Executive Summary

INTRODUCTION

This and a companion report constitute one of twenty-one Synthesis and Assessment Products called for in the *Strategic Plan for the U.S. Climate Change Science Program*. These studies are structured to provide high-level, integrated research results on important science issues with a particular focus on questions raised by decision-makers on dimensions of climate change directly relevant to the U.S. One element of the CCSP's strategic vision is to provide *decision support tools* for differentiating and evaluating response strategies. Scenario-based analysis is one such tool. The scenarios in this report explore the implications of alternative stabilization levels of anthropogenic greenhouse gases (GHGs) in the atmosphere, and they explicitly consider the economic and technological foundations of such response options. Such scenarios are a valuable complement to other scientific research contained in the twenty-one CCSP Synthesis and Assessment Products. The companion to the research reported here, *Global-Change Scenarios: Their Devleopment and Use*, explores the broader strategic frame for developing and utilizing scenarios in support of climate decision making.

STUDY DESIGN

The scenarios in this report were developed using integrated assessment models (IAMs). These analysis capabilities integrate computer models of socioeconomic and technological determinants of the emissions of GHGs with models of the natural science of Earth system response, including the atmosphere, oceans, and terrestrial biosphere. Three IAMs were applied in the scenario development:

- The Integrated Global Systems Model (IGSM) of the Massachusetts Institute of Technology's Joint Program on the Science and Policy of Global Change.
- The Model for Evaluating the Regional and Global Effects (MERGE) of GHG reduction policies developed jointly at Stanford University and the Electric Power Research Institute.
- The MiniCAM Model of the Joint Global Change Research Institute, a partnership between the Pacific Northwest National Laboratory and the University of Maryland.

Each modeling group first produced a reference scenario under the assumption that no climate policies are imposed beyond current commitments, namely the 2008-12 first period of the Kyoto Protocol and the U.S. goal of reducing reduce GHG emissions per unit of its gross domestic product by 18% by 2012. The resulting reference cases are not predictions or best-judgment forecasts but scenarios designed to provide clearly defined points of departure for studying the implications of alternative stabilization goals. As instructed in the Prospectus for the study, the modeling teams used model input assumptions they considered *meaningful* and *plausible*. The resulting reference scenarios provide insights into how the world might evolve without additional efforts to constrain GHG emissions, given various assumptions about principal drivers of these emissions such as population increase, economic growth, land and labor productivity growth, technological options, and resource endowments.

Each modeling group then produced four additional stabilization scenarios framed as departures from its reference scenario. The stabilization levels are common across the modeling groups and are defined in terms of the total long-term effect on the Earth's heat balance of the combined effect of the primary anthropogenic GHGs: carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). The potential for climate-related controls on other human emissions, such as aerosols and their precursors, was not incorporated into the stabilization constraints, although the participating models represent the emissions of many of these substances. With the exception of these stabilization levels, and a common hypothesis about the sharing among nations of the mitigation task, there was no direct coordination among the modeling groups either in the assumptions underlying the reference scenario or the precise paths to stabilization.

The results drawn from the simulations were selected to provide insight into questions such as the following:

- What emissions trajectories over time are consistent with meeting the four stabilization levels, and what are the key factors that shape them?
- What energy system characteristics are consistent with each of the four alternative stabilization levels, and how might these characteristics differ among stabilization levels?
- What are the possible economic consequences of meeting each of the four alternative stabilization levels?

With its focus on reducing emissions to meet various stabilization levels the study does not explore climate damages that might be avoided or ancillary benefits (such as lower air pollution) of emissions reduction. Thus, though the scenarios provide a useful input to climate-related decision making they address only one of several components of a cost-benefit analysis of climate policy. In addition , although these scenarios incorporate new thinking on GHG emissions and possible mitigation paths they were not designed to span the full range of possible futures or to provide an uncertainty analysis of key forces. They are intended, rather, to enhance understanding of the implications of different ways that the future might evolve without assigning likelihoods to outcomes.

POTENTIAL APPLICATIONS

There are many potential applications of scenarios of this form, and to facilitate their use the numerical results are provided in a companion data set. Possible users 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. Insights from the scenarios may be used directly as inputs to the decision-making processes, or the scenarios may serve as inputs to further analyses in support of climate decision making. A sample of possible further analyses would include the following:

- The scenarios can provide a basis for study of the climate implications of alternative stabilization levels, as an input to climate models, and then to follow-on studies of potential climate impacts.
- The scenarios can serve as a point of departure for exploring possible technology cost and performance goals, using information from the scenarios on energy prices and technology deployment levels.
- The scenarios can provide a foundation for analysis of the non-climate environmental implications of new energy sources at large scale.
- The scenarios could serve as an input to a more complete analysis of the economic effects of stablizing and the different radiative forcing levels, such as indicators of consumer impact in the U.S.
- The scenarios can be applied in comparative mode, extending the lessons to be learned from the three models in this research to those to be gained from scenarios developed using different approaches.

The varied clientele for these scenarios and the variety of questions they might inform implies a highly diverse set of possible needs, and no single scenario exercise can hope to fully satisfy all of them. Therefore these scenarios likely will stimulate further questions and the demand for more detailed analysis, some of which might be satisfied by further scenario development from models like those used here, but others demanding detail that can only be provided with alternative modeling and analysis techniques.

Several characteristics of these scenarios make them particularly valuable for these and other types of applications. One advantage is the update of economic and technology data and assumptions and the use of improved scenario development tools. It has been over a decade since the last emissions scenario development project of the Intergovernmental Panel on Climate Change (IPCC) – its *Special Report on Emissions Scenarios* (SRES) – and over five years since the subsequent CO_2 stabilization scenarios in the IPCC's Third Assessment Report. Over this time, substantial advances have been made in both economic and natural science components of the IAMs used to simulate the various scenarios. A second advance of this research is its all-gas approach. Many other stabilization scenarios have focused on CO_2 with little attention to other human influences. The scenarios presented here consider stabilization in terms of the combined effect of all six categories of GHGs listed earlier so that the full range of policy options is considered simultaneously. Finally, there is great advantage in the simultaneous application to the task, and parallel presentation of results, by three independent modeling groups, applying IAMs each of which has its own special strengths. Comparison of scenarios across the models provides useful insights into the role of key assumptions, the realms of most fruitful technology development, and aspects of the natural science (particularly the carbon cycle) that have a substantial effect on the difficulty of the stabilization task.

SCENARIO HIGHLIGHTS

The report and supporting database provide many details of the implications for the U.S. and global economy, with particular focus on the energy sector, for the reference conditions and the four levels of possible atmospheric stabilization. Highlights of the picture that is found there include the following:

In the reference scenarios, economic and energy growth, combined with continued fossil fuel use, lead to changes in the Earth's radiation balance that are three to four times that already experienced since the beginning of the industrial age. By 2100, primary energy consumption increases from over 3 to nearly 4 times 2000 levels as economic growth outpaces improvements in the efficiency of energy use. Non-fossil energy use grows from over 4 to almost 9 times over the century, but this growth is insufficient to supplant fossil fuels as the major source of energy. As a result, global CO_2 emissions more than triple between 2000 and 2100, and emissions are rising at the end of the twenty-first century in all three reference scenarios. Combined with the effects of non-CO_2 GHGs, the increase in anthropogenic radiative forcing from preindustrial levels is substantial.

In the stabilization scenarios, CO_2 emissions peak and decline during the twenty-first century or soon thereafter. Emissions of non-CO_2 GHGs are also reduced. The timing of GHG emissions reductions varies substantially across the four radiative forcing stabilization levels. Under the most stringent stabilization levels, CO_2 emissions begin to decline immediately or within a matter of decades. Under the less stringent stabilization levels, CO_2 emissions do not peak until late in the century or beyond, and they are 1½ to over 2½ times today's levels in 2100.

In the stabilization scenarios, GHG emissions reductions require a transformation of the global energy system, including reductions in the demand for energy (relative to the reference scenarios) and changes in the mix of energy technologies and fuels. This transformation is more substantial and takes place more quickly at the more stringent stabilization levels. Fossil fuel use and energy consumption are reduced in all the stabilization scenarios due to increased

consumer prices for fossil fuels. Use of shale oil, tar sands, and synthetic fuels from coal are greatly reduced or, under the most stringent stabilization levels, eliminated. Across the stabilization scenarios, CO_2 emissions from electric power generation are reduced at relatively lower prices than CO_2 emissions from other sectors, such as transport, industry, and buildings. Emissions are reduced from electric power by increased use of technologies such as CO_2 capture and storage, nuclear energy, and renewable energy. Other sectors respond to rising GHG prices by reducing demands for fossil fuels; substituting low- or non-emitting energy sources such as bioenergy and low-carbon electricity or hydrogen; and applying CO_2 capture and storage where possible.

Substantial differences in GHG emissions prices and associated economic costs arise among the modeling groups for each stabilization level. These differences are illustrative of some of the unavoidable uncertainties in long-term scenarios. Among the most important factors influencing the variation in economic costs are: (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 that 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. All other things being equal, scenarios with more low-cost technology options and lower required emissions reductions have lower economic costs.

FOLLOW-ON EFFORTS

Generating scenarios is not a once-and-for-all activity. The scenarios in this report represent but one step in a long process of research and assessment, continuing an over 20-year tradition of research and analysis in the climate area. They will need to be updated as knowledge advances and conditions change. Indeed, the research presented here suggests several areas of potentially fruitful research:

- Analysis of the sensitivity of results to assumptions about the cost, performance and environmental issues surrounding key technologies such as nuclear power, carbon capture and storage, and biofuels.
- Consideration of scenarios based on different assumptions than used here about the way that the burdens of emissions mitigation may be shared among nations and over time.
- Expansion and improvement of analysis of human land use and the terrestrial carbon cycle.
- Inclusion of other anthropogenic emissions that affect the Earth's heat balance, such as the different types of aerosols, and the effect of the tropospheric ozone (another GHG) that results from urban air pollution.
- Addition of uncertainty analysis and consideration of decision-making under these conditions.