CHAPTER 5

Findings, Uses, and Future Directions

INTRODUCTION

Scenarios based on formal, computer-based models, such as the scenarios developed in this research, can help illustrate how key drivers such as economic and population growth or policy options lead to particular levels of GHG emissions. An important benefit of models such as those used in this research is that they ensure basic accounting identities and consistent application of behavioral assumptions. However, model-based scenarios are only one approach to scenario development, and models designed for one set of purposes may not be the most appropriate for other applications. Thus, the scenarios developed here should be viewed as complementary to other ways of thinking about the future, such as formal uncertainty analyses, story lines, baselines for further model-based scenarios, and analyses using other types of models.

The users of emissions scenarios are many and diverse and include climate modelers and the science community; those involved in national public policy formulation; managers of Federal research programs; state and local government officials who face decisions that might be affected by climate change and mitigation measures; and individual firms, non-governmental organizations, and members of the public. Such a varied clientele implies an equally diverse set of possible needs, and no single scenario exercise can hope to satisfy all of them. Scenario analysis is most effective when its developers can work directly with users, and initial scenarios lead to further *what if* questions that can be answered with additional scenarios or by probing more deeply into particular issues. The Prospectus for this research did not, however, prescribe such an interactive approach with a focused set of users. Instead, it called for a set of scenarios that provide broad insights into the energy, economic, and emissions implications of stabilizing radiative forcing. For the issue of stabilization, these scenarios are an initial offering to potential user communities that, if successful, will generate further questions and more detailed analysis.

This research focuses on three sets of scenarios, each including a reference scenario and four scenarios in which the radiative forcing from a common suite of GHGs is stabilized at four alternative levels. The stabilization scenarios describe a range of possible long-term goals for global climate policy. The stabilization levels imply a range of policy efforts and levels of urgency, from relatively little deviation from reference scenarios over the course of the century to major deviations starting very soon. Although the Prospectus did not mandate a formal treatment of likelihood or uncertainty, such analysis could be a useful follow-on activity. Here, however, the range of outcomes from the different modeling groups helps to illustrate, if incompletely, the range of possibilities.

For this research, a scenario is an illustration of future developments based on a model of the economy and the Earth system, applying a plausible set of model parameters and providing a basis for future work. None of the reference scenarios is a prediction or best-judgment forecast of the future, and none can be said to have the highest probability of being right. Nor does any single stabilization scenario provide the most correct picture of the changes to energy and other systems that would be required for stabilization. Instead, each scenario in this report is a thought experiment that helps illuminate the implications of different long-term policy goals.

OVERVIEW OF THE SCENARIOS

The scenarios are presented in text and figures in Chapters 3 and 4, and here a summary is provided of some of their key characteristics, some of the magnitudes involved, and the assumptions that lie behind them.

Reference Scenarios

The difficulty in achieving any specified radiative forcing stabilization level depends heavily on the emissions that would occur absent actions to address GHG emissions. In other words, the reference scenario strongly influences the stabilization scenarios. If the reference scenario has inexpensive fossil fuels and high economic growth, then larger changes to the energy sector and other parts of the economy may be required to stabilize the atmosphere. On the other hand, if the reference scenario shows lower growth and emissions, and perhaps increased exploitation of non-fossil sources even in the absence of climate policy, then the effort required to stabilize radiative forcing will not be as great.

Energy production, transformation, and consumption are central features in all of these scenarios, although non-CO_2 gases and changes in land use also make a significant contribution to aggregate GHG emissions. Demand for energy over the coming century will be driven by economic growth and will also be strongly influenced by the way that energy systems respond to depletion of resources, changes in prices, and improvements in technology. Demand for energy in developed countries remains strong in all the scenarios and is even stronger in developing countries, where millions of people seek greater access to commercial energy. These developments strongly influence the emissions of GHGs, their disposition, and the resulting change in radiative forcing in the reference scenarios.

The three reference scenarios show the implications of this increasing demand and the improved access to energy. The variation between the reference scenarios reflects the differing assumptions used by the modeling groups.

- Global primary energy consumption rises substantially in all three reference scenarios, from about 400 EJ/yr in 2000 to between roughly 1275 EJ/yr and 1500 EJ/yr in 2100 (Figure ES.1). U.S. primary energy consumption also grows substantially, about 1¼ to 2½ times present levels by 2100. Primary energy consumption growth occurs despite continued improvements in the efficiency of energy use and energy production technologies. For example, the U.S. energy intensity – the ratio of primary energy consumption to economic output – declines 60% to 75% between 2000 and 2100 across the three reference scenarios.

- All three reference scenarios include a gradual reduction in the consumption of conventional oil resources. However, in all three, a range of alternative fossil-based resources, such as synthetic fuels from coal and unconventional oil resources (e.g., tar sands and oil shales), are available and become economically viable. Fossil fuels provided almost 90% of the global primary energy in 2000, and they remain the dominant energy source in the three reference scenarios throughout the twenty-first century, supplying 70% to 80% of total primary energy in 2100.

- Non-fossil fuel energy use also grows over the century in all three reference scenarios. Contributions to primary energy consumption in 2100 range from 250 EJ to 450 EJ – a range that at the hight end exceeds global primary energy consumption today. Despite this growth, these sources never supplant fossil fuels, although they provide an increasing share of the total, particularly in the second half of the century.

- Consistent with the characteristics of primary energy consumption, global and U.S. electricity production continues to rely on coal, although this contribution varies among the reference scenarios. The contribution of renewable and nuclear energy varies considerably in the different reference scenarios, depending on resource availability, technology, and non-climate policy considerations. For example, global nuclear power in the reference scenarios ranges from about 1½ times current levels (if non-climate concerns such as safety, waste, and proliferation constrain its growth as is the case in one reference scenario), to an expansion of almost an order of magnitude assuming relative economics as the only constraint.

- Oil and natural gas producer prices rise through the century relative to year 2000 levels, whereas coal and electricity prices remain relatively stable. It should be emphasized that the models used in this research were not designed to simulate short-term fuel-price spikes, such as those that occurred in the 1970s, early 1980s, and more recently in 2005. Thus, price trends in the scenarios should be interpreted as multi-year averages.

- As a combined result of all these influences, CO_2 emissions from fossil fuel combustion and industrial processes in the reference scenarios increase from approximately 7 GtC/yr in 2000 to between 22.5 GtC/yr and 24.0 GtC/yr in 2100; that is, to roughly 3 to 3½ times current levels.

The non-CO_2 GHGs, CH_4, N_2O, SF_6, PFCs, and HFCs, are emitted from various sources including agriculture, waste management, biomass burning, fossil fuel production and consumption, and a number of industrial activities.

- Future global anthropogenic emissions of CH_4 and N_2O vary widely among the reference scenarios, ranging from flat or declining emissions to increases of 2 to 2½ times present levels. These differences reflect alternative assumptions about technological opportunities and about whether current emissions rates will be reduced significantly for non-climate reasons, such as air pollution control and/or higher natural gas prices that would further stimulate the capture of CH_4 emissions for its fuel value.

Increases in emissions from the global energy system and other human activities lead to higher atmospheric GHG concentrations and radiative forcing. This increase is moderated by natural biogeochemical removal processes.

- The oceans are a major sink for CO_2, and the rate at which they take up CO_2 generally increases in the reference scenarios as concentrations rise early in the century. However, processes in the ocean can slow this rate of increase at high concentrations late in the century. Ocean uptake in the three reference scenarios is in the range of 2 GtC/yr in 2000, rising to about 5 GtC/yr to 11 GtC/yr by 2100. The three ocean models behave more similarly in the stabilization scenarios; for example, the difference in ocean uptake among the models at the most stringent stabilization levels is less than 1 GtC/yr in 2100.

- Two of the three participating models include sub-models of the exchange of CO_2 with the terrestrial biosphere, including the net uptake by plants and soils and the emissions from deforestation. In the reference scenarios from these modeling groups, the terrestrial biosphere acts as a small annual net sink (less than 1 GtC/yr of carbon) in 2000, increasing to an annual net sink of roughly 2 GtC/yr to 3 GtC/yr by the end of the century. The third modeling group assumed a zero net exchange. Changes in emissions from terrestrial systems over time in the reference scenarios reflect assumptions about human activity (including a decline in deforestation) as well as increased CO_2 uptake by vegetation as a result of the positive effect of CO_2 on plant growth. There remains substantial uncertainty about this carbon fertilization effect and its evolution under a changing climate.

- As a result of the various influences, GHG concentrations rise substantially over the century in the reference scenarios. By 2100, CO_2 concentrations range from about 700 ppmv to 900 ppmv, up from 365 ppmv in 1998. CH_4 concentrations in 2100 range from 2000 ppbv to 4000 ppbv, up from 1745 ppbv in 1998, and N_2O concentrations in 2100 range from about 375 ppbv to 500 ppbv, up from 314 ppbv in 1998.

- As a result, radiative forcing in 2100 ranges from 6.4 W/m^2 to 8.6 W/m^2 from preindustrial, up from a little over 2 W/m^2 today. The non-CO_2 GHGs account for about 20% to 25% of radiative forcing at the end of the century.

Stabilization Scenarios

Important assumptions underlying the stabilization scenarios include the flexibility that exists in a policy design, as represented by the modeling groups, to seek out least cost options for emissions control regardless of where they occur, what substances are controlled, or when they occur. This set of conditions is referred to as *where*, *what*, and *when* flexibility. Equal marginal costs of abatement among regions across time (taking into account discount rates and the lifetimes of substances), and among substances (taking into account their relative warming potential and different lifetimes) will, under specified conditions, lead to least cost abatement. Each modeling group applied an economic instrument that priced GHGs in a manner consistent with the group's interpretation of *where*, *what*, and *when* flexibility. The economic characteristics of the scenarios thus assume a policy designed with the intent of achieving the required reductions in GHG emissions in a least-cost way. Key implications of these assumptions are that: (1) all nations proceed together in restricting GHG emissions from 2012 and continue together throughout the century, and that the same marginal cost is applied across sectors (*where* flexibility); (2) the marginal cost of abatement rises over time in these three sets of scenarios based on each modeling group's interpretation of *when* flexibility, with the effect of linking emissions mitigation efforts over the time horizon of the scenarios; and (3) stabilization of radiative forcing is achieved by combining control of all GHGs, with differences in how modeling groups compared them and assessed the implications of this *what* flexibility.

Although these assumptions are convenient for analytical purposes, to gain an impression of the implications of stabilization, they are idealized versions of possible outcomes. For the abatement costs in these scenarios to be representative of actual abatement costs would require, among other things, that a negotiated international agreement include these flexibility mechanisms. Failure in that regard could have a substantial effect on the difficulty of achieving any of the stabilization levels considered in this research. For example, a delay of many years in the participation of some large countries would require greater effort by the others, and policies that impose differential burdens on different sectors without mechanisms to allow for equalizing marginal costs across sectors can result in a many-fold increase in the cost of any environmental gain. Therefore, *it is important to view these scenarios as representing possible futures under specified conditions, not as forecasts of the most likely outcome within the national and international political system.* Further, none of the scenarios considered the extent to which variation from these least-cost rules might be improved upon given interactions with existing taxes, technology spillovers, or other non-market externalities.

If the developments in the three reference scenarios were to occur, concerted efforts to reduce GHG emissions would be required to stabilize radiative forcing at the levels considered in this research. Such limits would shape technology deployment throughout the century and have important economic consequences. The stabilization scenarios demonstrate that there is no single technology pathway consistent with a given level of radiative forcing. Furthermore, there are other possible pathways than those considered in this research.

- Stabilization efforts are made more challenging by the fact that ocean uptake of CO_2 declines as the stringency of the stabilization level increases, and, in the scenarios from two of the models, because CO_2 uptake in terrestrial systems also declines with the stringency of the stabilization level.

- Stabilization of radiative forcing at the levels examined in this research would require a substantially different energy system globally, and in the U.S., than what emerges in the reference scenarios. The degree and timing of change in the global energy system depends on the level at which radiative forcing is stabilized. The lower the radiative forcing stabilization level, the larger the scale of change in the global energy system relative to the reference scenario and the sooner those changes would need to occur.

- Across the stabilization scenarios, the energy system relies more heavily on non-fossil energy sources, such as nuclear, solar, wind, biomass, and other renewable energy forms, than in the associated reference scenarios. The stabilization scenarios differ in the degree to which these technologies are deployed, depending on assumptions about: technological improvements; the ability to overcome obstacles, such as intermittency in the case of solar and wind power, or safety, waste, and proliferation issues in the case of nuclear power; and the policy environment surrounding these technologies. Energy consumption, while still higher than today's levels, is lower in the stabilization scenarios than in the reference scenarios.

- CCS is widely deployed in the stabilization scenarios because each modeling group assumed that the technology can be successfully developed and that concerns about storing large amounts of carbon do not impede its expansion. Removal of this assumption would make the stabilization levels more difficult to achieve and would lead to greater demand for low-carbon sources such as renewable energy and nuclear power, to the extent that growth of these other sources is not otherwise constrained.

- Significant fossil fuel use continues across the stabilization scenarios, both because stabilization allows for some level of carbon emissions through 2100, depending on the stabilization level, and because of the presence of CCS technology in all the stabilization scenarios.

- Emissions of non-CO_2 GHGs, such as CH_4, N_2O, HFCs, PFCs, and SF_6, are all reduced in the stabilization scenarios.

- Increased use is made of biomass energy crops in all the stabilization scenarios, but their contribution is ultimately limited by competition with agriculture and forestry, and, in one participating model, by the associated impacts of biomass expansion on carbon emissions from changes in land use.

- The lower the radiative forcing stabilization level, the larger the scale of change in the global energy system relative to the reference scenario required over the coming century and the sooner those changes would need to occur.

- Across the stabilization scenarios, the scale of the emissions reductions required relative to the reference scenario increases over time, with the bulk of emissions reductions taking place in the second half of the century. But emissions reductions occur in the first half of the century in every stabilization scenario.

- The 2100 time horizon of this research limited examination of the ultimate stabilization requirements. Further reductions in CO_2 emissions after 2100 would be required in all of the stabilization scenarios, because stabilization of radiative forcing at any of the levels considered in this research requires human emissions of CO_2 in the long term to be essentially halted. Despite the fact that much of the carbon emissions will eventually make its way into oceans and terrestrial sinks, some will remain in the atmosphere for thousands of years. Only CCS can allow continued burning of fossil fuels. Higher radiative forcing limits can delay the point in time at which emissions must be reduced toward zero, but this requirement must ultimately be met.

Fuel sources and electricity generation technologies change substantially, both globally and in the U.S., in the stabilization scenarios compared to the reference scenarios. There are a variety of technological options in the electricity sector that reduce carbon emissions in these scenarios.

- Nuclear power, renewable energy, and CCS all play important roles in stabilization scenarios. The contribution of each varies, depending on assumptions about technological improvements, the ability to overcome obstacles such as intermittency of supply, and the policy environment surrounding them.

- By the end of the century, electricity produced by conventional fossil technology that freely emits CO_2 is reduced in the stabilization scenarios relative to reference scenarios. Electricity production from technologies that emit CO_2 varies substantially with the stabilization level; in the lowest stabilization level, electricity production from these technologies is reduced toward zero.

The economic effects of stabilization are substantial in many of the stabilization scenarios, although much of this cost is borne later in the century. As noted earlier, each of the modeling groups assumed that a global policy was implemented after 2012, with universal participation by the world's nations, and that the time path of reductions approximated a least-cost solution. These assumptions of *where*, *when*, and *what* flexibility lower the economic consequences of stabilization relative to what they might be with other implementation approaches.

- The stabilization scenarios follow a pattern where, in most scenarios, the carbon price rises steadily over time, providing an opportunity for the energy system to adjust gradually.

- Although the general shape of the carbon price trajectory over time is similar across the models, the carbon prices vary substantially across the models. For example, two of the scenarios have prices of \$10 or below per tonne of carbon in 2020 for the less stringent scenarios, with their prices rising to roughly \$100 per tonne in 2020 for the most stringent stabilization level. A third scenario shows higher initial carbon prices in 2020, ranging from around \$20 for the least stringent stabilization level to over \$250 for the most stringent stabilization level.

- Factors contributing to differences in carbon prices include (1) differences in assumptions – such as those regarding economic growth over the century, the behavior of the oceans and terrestrial biosphere in taking up CO_2, and opportunities for reduction in non-CO_2 GHG emissions – that determine the amount that CO_2 emissions must be reduced to meet the radiative forcing stabilization levels; and (2) differences in assumptions about technologies, particularly in the second half of the century, to shift final demand to low-carbon sources such as biofuels and low-carbon electricity or hydrogen, in transportation, industrial, and buildings end uses. Differences among the scenarios reflect the uncertainty that attends the far future.

- Differences in non-CO_2 gases also contribute to differences in abatement costs. Scenarios that assume relatively better performance of non-CO_2 emissions mitigation require less CO_2 abatement and therefore less stringent changes in the energy system, to meet the same overall radiative forcing goal.

- These differences in carbon prices, along with other model features, lead to similar variation in the costs of stabilization. At the most stringent radiative forcing stabilization level, for example, gross world product (aggregating country figures using market exchange rates) is reduced in 2050 by around 1% in the scenarios from two of the modeling groups and approximately 5% in the scenario from the third, and in 2100 it is reduced by less than 2% in two of the scenarios and over 16% in the third.

- The assumption of *when* flexibility links elements of the stabilization scenarios through time. This in turn means that, in addition to near-term technology availability, differences in assumptions about technology in the post-2050 period are also reflected in near-term emissions reductions and GHG prices.

- In all of the stabilization scenarios, emissions reductions in electric power sector come at relatively lower prices than in other sectors (e.g., buildings, industry, and transport) so that the electricity sector is essentially decarbonized in the most stringent scenarios. At somewhat higher cost other sectors can respond to rising carbon prices by reducing demands for fossil fuels, applying CCS technologies where possible, and substituting low-carbon energy sources such as bioenergy and low-carbon electricity or hydrogen. The amount of electricity used per unit of total primary energy increases in all of the stabilization scenarios, but those scenarios with the highest relative use of electricity tend to exhibit lower stabilization costs in part because of the larger role of decarbonized power generation. Assumptions regarding costs and performance of technologies to facilitate these adjustments, particularly in the post-2050 period, play an important role in determining stabilization costs

- As noted earlier, the overall cost levels are strongly influenced by the idealized policy scenario that has all countries participating from the start, the assumption of *where* flexibility, an efficient pattern of emissions reductions over time, and integrated reductions in emissions of the different GHGs. Assumptions in which policies are implemented in a less efficient manner would lead to higher cost. Thus, these scenarios should not be interpreted as applying beyond the particular conditions assumed.

- GHG mitigation would also affect fuel prices. Generally, producer prices for fossil fuels fall as demand for them is depressed by the stabilization measures. Consumers of fossil fuels, on the other hand, pay for fuel plus a carbon price if the CO_2 emissions are freely released to the atmosphere. Therefore, consumer costs of energy rise with more stringent stabilization levels in these scenarios.

Achieving stabilization of atmospheric GHGs poses a substantial technological and policy challenge. It would require important transformations of the global energy system. The cost and feasibility of such a goal depends on the evolution of technology and its ability to overcome existing limits and barriers to adoption, and it depends on the efficiency and effectiveness of the policy instruments employed to achieve stabilization.

APPLICATION OF THE SCENARIOS IN FURTHER ANALYSIS

These scenarios, supported by the accompanying database described in the Appendix, can be used as the basis of further analysis. There are a variety of possible applications for these scenarios. For example, the scenarios could be used as the basis for analysis of the climate implications, and then follow-on studies of potential climate impacts. Such studies might begin with the radiative forcing levels of each scenario, with the individual GHG concentrations (applying separate radiation codes) or with the emissions (applying separate models of the carbon cycle and of the atmospheric chemistry of the non-CO_2 GHGs). Such applications could be made directly in climate models that do not incorporate a three-dimensional atmosphere and detailed biosphere model. For the larger models, some approximation would need to be imposed to allocate the short-lived gases by latitude or grid cell. Such an effort would need to include scenarios of the emissions (or concentrations) of the reflecting and absorbing aerosols. This could be achieved by the use of sub-models linked to scenario for energy use by fuel.

The scenarios could also be used as a point of departure for partial equilibrium analysis of technology development. Because these models compute energy prices, the scenarios can be used for analysis of the cost performance of new technologies and to serve as a basis for analysis of rates of market penetration. Differences in the scenarios among the three modeling groups give an impression of the types of market challenges that new options will face.

In addition, these studies could form the foundation of analysis of the non-climate environmental implications of implementing potential new energy sources at a large scale. Such analysis was beyond the scope of the present research, but information is provided that could form a basis for such analysis, for example, the potential effects on the U.S. and the globe of implied volumes of CCS and biomass production or of nuclear power expansion in some of the scenarios.

The scenarios could also be used in comparative mode. Just as many lessons were learned by comparing the differences between the three modeling groups' scenarios, still more could be learned by extending the comparison to scenarios that predate these or come after, including scenarios developed using entirely different approaches. For example, some scenario exercises do not apply economic models with detailed analysis of energy markets of the type used here. Such scenarios could be compared against those presented here to gain insight into the role of economic factors.

Finally, these scenarios might be used to explore the economic effects of stabilization at different levels. Such work was beyond the scope of the research specified in the Prospectus. However, the scenarios do contain information that can be used to calculate indicators of consumer impact in the U.S., for example, by using the changes in prices and quantities of fuels in moving from one stabilization level to another. (The reader is reminded, however, that these welfare effects do not include the benefits that alternative stabilization levels might yield in reduced climate change risk or ancillary effects, such as effects on air pollution).

MOVING FORWARD

As noted earlier, this work is neither the first nor is it likely to be the last of its kind. Throughout the report, a number of limitations to the approach and the participating models have been highlighted. Studies such as the one presented here would benefit from further research and model development and this section suggests several productive paths to pursue.

Technology Sensitivity Analysis

The importance of future technology development is clear in this report, and sensitivity testing of key assumptions would be of use. For example, what are the implications of various non-climate constraints on nuclear power or on the large-scale expansion of CCS or biofuels production? If particular supply technologies – nuclear, wind, natural gas combined cycle generation, and biomass – were assumed to be more or less expensive, how would that affect market penetration and policy cost? On the demand side, what are the effects of alternative views of the technical developments needed to facilitate substitution of electricity for liquid and gaseous fuels in various sectors, particularly in transport? Since technology deployment will be influenced by the policy environment, how would the consideration of less optimistic policy regimes affect this aspect of the scenarios?

Consideration of Less Optimistic Policy Regimes

The discussion in Chapter 4 emphasizes that the difficulty of the stabilization task emerging from any scenario research is crucially dependent on underlying institutional assumptions, and the insight to be gained from a single representation of control policy such as the one adopted in this research is limited. The scenarios assume a wide array of idealized institutions both in individual nations and in the international community. Both developed and developing economies are assumed to possess markets that efficiently pass price information to decision makers. Rules and regulations ranging from accounting and property rights to legal and enforcement systems are assumed to operate efficiently. While such assumptions provide a well-defined reference scenario and lower-bound information on potential costs, the probability is low that the world will actually implement such an idealized architecture. In that light, a natural direction for future research is to supplement the analysis presented here with analyses of policy regimes that are under discussion by nations and international organizations and that have a greater potential for being implemented. Such research would broaden the understanding of the stabilization challenge in areas ranging from technology development to the economics of global mitigation.

Expansion and/or Improvement of the Land-Use Components of the Models

A significant weakness in this research is the handling of the role of forest and agricultural sinks and sources. The major reason for this gap is that the models employed here were not well suited to analyze some of the complexities of this aspect of the carbon cycle. Yet, as this analysis has shown, agriculture, land-use and terrestrial carbon cycle issues play an important role in shaping the long-term radiative character of the atmosphere. Research that would improve the characterization of land use and land cover as well as improve the linkages among energy and economic systems, land use, land cover, terrestrial carbon processes, and other bio-geochemical cycles has potentially high payoff.

Inclusion of other Radiatively Important Substances

The focus in this research is on the relatively long-lived GHGs, but shorter-lived substances, such as ozone and aerosols, have strong radiative effects as well. More complete analysis would include these short-lived contributors, and their control possibilities, directly within the scenario analysis.

Decision Making under Uncertainty

Finally, the problem of how to respond to the threat of climate change is ultimately a problem of decision making under uncertainty that requires an assessment of the risks of climate change and how policies might reduce the odds of extremely bad outcomes. One would like to compare the expected benefits of policies to reduce GHG emissions against the expected costs of achieving those reductions. By focusing only on emission paths that would lead to stabilization, this research considers only the costs of stabilization without consideration of the benefits. Moreover, given the direction provided in the Prospectus, this research focused on scenarios and not on uncertainty analysis. It is not possible to attach probabilities to scenarios constructed in this way; formal probabilities can only be attached to a range, which requires exploration of the effects of many uncertain model parameters.