A Question of Balance

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Weighing the Options on Global Warming Policies

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Simplicity is the highest form of sophistication.

—Leonardo

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In October 2007, the Nobel Peace Prize was awarded to the Intergovernmental Panel on Climate Change (IPCC) and Albert Gore Jr. "for their efforts to build up and disseminate greater knowledge about man-made climate change, and to lay the foundations for the measures that are needed to counteract such change." This award highlights the importance and complexity of the scientific, social, environmental, and policy issues involved in global warming. The present work is deeply indebted to the extraordinary contributions of social and natural scientists working in this area. The author has benefited from the fundamental research of an earlier generation of researchers, notably Tjalling Koopmans, Lester Machta, Alan Manne, Howard Raiffa, Roger Ravelle, Thomas Schelling, Joseph Smagorinsky, Robert Solow, and James Tobin, as well as dozens of friends and colleagues who have contributed to the four assessment reports of the IPCC. To paraphrase Newton, if I have seen anything, it is by standing on the shoulders of giants. Therefore, it is to the giants of the past and to the current generation of social and natural scientists working on global warming that this book is dedicated.

Introduction

The issues involved in understanding global warming and taking actions to slow its harmful impacts are the major environmental challenge of the modern age. Global warming poses a unique mix of problems that arise from the fact that global warming is a global public good, is likely to be costly to slow or prevent, has daunting scientific and economic uncertainties, and will cast a shadow over the globe for decades, perhaps even centuries, to come.

The challenge of coping with global warming is particularly difficult because it spans many disciplines and parts of society. Ecologists may see it as a threat to ecosystems, marine biologists as a problem leading to ocean acidification, utilities as a debit on their balance sheets, and coal miners as an existential threat to their livelihood. Businesses may view global warming as either an opportunity or a hazard, politicians as a great issue as long as they do not need to mention taxes, ski resorts as a mortal danger to their already-short seasons, golfers as a boon to year-round recreation, and poor countries as a threat to their farmers, as well as a source of financial and technological aid. This multifaceted nature also poses a challenge to natural and social scientists, who must incorporate a wide variety of geophysical, economic, and political disciplines into their diagnoses and prescriptions.

This is the age of global warming—and of global-warming studies. This book uses the tools of economics and mathematical modeling to analyze efficient and inefficient approaches to slowing global warming. It describes a small but comprehensive model of the economy and climate called the DICE-2007 model, for Dynamic Integrated model of Climate and the Economy.

This book reports on a completely revised version of earlier models developed by the author and collaborators to understand the economic and environmental dynamics of alternative approaches to slowing global warming. It represents the fifth major version of modeling efforts, with earlier versions developed in the periods 1974–1979, 1980–1982, 1990–1994, and 1997–2000.[1] Many of the equations and details have changed during the different generations, but the basic modeling philosophy remains unchanged: to incorporate the latest economic and scientific knowledge and to capture the major elements of the economics of climate change in as simple and transparent a fashion as possible. The guiding philosophy is, in Leonardo's words, that "simplicity is the highest form of sophistication."

The book combines a description of the new version of the DICE model with analyses of several major issues and policy proposals. We begin with a brief outline of the major chapters for those who would like a map of the terrain.

Chapter 1 is a "Summary for the Concerned Citizen" that describes the underlying approach and major results of the study. This chapter stands alone and can usefully be read by noneconomists who want a broad overview, as well as by specialists who would like an intuitive summary.

Chapter 2 provides a verbal description of the DICE model. Chapter 3 provides a detailed description of the model's equations. The actual equations of the model are presented in the Appendix.

Chapter 4 describes the alternative policies that are analyzed in the computer runs. These include everything from the current Kyoto Protocol to an idealized perfectly efficient or "optimal" economic approach. Chapter 5 presents the major analytical results of the different policies, including the economic impacts, the carbon prices and control rates, and the effects on greenhouse-gas concentrations and temperature.

Chapters 6 through 9 provide further analyses using the DICE model. Chapter 6 begins with an analysis of the impacts of incomplete participation. This new modeling approach is able to capture analytically the economic and geophysical impacts of policies that include only a fraction of countries or sectors; it shows the importance of full participation. Chapter 7 presents preliminary results on the impacts of uncertainty on policies and outcomes. Chapter 8 is a policy-oriented chapter that examines the two major approaches to controlling emissions—prices and quantities—and describes the surprising advantages of price-type approaches.

Chapter 9 provides an analysis, using the DICE-model framework, of the recent *Stern Review* of the economics of climate change. The final chapter contains some reservations about the results and then presents the major conclusions of the study. The GAMS computer code, the derivation of the model, and technical details are provided in "Accompanying Notes and Documentation on Development of DICE-2007 Model" (Nordhaus 2007a). The Web site for the DICE model and results is http://www.econ.yale.edu/~nordhaus/homepage/DICE2007.htm.

I
Summary for the Concerned Citizen

Often, technical studies of global warming begin with an executive summary for policymakers. Instead, I would like to provide a summary for the audience of concerned citizens. The points that follow are prepared for both scientists and nonspecialists who would like a succinct statement of what economics, or at least the economics in this book, concludes about the dilemmas posed by global warming.

Global warming has taken center stage in the international environmental arena during the past decade. Concerned and disinterested analysts across the entire spectrum of economic and scientific research take the prospects for a warmer world seriously. A careful look at the issues reveals that there is at present no obvious answer as to how fast nations should move to slow climate change. Neither extreme—either do nothing or stop global warming in its tracks—is a sensible course of action. Any well-designed policy must balance the economic costs of actions today with their corresponding future economic and ecological benefits. How to balance costs and benefits is the central question addressed by this book.

Overview of the Issue of Global Warming

The underlying premise of this book is that global warming is a serious, perhaps even a grave, societal issue. The scientific basis of global warming is well established. The core problem is that the burning of fossil (or carbon-based) fuels such as coal, oil, and natural gas leads to emissions of carbon dioxide (CO_2).

Gases such as CO_2, methane, nitrous oxide, and halocarbons are called greenhouse gases (GHGs). They tend to accumulate in the atmosphere and have a very long residence time, from decades to centuries. Higher concentrations of GHGs lead to surface warming of the land and oceans. These warming effects are indirectly amplified through feedback effects in the atmosphere, oceans, and land. The resulting climate changes, such as changes in temperature extremes, precipitation patterns, storm location and frequency, snowpacks, river runoff and water availability, and ice sheets, may have profound impacts on biological and human activities that are sensitive to the climate.

Although the exact future pace and extent of warming are highly uncertain—particularly beyond the next few decades—there can be little scientific doubt that the world has embarked on a major series of geophysical changes that are unprecedented in the past few thousand years. Scientists have detected early symptoms of this syndrome clearly in several areas: Emissions and atmospheric concentrations of greenhouse gases are rising, there are signs of rapidly increasing average surface temperatures, and scientists have detected diagnostic

signals—such as greater high-latitude warming—that are distinguishing indicators of this particular type of warming. Recent evidence and model predictions suggest that global mean surface temperature will rise sharply in the next century and beyond. *Climate Change 2007*, the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2007a, 2007b), gives a best estimate of the global temperature increase over the coming century as from 1.8 to 4.0°C. Although this seems like a small change, it is much more rapid than any changes that have occurred in the past 10,000 years.

Global emissions of CO_2 in 2006 were estimated to be around 7.5 billion tons of carbon. It will be helpful to bring this astronomical number down to the level of the individual. Suppose that you drive 10,000 miles a year in a car that gets 28 miles per gallon. Your car will emit about 1 ton of carbon per year. (While this book focuses on carbon weight, other studies sometimes discuss emissions in terms of tons of CO_2, which has a weight 3.67 times the weight of carbon. In this case, your automobile emissions are about 4 tons of CO_2 per year.) Or you might consider a typical U.S. household, which uses about 10,000 kilowatt-hours (kWh) of electricity each year. If this electricity were generated from coal, it would release about 3 tons of carbon (or 11 tons of CO_2) per year. On the other hand, if the electricity were generated from nuclear power, or if you rode a bicycle to work, the carbon emissions of these activities would be close to zero. In all, the United States emits about 1.6 billion tons of carbon a year, which is slightly more than 5 tons per person annually. For the world, the emissions rate is about 1.25 tons per person.

The Economic Approach to Climate-Change Policy

This book uses an economic approach to weighing alternative options for dealing with climate change. The essence of an economic analysis is to convert or translate all economic activities into a common unit of account and then to compare different approaches by their impact on the total amount. The units are generally the value of goods in constant prices (such as 2005 U.S. dollars). However, the values are not really money. Rather, they represent a standard bundle of goods and services (such as $1,000 worth of food, $3,000 of housing, $900 of medical services, and so forth). So we are really translating all activities into the number of such standardized bundles.

To illustrate the economic approach, suppose that an economy produces only corn. We might decide to reduce corn consumption today and store it for the future to offset the damages from climate change on future corn production. In weighing this policy, we consider the economic value of corn both today and in the future in order to decide how much corn to store and how much to consume today. In a complete economic account, "corn" would be all economic consumption. It would include all market goods and services, as well as the value of nonmarket and environmental goods and services. That is, economic welfare—properly measured—should include everything that is of value to people, even if those things are not included in the marketplace.

The central questions posed by economic approaches to climate change are the following: How sharply should countries reduce CO_2 and other GHG emissions? What should be the time profile of emissions reductions? How should the

reductions be distributed across industries and countries? Other important and politically divisive issues concern how to impose cuts on consumers and businesses. Should there be a system of emissions limits imposed on firms, industries, and nations? Or should emissions reductions be imposed primarily through taxes on GHGs? What should be the relative contributions of rich and poor households or nations?

In practice, an economic analysis of climate change weighs the costs of slowing climate change against the damages of more rapid climate change. On the side of the costs of slowing climate change, countries must consider whether, and by how much, to reduce their GHG emissions. Reducing GHGs, particularly if the reductions are to be deep, will primarily require taking costly steps to reduce CO_2 emissions. Some steps involve reducing the use of fossil fuels; others involve using different production techniques or alternative fuels and energy sources. Societies have considerable experience in employing different approaches to changing energy production and use patterns. Economic history and analysis indicate that it will be most effective to use the market mechanism, primarily higher prices on carbon fuels, to give signals and provide incentives for consumers and firms to change their energy use and reduce their carbon emissions. In the longer run, higher carbon prices will provide incentives for firms to develop new technologies to ease the transition to a low-carbon future.

On the side of climate damages, our knowledge is very meager. For most of the time span of human civilizations, global climatic patterns have stayed within a very narrow range, varying at most a few tenths of a degree Celsius (°C) from century to century. Human settlements, along with their ecosystems and pests, have generally adapted to the climates and geophysical features they have grown up with. Economic studies suggest that those parts of the economy that are insulated from climate, such as air-conditioned houses and most manufacturing operations, will be little affected directly by climatic change during the next century or so.

However, those human and natural systems that are "unmanaged," such as rain-fed agriculture, seasonal snowpacks and river runoffs, and most natural ecosystems, may be significantly affected. Although economic studies in this area are subject to large uncertainties, the best guess in this book is that the economic damages from climate change with no interventions will be on the order of 2.5 percent of world output per year by the end of the twenty-first century. The damages are likely to be most heavily concentrated in low-income and tropical regions such as tropical Africa and India. Although some countries may benefit from climate change, there is likely to be significant disruption in any area that is closely tied to climate-sensitive physical systems, whether through rivers, ports, hurricanes, monsoons, permafrost, pests, diseases, frosts, or droughts.

The DICE Model of the Economics of Climate Change

The purpose of this book is to examine the economics of climate change in the framework of the DICE model, which is an acronym for Dynamic Integrated model of Climate and the Economy. The DICE model is the latest generation in a series of models in this area. The model links the factors affecting economic growth, CO_2 emissions, the carbon cycle, climate change, climatic damages, and climate-change policies. The equations of the model are taken from different disciplines—

economics, ecology, and the earth sciences. They are then run using mathematical optimization software so that the economic and environmental outcomes can be projected.

The DICE model views the economics of climate change from the perspective of economic growth theory. In this approach, economies make investments in capital, education, and technologies, thereby abstaining from consumption today, in order to increase consumption in the future. The DICE model extends this approach by including the "natural capital" of the climate system as an additional kind of capital stock. By devoting output to investments in natural capital through emissions reductions; reducing consumption today, economies prevent economically harmful climate change and thereby increase consumption possibilities in the future. In the model, different policies are evaluated on the basis of their contribution to the economic welfare (or, more precisely, consumption) of different generations.

The DICE model takes certain variables as given or assumed. These include, for each major region of the world, population, stocks of fossil fuels, and the pace of technological change. Most of the important variables are endogenous, or generated by the model. The endogenous variables include world output and capital stock, CO_2 emissions and concentrations, global temperature change, and climatic damages. Depending upon the policy investigated, the model also generates the policy response in terms of emissions reductions or carbon taxes (these are further discussed later). One of the shortcomings of the DICE model is that, as in most other integrated assessment models, technological change is exogenous rather than produced in response to changing market forces.

The DICE model is like an iceberg. The visible part contains a small number of mathematical equations that represent the laws of motion of output, emissions, climate change, and economic impacts. Yet beneath the surface, so to speak, these equations rest upon hundreds of studies of the individual components made by specialists in the natural and social sciences.

Good modeling practice in the area of climate change, as in any area, requires that the components of the model be accurate on the scale that is used. The DICE model contains a representation of each of the major components required for understanding climate change during the coming decades. Each of the components is a submodel that draws upon the research in that area. For example, the climate module uses the results of state-of-the-art climate models to project climate change as a function of GHG emissions. The impacts module draws upon the many studies of the impacts of climate change. The submodels used in the DICE model cannot produce the regional, industrial, and temporal details that are generated by the large specialized models. However, the small submodels have the advantage that, while striving to accurately represent the current state of knowledge, they can easily be modified. Most important, they are sufficiently concise that they can be incorporated into an integrated model that links all the major components.

For most of the submodels of the DICE model, such as those concerning climate or emissions, there are multiple approaches and sometimes heated controversies. In all cases, we have taken the scientific consensus for the appropriate models, parameters, or growth rates. In some cases, such as the long-run response of global mean temperature to a doubling of atmospheric CO_2, there is a long history of estimates and analyses of the uncertainties. In other areas, such as the impact of climate change on the economy, the central tendency and

uncertainties are much less well understood, and we have less confidence in the assumptions. For example, the impacts of future climate change on low-probability but potentially catastrophic events, such as melting of the Greenland and Antarctic ice caps and a consequent rise in sea level of several meters, are imperfectly understood. The quantitative and policy implications of such uncertainties are addressed at the end of this summary.

The major advantage of using integrated assessment models like the DICE model is that questions about climate change can be answered in a consistent framework. The relationships that link economic growth, GHG emissions, the carbon cycle, the climate system, impacts and damages, and possible policies are exceedingly complex. It is extremely difficult to consider how changes in one part of the system will affect other parts of the system. For example, what will be the effect of higher economic growth on emissions and temperature trajectories? What will be the effect of higher fossil-fuel prices on climate change? How will the Kyoto Protocol or carbon taxes affect emissions, climate, and the economy? The purpose of integrated assessment models like the DICE model is not to provide definitive answers to these questions, for no definitive answers are possible, given the inherent uncertainties about many of the relationships. Rather, these models strive to make sure that the answers at least are internally consistent and at best provide a state-of-the-art description of the impacts of different forces and policies.

The Discount Rate

One economic concept that plays an important role in the analysis is the discount rate. In choosing among alternative trajectories for emissions reductions, we need to translate future costs into present values. We put present and future goods into a common currency by applying a discount rate on future goods. The discount rate is generally positive, but in situations of decline or depression it might be negative. Note also that the discount rate is calculated as a real discount rate on a bundle of goods and is net of inflation.

In general, we can think of the discount rate as the rate of return on capital investments. We can describe this concept by changing our one-commodity economy from corn to trees. Trees tomorrow (or, more generally, consumption tomorrow) have a different "price" than trees or consumption today because through production we can transform trees today into trees tomorrow. For example, if trees grow costlessly at a rate of 5 percent a year, then from a valuation point of view 105 trees a year from now is the economic equivalent of 100 trees today. That is, 100 trees today equal 105 trees tomorrow discounted by 1+.05. Therefore, to compare different policies, we take the consumption flows for each policy and apply the appropriate discount rate. We then sum the discounted values for each period to get the total present value. Under the economic approach, if a stream of consumption has a higher present value under policy A than under policy B, then A is the preferred policy.

The choice of an appropriate discount rate is particularly important for climate-change policies because most of the impacts are far in the future. The approach in the DICE model is to use the estimated market return on capital as the discount rate. The estimated discount rate in the model averages 4 percent per year over the next century. This means that $1,000 worth of climate damages in a century is valued at $20 today. Although $20 may seem like a very small amount, it reflects the observation that capital is productive. Put differently, the discount rate is high to reflect the fact that investments in reducing future climate damages to corn and trees should compete with investments in better seeds, improved equipment, and other high-yield investments. With a higher discount rate, future damages look smaller, and we do less emissions reduction today; with a lower discount rate, future damages look larger, and we do more emissions reduction today. In thinking of long-run discounting, it is always useful to remember that the funds used to purchase Manhattan Island for $24 in 1626, when invested at a 4 percent real interest rate, would bring you the entire immense value of land in Manhattan today.

The Prices of Carbon Emissions and Carbon Taxes

Another key concept in the economics of climate change is the "carbon price," or, more precisely, the price that is attached to emissions of carbon dioxide. One version of a carbon price is the "social cost of carbon." This measures the cost of carbon emissions. More precisely, it is the present value of additional economic damages now and in the future caused by an additional ton of carbon emissions. We estimate that the social cost of carbon with no emissions limitations is today and in today's prices approximately $30 per ton of carbon for our standard set of assumptions. Therefore, in the automobile case discussed earlier, the total social cost or discounted damages from driving 10,000 miles would be $30, while the total social cost from the coal-generated electricity used by a typical U.S. household would be $90 per year. The annual social cost per capita of all CO_2 emissions for the United States would be about \$150 per person (5 tons of carbon × \$30 per ton). From an economic point of view, CO_2 emissions are an "externality," meaning that the driver or household is imposing these costs on the rest of the world today and in the future without paying the costs of these emissions.

In a situation where emissions are limited, it is useful to think of the market signal as a "carbon price." This represents the market price or penalty that would be paid by those who use the fossil fuels and thereby generate the CO_2 emissions. The carbon price might be imposed via a "carbon tax," which is like a gasoline tax or a cigarette tax except that it is levied on the carbon content of purchases. The units here are 2005 U.S. dollars per ton of carbon or CO_2. (Because of the different weights, to convert from dollars per ton of carbon to dollars per ton of CO_2 requires multiplying the dollars per ton of carbon by 3.67.) For example, if a country wished to impose a carbon tax of \$30 per ton of carbon, this would involve a tax on gasoline of about 9 cents per gallon. Similarly, the tax on coal-generated electricity would be about 1 cent per kWh, or 10 percent of the current retail price. At current levels of carbon emissions in the United States, a tax of \$30 per ton of carbon would generate \$50 billion of revenue per year.

Another situation where a market price of carbon arises is in a "cap-and-trade" system. Cap-and-trade systems are the standard design for global-warming policies today, for example, under the Kyoto Protocol or under California's proposal for a state policy. Under this approach, total emissions are limited by governmental regulations (the cap), and emissions permits that sum to the total are allocated to firms and other entities or are auctioned. However, those who own the permits are allowed to sell them to others (the trade).

Trading emissions permits is one of the great innovations in environmental policy. The advantage of allowing trade is that some firms can reduce emissions more economically than others. If a firm has extremely high costs of reducing emissions, it is more efficient for that firm to purchase permits from firms whose emissions reductions can be made more inexpensively. This system has been widely used for environmental permits and is currently in use for CO_2 in the European Union (EU). As of the summer of 2007, permits in the EU were selling for about €20 per ton of CO_2, the equivalent of about \$100 per ton of carbon.

Major Results

This book begins with an analysis of the likely future trajectory of the economy and the climate system if no significant emissions reductions are imposed, which we call the "baseline case." Our modeling projections indicate a rapid continued increase in CO_2 emissions from 7.4 billion tons of carbon per year in 2005 to 19 billion tons per year in 2100. The model's projected carbon emissions imply a rapid increase in atmospheric concentrations of CO_2 from 280 parts per million (ppm) in preindustrial times to 380 ppm in 2005 and to 685 ppm in 2100.

Measured mean global surface temperature in 2005 increased by 0.7°C relative to 1900 levels and is projected in the DICE model to increase by 3.1°C in 2100 relative to 1900. Although the longer-run future is subject to very great uncertainties, the DICE model's projected baseline increase in temperature for 2200 relative to 1900 is very large, 5.3°C. The climate changes associated with these temperature changes are estimated to increase damages by almost 3 percent of global output in 2100 and by close to 8 percent of global output in 2200.

This book analyzes a wide range of alternative policy responses to global warming. We start with an idealized policy that we label the "optimal" economic response. This is a policy in which all countries join to reduce GHG emissions in a fashion that is efficient across industries, countries, and time. The general principle behind the concept of the efficient policy is that the marginal costs of reducing CO_2 and other GHGs should be equalized in each sector and country; furthermore, in every year the marginal cost should be equal to the marginal benefit in lower future damages from climate change.

According to our estimates, efficient emissions reductions follow a "policy ramp" in which policies involve modest rates of emissions reductions in the near term, followed by sharp reductions in the medium and long terms. Our estimate of the optimal emissions-reduction rate for CO_2 relative to the baseline is 15 percent in the first policy period, increasing to 25 percent by 2050 and 45 percent by 2100. This path reduces CO_2 concentrations, and the increase in global mean temperature relative to 1900 is reduced to 2.6°C for 2100 and 3.4°C for 2200. (We pause to note that these calculations measure the emissions-reduction rates relative to the calculated baseline or no-controls emissions scenario. In most policy applications, the reductions are calculated relative to a historical baseline, such as, for the Kyoto Protocol, 1990 emissions levels. For example, when the German government proposed global emissions reductions of 50 percent by 2050 relative to 1990, this represented an 80 percent cut relative to the DICE model's calculated baseline because that baseline is projected to grow over the period from 1990 to 2050.)

The efficient climate-change policy would be relatively inexpensive and would have a substantial impact on long-run climate change. The net present-value global benefit of the optimal policy is $3 trillion relative to no controls. This total involves $2 trillion of abatement costs and $5 trillion of reduced climatic damages. Note that even after the optimal policy has been taken, there will still be substantial residual damages from climate change, which we estimate to be $17 trillion. More of the climate damages are not eliminated because the additional abatement would cost more than the additional reduction in damages.

An important result of the DICE model is to estimate the "optimal carbon price," or "optimal carbon tax." This is the price on carbon emissions that balances the incremental costs of reducing carbon emissions with the incremental benefits of reducing climate damages. We calculate that the economically optimal carbon price or carbon tax would be $27 per metric ton in 2005 in 2005 prices. (If prices are quoted in prices for carbon dioxide, which are smaller by a factor of 3.67, the optimal tax is $7.40 per ton of CO_2.)

We have examined several alternative approaches to global-warming policies. One important set of alternatives adds climatic constraints to the cost-benefit approach of the optimal policy. For example, these approaches might add a constraint that limits the atmospheric concentration of CO_2 to two times its preindustrial level. Alternatively, the constraint might limit the global temperature increase to 2.5°C. We found that for most of the climatic-limits cases, the net value of the policy is close to that of the optimal case. Moreover, the near-term carbon taxes that would apply to the climatic limits, except for the very stringent cases, are close to that of the economic optimum. For example, the 2005 carbon prices associated with CO_2 doubling and the 2.5°C increase are $29 and $31 per ton of carbon, respectively, compared with $27 per ton for the pure optimum without climatic limits.

This book also shows that the trajectory of optimal carbon prices should rise sharply over the coming decades to reflect rising damages and the need for increasingly tight restraints. This is the policy ramp for carbon prices. The optimal price would rise steadily over time, at a rate between 2 and 3 percent per year in real terms, to reflect the rising damages from climate change. In the optimal trajectory, the carbon price would rise from $27 per ton of carbon in the first period to $90 per ton of carbon by 2050 and $200 per ton of carbon in 2100.

The upper limit on the carbon price would be determined by the price at which all uses of fossil fuels can be economically replaced by other technologies. We designate this level as the cost of the backstop technology. We estimate that the upper limit will be around $1,000 per ton of carbon over the next half century or so, but beyond that the projections for technological options are extremely difficult.

It should be emphasized that these prices are the best estimates, given current scientific and economic knowledge, and should be adjusted in accordance with new scientific information. Note as well that the price trajectory would involve a very substantial increase in the prices of fossil fuels over the longer run. For coal, a carbon tax of $200 per ton would involve a coal-price increase of 200 to 400 percent depending upon the country, while for oil it would involve a price increase of about 30 percent relative to a price of $60 per barrel. This sharp increase in the prices of fossil fuels is necessary to reduce their use and thereby reduce emissions. It also plays an

important role in stimulating research, development, and investments in low-carbon or zero-carbon substitute energy sources.

The Importance of Efficient Policies

The results of this book emphatically point to the importance of designing cost-effective policies and avoiding inefficient policies. The term "cost-effective" denotes an approach that achieves a given objective at minimum cost. For example, it might be decided that a global temperature increase of 2.5°C is the maximum that can be safely allowed without setting in motion dangerous feedback effects. The economic approach is to find ways to achieve this objective with the lowest cost to the economy.

One important requirement—sometimes called "where-efficiency"—is that the marginal costs of emissions reductions be equalized across sectors and across countries. The only realistic way to achieve this is by imposing harmonized carbon prices that apply everywhere, with no exempted or favored sectors or excluded countries. One approach to price harmonization is universal carbon taxes. The second approach is a cap-and-trade system (or effectively linked multiple national cap-and-trade systems) in which all countries and sectors participate and all emissions are subject to trades.

A second requirement for efficiency is "when-efficiency," which requires that the timing of emissions reductions be efficiently designed. As described earlier, we estimate that the when-efficiency carbon price should rise between 2 and 3 percent per year in real terms. When-efficiency is much more difficult to estimate than where-efficiency because when-efficiency depends upon the discount rate and the dynamics of the carbon cycle and the climate system, as well as the economic damages from climate change.

All the policies that have been implemented to date fail the tests of where- and when-efficiency. The analyses in this book and several earlier studies indicate that the current Kyoto Protocol is seriously flawed in its environmental rationale, is inefficiently designed, and is likely to be ineffective. For example, in the current Kyoto Protocol, carbon prices are different across countries, ranging from relatively high in Europe to zero in the United States and developing countries. Moreover, within covered countries, some sectors are favored over others, and there is no mechanism to guarantee an efficient allocation over time. We estimate that the current Kyoto Protocol is extremely weak and inefficient without U.S. participation. It is only about 0.02 as effective as the optimal policy in reducing climatic damages and still incurs substantial abatement costs. Even if the United States were to join the current Kyoto Protocol, this approach would make only a small contribution to slowing global warming, and it would continue to be highly inefficient.

We have also analyzed several "ambitious" policies, such as the one proposed in 2007 by the German government, a proposal by Al Gore, and proposals generated using the objectives in the *Stern Review* (Stern 2007). For example, the 2007 Gore proposal for the United States was for a 90 percent reduction in CO_2 emissions below current levels by 2050, while the 2007 German proposal was to limit global CO_2 emissions in 2050 to 50 percent of 1990 levels. These proposals have the opposite problem to that of the current Kyoto Protocol. They are inefficient because they impose excessively large emissions reductions in the short run. According to the DICE model, they imply carbon taxes rising to around $300 per ton of carbon in the next two decades, and to the range of $600 to $800 per ton

by midcentury. To return to our earlier examples, a $700 carbon tax would increase the price of coal-fired electricity in the United States by about 150 percent, and, at current levels of CO_2 emissions, it would impose a tax bill of $1,200 billion on the U.S. economy. From an economic point of view, such a high carbon tax would prove much more expensive than necessary to achieve a given climate objective.

Our modeling results point to the importance of near-universal participation in programs to reduce greenhouse gases. Because of the structure of the costs of abatement, with marginal costs being very low for the initial reductions but rising sharply for higher reductions, there are substantial excess costs if the preponderance of sectors and countries are not fully included. We preliminarily estimate that a participation rate of 50 percent, as compared with 100 percent, will impose an abatement-cost penalty of 250 percent. Even with the participation of the top 15 countries and regions, consisting of three-quarters of world emissions, we estimate that the cost penalty is about 70 percent.

We have determined that a low-cost and environmentally benign substitute for fossil fuels would be highly beneficial. In other words, a low-cost backstop technology would have substantial economic benefits. We estimate that such a low-cost zero-carbon technology would have a net value of around $17 trillion in present value because it would allow the globe to avoid most of the damages from climate change. No such technology presently exists, and we can only speculate on it. It might be low-cost solar power, geothermal energy, some nonintrusive climatic engineering, or genetically engineered carbon-eating trees. Although none of these options is currently feasible, the net benefits of zero-carbon substitutes are so high as to warrant very intensive research.

The Necessity of Raising Carbon Prices

Economics contains one fundamental inconvenient truth about climate-change policy: For any policy to be effective in slowing global warming, it must raise the market price of carbon, which will raise the prices of fossil fuels and the products of fossil fuels. Prices can be raised by limiting the number of carbon-emissions permits that are available (cap-and-trade) or by levying a tax (or some euphemism such as a "climate damage charge") on carbon emissions. Economics teaches us that it is unrealistic to hope that major reductions in emissions can be achieved by hope, trust, responsible citizenship, environmental ethics, or guilt alone. The only way to have major and durable effects on such a large sector for millions of firms and billions of people and trillions of dollars of expenditure is to raise the price of carbon emissions.

Raising the price of carbon will achieve four goals. First, it will provide signals to consumers about what goods and services are high-carbon ones and should therefore be used more sparingly. Second, it will provide signals to producers about which inputs use more carbon (such as coal and oil) and which use less or none (such as natural gas or nuclear power), thereby inducing firms to substitute low-carbon inputs. Third, it will give market incentives for inventors and innovators to develop and introduce low-carbon products and processes that can replace the current generation of technologies.

Fourth, and most important, a high carbon price will economize on the information that is required to do all three of these tasks. Through the market mechanism, a high carbon price will raise the price of products according to their carbon content. Ethical consumers today, hoping to minimize their

"carbon footprint," have little chance of making an accurate calculation of the relative carbon use in, say, driving 250 miles as compared with flying 250 miles. A harmonized carbon tax would raise the price of a good proportionately to exactly the amount of CO_2 that is emitted in all the stages of production that are involved in producing that good. If 0.01 of a ton of carbon emissions results from the wheat growing and the milling and the trucking and the baking of a loaf of bread, then a tax of $30 per ton carbon will raise the price of bread by $0.30. The "carbon footprint" is automatically calculated by the price system. Consumers would still not know how much of the price is due to carbon emissions, but they could make their decisions confident that they are paying for the social cost of their carbon footprint.

Because of the political unpopularity of taxes, it is tempting to use subsidies for "clean" or "green" technologies as a substitute for raising the price of carbon emissions. This is an economic and environmental snare to be avoided. The fundamental problem is that there are too many clean activities to subsidize. Virtually everything from market bicycles to nonmarket walking has a low carbon intensity relative to driving. There are simply insufficient resources to subsidize all activities that are low emitters. Even if the resources were available, the calculation of an appropriate subsidy for a particular activity would be a horrendously complicated task. An additional problem is that the existence of subsidies encourages a pell-mell race for benefits—an environmental form of rent-seeking activity. Ethanol subsidies in the United States, which are rapidly turning into an economic nightmare by diverting precious agricultural resources to the inefficient production of energy, are a case study in the folly of subsidies. To some extent, subsidies are simply the attempt of those who have the responsibility to clean up their activities by reducing emissions to place the fiscal burden elsewhere. Finally, subsidies have the public-finance problem of requiring revenues, which would involve raising the inefficiency of the tax system.

There are exceptions to the general rule to avoid subsidies in combating global warming. It is economically appropriate to subsidize activities such as invention, innovation, and education—which are public goods rather than public bads—through government funding or tax credits. For example, the tax credit on research and development and government funding of basic research in energy science are appropriate uses of the subsidy approach. But these are the economic opposites of harmful activities such as the burning of fossil fuels.

Whether someone is serious about tackling the global-warming problem can be readily gauged by listening to what he or she says about the carbon price. Suppose you hear a public figure who speaks eloquently of the perils of global warming and proposes that the nation should move urgently to slow climate change. Suppose that person proposes regulating the fuel efficiency of cars, or requiring high-efficiency lightbulbs, or subsidizing ethanol, or providing research support for solar power—but nowhere does the proposal raise the price of carbon. You should conclude that the proposal is not really serious and does not recognize the central economic message about how to slow climate change. To a first approximation, raising the price of carbon is a necessary and sufficient step for tackling global warming. The rest is at best rhetoric and may actually be harmful in inducing economic inefficiencies.

The Advantage of Carbon Taxes and Price-Type Approaches

If an effective climate-change policy requires raising the market price of carbon emissions, then there are two alternative approaches for doing so. The first is a price-type approach such as carbon taxes, and the second is a quantity-type approach such as the cap-and-trade systems that are envisioned in the Kyoto Protocol and most other policy proposals.

It is worth pausing here to describe an international system for the price-type alternative. One approach is called "harmonized carbon taxes." Under this approach, all countries would agree to penalize carbon emissions in all sectors at an internationally harmonized carbon price or carbon tax. The carbon price might be determined by estimates of the price necessary to limit GHG concentrations or temperature changes below some level thought to trigger "dangerous interferences" with the climatic system (this is the term used in the United Nations Framework Convention on Climate Change as a goal of international climate policy). Alternatively, it might be the price that would induce the estimated "optimal" level of control. The results of this book suggest, as stated earlier, a tax of around $27 per ton of carbon at present, rising at between 2 and 3 percent per year in real terms. Because carbon prices would be equalized across countries and sectors, this approach would satisfy where-efficiency. If the carbon-tax trajectory grows at the appropriate rate, it will also satisfy the rules for when-efficiency.

We have examined the relative advantages of the two regimes and conclude that price-type approaches have many advantages. One advantage of carbon taxes is that they can more easily and flexibly integrate the economic costs and benefits of emissions reductions. The quantity-type approach in the Kyoto Protocol has no discernible connection with ultimate environmental or economic goals, although some recent revisions, such as the 2007 German proposal, are linked to global temperature objectives. The advantage of a price-type approach is emphatically reinforced by the large uncertainties and evolving scientific knowledge in this area. Emissions taxes are more efficient in the face of massive uncertainties because of the relative linearity of the benefits compared with the costs. Quantitative limits will produce high volatility in the market price of carbon under an emissions-targeting approach, as has already been seen in the EU's cap-and-trade system for CO_2.

In addition, a tax approach allows the public to get the revenues from restrictions more easily than allocational quantitative approaches, and it may therefore be seen as fairer and can minimize the distortions caused by the tax system. Because taxes raise revenues (whereas allocations give the revenues to the recipient), the public revenues can be used to soften the economic impacts on lower-income households, to fund necessary research on low-carbon energy, and to help poor countries move away from high-carbon fuels. The tax approach also provides less opportunity for corruption and financial finagling than quantitative limits because a price-type approach creates no artificial scarcities to encourage rent-seeking behavior.

It should be noted that many recent successors to the Kyoto Protocol that are being discussed propose auctioning some or all of the emissions permits. This is an important innovation, for auctions raise revenues and therefore can have the advantageous effect on tax efficiency of a carbon tax. Moreover, there is a temptation in tax systems to grant exemptions, thereby reducing their environmental integrity and

cost-effectiveness, and quantitative systems have often been more successful in being comprehensive within a country. The major point to emphasize here is that whichever approach is taken—quantitative or tax-based—the public should capture the revenues through taxes or auctions, and there should be an absolute minimum of exemptions.

Carbon taxes have the apparent disadvantage that they do not steer the world economy toward a particular climatic target, such as either a CO_2 concentration or a global temperature limit. People might worry that we need quantitative emissions limits to ensure that the globe remains on the safe side of "dangerous interferences" with the climate system. However, this advantage of quantitative limits is probably illusory. We do not currently know what emissions levels would actually lead to dangerous interferences, or even if there are dangerous interferences. We might make a huge mistake—either on the high or the low side—and impose much too rigid and expensive, or much too lax, quantitative limits. In other words, whatever initial target we set is likely to prove incorrect for either taxes or quantities. The major question is whether it would prove easier to make periodic large adjustments to incorrectly set harmonized carbon taxes or to incorrectly set negotiated emissions limits.

We conclude that more emphasis should be placed on including price-type features in climate-change policy rather than relying solely on quantity-type approaches such as cap-and-trade schemes. A middle ground between the two is a hybrid, called the "cap-and-tax" system, in which quantitative limits are buttressed by a carbon tax along with a safety valve that prevents excessively high carbon prices. An example of a hybrid plan would be a cap-and-trade system with an initial carbon tax of $30 per ton along with a provision for firms to purchase additional permits at a penalty price of $45 per ton of carbon. This hybrid plan would combine some of the advantages of both price and quantity approaches.

Tax Bads Rather than Goods

Taxes are almost a four-letter word in the American political lexicon. But the discussion of taxes sometimes makes a fundamental mistake in failing to distinguish between different kinds of taxes. Some people have objected to carbon taxes because, they argue, taxes lead to economic inefficiencies. While this analysis is generally correct for taxes on "goods" like consumption, labor, and savings, it is incorrect for taxes on "bads" like CO_2 emissions.

Taxes on labor distort people's decisions about how much to work and when to retire, and these distortions can be costly to the economy. Taxes on bads like CO_2 are precisely the opposite; they serve to remove implicit subsidies on harmful or wasteful activities. Allowing people to emit CO_2 into the atmosphere for free is similar to allowing people to smoke in a crowded room or dump trash in a national park. Carbon taxes therefore enhance efficiency because they correct market distortions that arise when people do not take into account the external effects of their energy consumption. If the economy could replace inefficient taxes on goods like food and leisure with efficient taxes on bads like carbon emissions, there would be significant improvements in economic efficiency.

Two Cautionary Notes

We close with two cautionary notes. First, it is important to recognize that this book represents only one perspective on

how to approach climate change. It is a limited perspective because it uses economics to examine alternative approaches, and it is further narrowed because it represents the viewpoint of one person with all the blinders, cognitive constraints, and biases involved in individual research. There are many other perspectives through which to analyze approaches for slowing global warming. These perspectives differ in normative assumptions, estimated behavioral structures, scientific data and modeling, levels of aggregation, treatment of uncertainty, and disciplinary background. No sensible policymaker would base the globe's future on a single model, a single set of computer runs, a single viewpoint, or a single national, ethical, or disciplinary perspective. Sensible decision making requires a robust set of alternative scenarios and sensitivity analyses. But this is the role of committees and panels, not of individual scholars.

A second reservation concerns the profound uncertainties that are involved at every stage of modeling global warming. We are uncertain about the growth of output over the next century and beyond, about what energy systems will be developed in the decades ahead, about the pace of technological change in substitutes for carbon fuels or in carbon-removal technologies, about the climatic reaction to rising concentrations of GHGs, and perhaps most of all about the economic and ecological responses to a changing climate.

This book takes the standard economic approach to uncertainty known as the expected utility model, which relies on an assessment with subjective or judgmental probabilities. This approach uses the best available information on the level and uncertainties for the major variables to determine how the presence of uncertainty might change our policies relative to a best-guess policy. (The "best guess" is shorthand for basing our model on the mean or expected values of the parameters of the model.) This approach assumes that there are no genuinely catastrophic outcomes that would wipe out the human species or destroy the fabric of human civilizations. Estimating the likelihood of, and dealing with, potentially catastrophic outcomes is one of the continuing important subjects of research for the natural and social sciences.

Based on the expected utility model, one finding of the uncertainty analysis in this book is that the best-guess policy is a good approximation to the expected-value policy. There appears to be no empirical ground for paying a major risk premium for future uncertainties beyond what would be justified by the averages (subject to the caveats about catastrophic outcomes in the preceding paragraph).

At the same time, we must emphasize that, based on our formal analysis of uncertainty, we have relatively little confidence in our projections beyond 2050. For example, in our uncertainty analysis, we project the "two-sigma" error bands for several variables on the basis of scientific and economic uncertainties about the various parameters and systems (the two-sigma error band is the range within which we believe the true figure lies with 68 percent confidence). Our estimate is that the two-sigma band for global mean temperature increase by 2100 is 1.9°C to 4.1°C. A similar calculation for the current social cost of carbon in the baseline projection lies between $10 and $41 per ton of carbon. These pervasive uncertainties are one of the most difficult features of dealing with climate change.

The final message of this book is a simple one: Global warming is a serious problem that will not solve itself. Countries should take cooperative steps to slow global warming. There is no case for delay. The most fruitful and effective

approach is for countries to put a harmonized price—perhaps a steep price—on greenhouse-gas emissions, primarily those of carbon dioxide resulting from the combustion of fossil fuels. Although other measures might usefully buttress this policy, placing a near-universal and harmonized price or tax on carbon is a necessary and perhaps even a sufficient condition for reducing the future threat of global warming.