (i.e., an aggregate flow of around 20 Gt CO_2e) by then, per capita emissions will have to be 2–2.5 tons. And since around 8 billion of these people will be in currently poor countries, those countries will have to be in that range[28] even if emissions in currently rich countries were to fall to zero. It is clear from this basic arithmetic that any effective global deal must have the currently poor countries at its center.

From the point of view of equity, the numbers are stark. The currently rich countries are responsible for around 70 percent of the existing stock, and are continuing to contribute substantially more to stock increases than developing countries. The United States, Canada, and Australia each emit over 20 tons of CO_2e (i.e., from all GHGs) per capita, Europe and Japan over 10 tons, China more than 5 tons, India around 2 tons, and most of sub-Saharan Africa much less than 1 ton. Recent per capita CO_2 emissions (i.e., omitting other GHGs) for some countries are illustrated in Figure 9.

In the lower part of this graph are three big, fast-growing developing countries. China is growing especially quickly. Even with fairly conservative estimates, it is likely that, under BAU, China will reach current European per capita emissions levels within 20–25 years. With its very large population, over this time China under BAU will emit cumulatively more than the USA and Europe combined over the last 100

[28] In this context, I am referring to absolute emissions originating in the country rather than who pays.

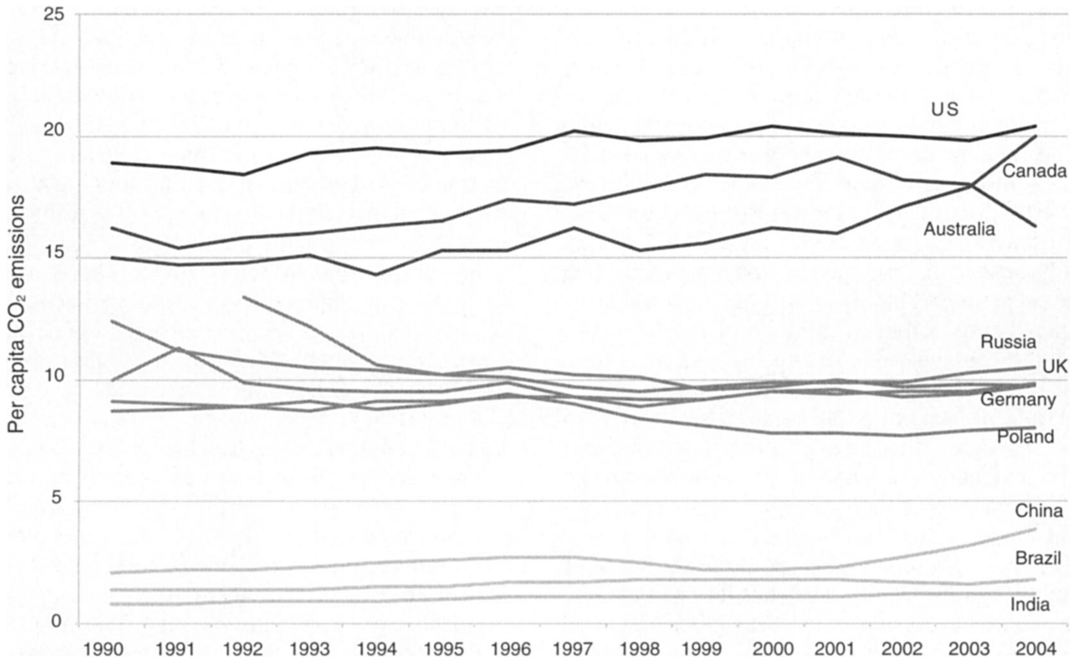

FIGURE 9. PER CAPITA CO_2 EMISSIONS (*in tons*)

Source: CDIAC 2007.

years. That is one indication of the urgency of finding a global response quickly.

But let us keep focused on equity. With 80 percent reductions by 2050, Europe and Japan would be around the required two-ton global average level. An 80 percent reduction by the United States, Australia, and Canada by 2050 would leave them around four tons, twice the required average level. Thus, a 50 percent overall reduction and an 80 percent rich country reduction would still leave average rich country flows above the world average in 2050.

Turning to stocks, let us think about the path from some initial level to a stock stabilization (to be specific, suppose that level is 550ppm CO_2e), and about who consumes what along the way. We can think of the initial level as 280ppm CO_2e, corresponding to preindustrial times (around 1850); or we could start 20 years ago (around 390ppm CO_2e), when the problems of climate change began to receive strong policy attention; or we could start now (around 430ppm CO_2e). One perspective on equity would be to see the difference between 280ppm CO_2e and 550ppm CO_2e as a reservoir sized 270ppm CO_2e, which the world will get close to exhausting over the 200 years between 1850 and 2050. If we start the clock in the late 1980s or now, it would be a reservoir sized around 140ppm CO_2e or 120ppm CO_2e, respectively.

From this perspective, equalizing the per capita flows of emissions—or the size of the glass drawn per person per year from the reservoir—by 2050, shortly before it is dry, is a very weak notion of equity. It takes no account of all the guzzling that took place by the better-off over the preceding 50–200 years (depending on when we start the clock). There is a very big difference between a stock and a flow notion of equity. An 80 percent reduction of flows by rich countries by 2050, in the context of a 50 percent reduction overall, is not a target for which rich countries should congratulate themselves warmly as demonstrating a splendidly powerful commitment to equity. And the contract-and-converge argument for some common flow level, or for using such a level as the eventual basis of trading, on the asserted grounds that there are "equal rights to emit or pollute," does not seem to me to have special claim on our attention.[29] Rather, the target of equalizing by 2050 (allowing for trade) may be seen as being a fairly pragmatic one, on which it might be possible to get agreement, and one that, while only weakly equitable, is a lot less inequitable than some other possibilities, such as less stringent targets for rich countries.

If we take any particular good, it will generally be true that rich people consume more than poor people. That is simply an expression of their being richer. In the case of the reservoir, or the "contents of the atmosphere," it is hard to think of an argument as to why rich people should have more of this shared resource than poor people. They are not exchanging their labor for somebody else's and they are not consuming the proceeds of their own land, or some natural resource that lies beneath it. I do not have any special "correct" answer to the challenge of understanding equity here, but it is a challenge we cannot avoid discussing. Any global deal will have to involve some implicit or explicit understanding over the sharing of this "reservoir."

The key elements of the global deal have, with one exception, now been raised and discussed. Let me express the deal or framework in terms of two groups of three headings, the first covering targets and trade and the second covering programs for which public funding is likely to be required. This set of six policies or programs is the international part of a deal. The domestic policies will vary across countries, using different combinations of policy instruments and technologies as discussed in Section III. The six elements of a global deal are expressed in bullet point form in Tables 3 and 4.

The first element of the first group covers the targets. The global target was explained and justified in Section I and the distribution of targets above in this section. The second, the importance of emissions trading, was emphasized in Section III: the justification for a major focus on GHG trading in policy lies in its promotion of both efficiency and collaboration. Unless financing flows for the extra costs of reducing emissions are available to poor countries, they are extremely unlikely to join the effort on the scale and pace required. They feel the inequities of the situation and phenomena acutely. Just when, they argue, they are beginning to overcome poverty, in part by rapid growth, they should not be asked to slow down. Financing, together with technology demonstration and transfer, will be needed to convince them that moving to a low-carbon growth path is not the same thing as moving to a low growth path.

The third element refers to the short- and medium-term approaches to trading between rich and poor countries. The current system, the Clean Development Mechanism (CDM), was established by Kyoto and operates at the level of a project in a poor country (a so called non-Annex 1 country in the Kyoto Protocol). If a firm in a rich country (an Annex 1 country) is part of a trading scheme (such as the EUETS) which recognizes the CDM, then that firm can buy an emissions reduction achieved by the project, subject to the project using technologies or approaches from an admissible list. The amount of the notional reduction comes from comparing the project with a counterfactual—what the entity doing the project might otherwise have done. Approval of a project goes through the poor country authorities and a special institutional structure, currently in Bonn. The system is slow, cumbersome, and very "micro."

Trading on the scale required to reach the type of targets discussed (see Table 3) requires a much simpler, "wholesale" system.[30] At the same time, to get agreement with poor countries, it will have to continue to be "one-sided," as in the CDM, i.e., you can gain from innovation, but are not penalized for BAU. Wholesale measures can include technological benchmarks such as employing CCS (currently excluded from CDM), or sectoral benchmarks such as getting below a certain amount of CO_2 per ton of cement. As one-sided trading measures, the benchmarks could be set ambitiously.

After these trading mechanisms have been in place (with associated technology sharing) for a while, developing countries will be able to have confidence that a trading system can work on an appropriate scale. Then it would be reasonable to ask them to accept targets consistent

[29] Asserting equal rights to pollute or emit seems to me to have a very shady ethical grounding. Emissions deeply damage and sometimes kill others. Do we have a "right" to do so?

[30] This scale is derived from preliminary calculations using a trading model at the UK Department of Environment, Food, and Rural Affairs (DEFRA).

TABLE 3—KEY ELEMENTS OF A GLOBAL DEAL: TARGETS AND TRADE

- Confirm Heiligendamm 50 percent cuts in world emissions by 2050 with rich country cuts at least 75 percent.
- Rich country reductions and trading schemes designed to be open to trade with other countries, including developing countries.
- Supply side from developing countries simplifed to allow much bigger markets for emissions reductions: "carbon flows" to rise to $50–$100 billion per annum by 2030. Role of sectoral or technological benchmarketing in "one-sided" trading to give reformed and much bigger CDM market.

TABLE 4—KEY ELEMENTS OF A GLOBAL DEAL: FUNDING ISSUES

- Strong initiatives, with public funding, on deforestation to prepare for inclusion in trading. For $10–15 billion per annum could have a programme which might halve deforestation. Importance of global action and involvement of IFIs.
- Demonstration and sharing of technologies: e.g., $5 billion per annum commitment to feed-in tariffs for CCS coal could lead to 30+ new commercial size plants in the next 7–8 years.
- Rich countries to deliver on Monterrey and Gleneagles commitments on ODA in context of extra costs of development arising from climate change: potential extra cost of development with climate change upward of $80 billion per annum.

with overall global goals in the context of a strong set of goals by rich countries. If we look for targets from poor countries now, the only ones that would be accepted would be far too loose and would knock the bottom out of international trading, i.e., collapse the price. And in the future these loose targets would be likely to form a base-line for subsequent discussion. That is why a staged approach is essential if currently poor countries are to accept participation in responsible global stabilization so that by 2050 their emissions average around 2 tons per capita. Recall that this is a half or a third of China's *current* level. It is very unlikely to be possible to find financial flows on the scale required to incentivize appropriate action from the public sector of rich countries. Witness the difficulty in getting resources for Overseas Development Assistance (ODA), which will be strained still further by the challenge of adaptation (see below). The trading system provides for private flows.

The public funding requirements are grouped in three elements in Table 4. Each would require a paper in itself for appropriate treatment, and we can give only headlines. Deforestation accounts for up to 20 percent of current emissions; the numbers are not easy to specify precisely—probably 5–8 Gt CO_2e per annum. These flows could be roughly halved, in my view, for around $5 per ton of CO_2, taking into account opportunity costs of land and the institutional, administrative, and enforcement measures necessary. Some have estimated higher costs (e.g., McKinsey—Enkvist, Nauclér, and Rosander 2007) but there appear to be large amounts of "initial" reductions available at lower costs, particularly if programs are large-scale and coordinated across countries (for further discussion see Myers 2007; Daniel Nepstad et al. 2007; Niels Anger and Jayant Sathaye 2007). This would help to avoid reduced deforestation in country A simply displacing activity and thus increasing deforestation in country B. Public sector flows can be combined with private sector flows as avoided deforestation is brought into the carbon trading process so that all countries are given incentives. Indeed, one of the responsibilities of the publicly funded program would be to work toward trading.

The second element in this second group, the demonstration and sharing of technologies, is urgent; financial resources must be made available and institutional arrangements designed. This is an important area for economic research. One problem of particular urgency, for reasons described above, is the demonstration of CCS for coal. There are no current plants using CCS for coal-fired generation on a commercial scale. From 2015 or 2020 on, the world will need most of its new coal-fired electricity generation plants to be operating with CCS if it is to have any chance of realizing its targets. If CCS cannot work on the necessary scale, then we need to know soon and follow alternative strategies. At present, however, it does look promising. There is geological work to be done to identify storage capacity, and careful legal and regulatory work to be done to allocate risk and responsibility. Geology and coal vary greatly across the world and many demonstrations of commercial-scale plants are necessary. Feed-in subsidies, worldwide, of around $5 billion per annum could support 30+ such plants over the next 7–8 years and cover a broad range of examples.[31]

There should also be support for many other technologies. We do not know what the most efficient clean technologies will be in the future, and the answers are likely to vary with location. CCS is emphasized here simply because we can be fairly confident that BAU will involve a great deal of coal for electricity over the next 20–30 years. Perhaps it will be a medium-term technology and be replaced by others over the longer term.

Finally, in the global deal, I would emphasize an element that has not been discussed here and that will be of great importance. Even with very responsible policies, the world is likely to see an additional 1–2°C of warming over and above the 0.8°C it has already experienced. Adaptation will be necessary worldwide and will be particularly difficult for poor countries. Recently, the United Nations Development Programme (UNDP) estimated additional costs for developing countries of around $85 billion per annum by 2015 (UNDP 2007, 15). And they will presumably rise after that.

Such extra financing will be hard to find. It may be compared with the $150–200 billion per annum extra that would arise if the Organisation for Economic Co-operation and Development (OECD) countries moved to 0.7 percent GDP in ODA by 2015, as many of them have promised. The ODA promises of the 2002 UN International Conference on Financing for Development in Monterrey, Mexico, in connection with the Millennium Development Goals, and of the 2005 UK-chaired G8 Gleneagles summit on Africa, and preceding EU commitments in July, were powerfully argued and justified at the time. They took little account of climate change. If that aspect is added, as it should be given the magnitude of the challenge, and combined with the historical responsibilities for stocks of GHGs and the implied consequences for poor countries, then the argument for 0.7 percent, in my view, becomes overwhelming. The Stern Review left the argument at that point, although a case could have been made for increasing the ODA targets.

The framework I have now described does, in my view, meet the criteria of: effectiveness—it is on the right scale; efficiency—it relies heavily on markets and market-orientated innovation; and equity—it does at least give some specificity to the "common but differentiated responsibility" already accepted internationally. It builds on existing commitments and some aspects of the current discussions in international fora. It is also designed to give some realistic opportunity for the major developing countries to become strongly involved, as they must if serious targets are to be agreed and achieved.

It is a framework that could allow all countries to move quickly along what they see to be a responsible path. What is very striking here is how broadly basic understanding has already been established. Country by country, we see targets being erected and measures being set by individual countries recognizing their own responsibilities as they see international agreement being built. People seem to understand the arguments for action and collaboration on climate change much more readily than they do for international trade. But I do not want to

[31] Own calculations using, for example, the McKinsey cost curve, and working with power stations of a few hundred megawatts. I am grateful to Dennis Anderson for his advice.

pretend that the problems and necessary actions are universally recognized and accepted. Scientific agreement seems broad and deep, but we cannot yet say that about economic policy, or about economists. This is a time for exchange of ideas and intensive discussion. Economic policy is much too important here to be left to noneconomists.

It is intensive public discussion that will, in my view, be the ultimate enforcement mechanism. For example, in November 2007 we saw an Australian prime minister thrown out of office in part because of his perceived weakness on this issue. It is remarkable that when elections come around, politicians recognize strong public interest and demand for action. And it has become a unifying and defining issue in the structures of Europe. It has not moved at the same pace in all countries, but we are also seeing strong changes in perception in the key countries of the United States, China, and India.

Beyond discussion, there are some promising movements in world and individual country policy. The UNFCCC 13th Conference of the Parties, COP 13, in Bali in December 2007 was a major step forward, with all countries involved broadly (but not universally) recognizing the need for overall 50 percent cuts by 2050 and 25–40 percent cuts by rich countries by 2020 (although only the phrase "deep cuts" was agreed). There was progress on international action on deforestation. But it was the launch of negotiations only; it was not an agreement on a shared global framework.

The discussion of that global framework will move forward strongly over the next few years. It is vital that economics and economists be more strongly involved, particularly if the criteria of efficiency and equity are to play their proper role. It is the analytical application of these two criteria to practical policy problems that is at the heart of public economics. The challenge of climate change is especially difficult because it covers so much of the economy, is so long term, is so full of risk and uncertainty, is so demanding internationally, and is so urgent because of the problem itself and the pace of public discussion and decision making. It is also a long-term problem for analysis. We will be learning all the time and policy will be made and reformed over coming decades.

It is dangerous, in my view, for us as economists to seem to advocate weak policy and procrastination and delay under the banner of "more research to do" or "let's wait and see." The former argument is always true but we have the urgent challenge of giving good advice now, based on what we currently understand. And the latter, in my view, is misguided—waiting will take us into territory that we can now see is probably very dangerous and from which it will be very difficult to reverse. Acting now will give us, at fairly modest cost, a cleaner world and environment, even if, as seems very improbable, the vast majority of climate scientists have got it wrong. If we conclude that whatever the merits of the argument, it is all too difficult to make and implement policy, then we should at least be clear about the great magnitude of the risks of moving to concentrations of 650ppm CO_2e or more, which are the likely consequences of no, weak, or delayed action.

It is hard to imagine a more important and fascinating problem for research. It will involve all our skills and more, and it will require collaboration across disciplines. This is a time and a subject for economists to prove their worth. Looking at the quality of this company here in New Orleans, I am confident that they will do so.

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