5. CCSP EMISSIONS SCENARIOS: SCENARIOS, FINDINGS, USES, AND FUTURE DIRECTIONS

5.1. Introduction

Emissions scenarios that describe future economic growth and energy use have been important tools for understanding the long-term implications for climate change. Such scenarios have been part of U.S. and international assessments of climate change that date back at least to the early 1980s. The process traces its roots back through numerous other efforts, among others, efforts undertaken by the National Academy of Science, the IPCC, the CCTP, and non-governmental forums such as the Energy Modeling Forum.

Scenarios based on formal, computer-based models, such as those used in this exercise, can help to illustrate how key drivers such as economic and population growth or policy options lead to particular levels of greenhouse gas (GHG) emissions. A main benefit of using models such as these to simulate future scenarios is that they ensure basic accounting identities and consistent application of behavioral assumptions. However, model simulation is only one approach to scenario development, and models designed for one set of purposes are not the most appropriate tools for other purposes. The scenarios developed here should thus be viewed as complementary to other ways of thinking about the future: e.g., formal uncertainty analyses, verbal story lines, baselines for further simulation, and analyses using other types of models. The scenarios developed here must also be seen as building on and contributing to past and ongoing scenario development work occurring elsewhere in the world and by other modeling groups.

The possible 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, farms, and members of the public. Such a diverse set of possible users implies an equally diverse set of possible needs from scenarios. No single scenario exercise can hope to satisfy all needs. Scenario analysis is most effective when scenario-developers can work directly with users, and initial scenarios lead to further "what if" questions that can be answered with additional simulations or by probing more deeply into particular issues.

However, the Prospectus does not prescribe such an interactive approach with a focused set of users. Instead, it focuses on creating a set of scenarios providing broad insights into the energy, economic, and emissions implications of stabilization of GHGs. 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. The outcome might be further scenario development from models like those used here but as likely will involve other modeling and analysis techniques.

This exercise focuses on a reference case and four stabilization levels to provide decision-makers the technical and economic implications of different levels of future GHG stabilization. What is described, then, is a range of possible long-term targets for global climate policy. The stabilization levels require a range of policy efforts and urgencies, from relatively little deviation from reference scenarios in this century to major deviations from reference scenarios starting very soon. Although the Prospectus did not mandate a formal treatment of likelihood or uncertainty, formal uncertainty analysis could be a useful follow-on or complementary exercise. Here, however, the range of outcomes from the different modeling teams helps to illustrate, if incompletely, the range of possibilities.

For this exercise, 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 the correct "prediction" of the future; none could be said to have the highest probability of being right. Nor is any single stabilization scenario the most correct "prediction" of the changes to energy and other systems that would be required for stabilization. Indeed, each scenario in this report is a "thought experiment" that helps illuminate the implications of different long-term policy goals. The reference scenarios assume no alteration in the policy path to 2100, no matter what happens to the climate along the way; the stabilization scenarios assume full global participation in addressing climate change beginning by 2012.

5.2. Summary of Scenario Results

The results of the scenario construction 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.

5.2.1. Reference Scenarios

The difficulty in achieving any specified level of atmospheric stabilization depends heavily on the emissions that would occur otherwise: i.e., the "no-climate-policy" reference strongly influences the stabilization cases. If a no-policy world has cheap fossil fuels and high economic growth, then dramatic 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 case shows lower growth and emissions, and perhaps increased exploitation of non-fossil sources even in the absence of climate policy, then the effort 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 net emissions. Demand for energy over the coming century will be driven by economic growth but will also be strongly influenced by the way that energy systems respond to depletion of resources, changes in prices, and technology advance. The projected demand for energy in developed countries remains strong in all scenarios but is even stronger in developing countries, where millions of people seek greater access to commercial energy. These developments determine the emissions of GHGs, their disposition, and the resulting change in radiative forcing under reference conditions.

The three reference scenarios show the implications of this increasing demand and the improved access to energy, with the ranges reflecting the variation in results from the different models:

- *Global primary energy production rises substantially in all three reference scenarios, from about 400 EJ/y in 2000 to between 1300 and 1550 EJ/y in 2100. U.S. primary energy production also grows substantially, about 1½ to 2½ times present levels by 2100. This growth occurs despite continued improvements in the efficiency of energy use and production. For example, the U.S. energy intensity declines 50 to 70% between 2000 and 2100.*

- *All three reference scenarios include a gradual reduction in the dependence on conventional oil resources. However, in all three reference scenarios, a range of alternative fossil-based resources, such as synthetic fuels from coal and unconventional oil resources (e.g., tar sands, oil shales) are available and become economically viable. Fossil fuels provided almost 90% of global energy supply in the year 2000, and they remain the dominant energy source in the three reference scenarios throughout the twenty-first century, supplying between 60 and 80% of total primary energy in 2100.*

- *Non-fossil fuel energy use grows over the century in all three reference scenarios. The range of contributions in 2100 is from 250 EJ to 600 EJ—between roughly half to a level equivalent to total global energy consumption today. Even with this growth, however, 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, global and U.S. electricity production shows continued reliance on coal although this contribution varies* *among the reference scenarios. The contribution of renewables and nuclear energy varies considerably in the different reference cases, depending on resource availability, technology, and non-climate policy considerations. For example, global nuclear generation range from an increase over current levels of around 50%, if political considerations constrain its growth, to an expansion by more than an order of magnitude, assuming economically driven growth.*

- *Oil and natural gas prices are projected to rise through the century relative to year 2000 levels, whereas coal and electricity prices remain relatively stable. The models used in the exercise were not designed to project short-term fuel price spikes, such as those that occurred in the 1970s and early 1980s, and more recently in 2005. Thus, the projected price trends should be interpreted as long-term average price trends.*

- *As a combined result of all these influences, emissions of* CO_2 *from fossil fuel combustion and industrial processes increase from approximately 7 GtC/y in 2000 to between 22 and 24 GtC/y in 2100; that is, anywhere from three to three and one-half times current levels.*

The non-CO_2 greenhouse gases—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:

- *Projected future global anthropogenic emissions of* CH_4 *and* N_2O *vary widely among the reference scenarios, ranging from flat or declining emissions to an increase of 2 to 2½ times present levels. These differences reflect alternative views of technological opportunities and different assumptions about whether current emissions rates will be reduced significantly for other 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.*

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

- *The ocean is a major sink for* CO_2 *that generally increases 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. The scenarios have ocean uptake in the range of 2-3 GtC/y in 2000, rising to about 5-8 GtC/y by 2100.*

- *Two of the three models include a sub-model of the exchange of* CO_2 *with the terrestrial biosphere, including the net uptake by plants and soils and the emissions from deforestation, which is modeled as a small annual net sink (less than 1 Gt of carbon) in 2000, increasing to an annual net sink of 2 to 3 GtC/y by the end of the century. The third model assumes a zero net exchange. In part, modeled changes reflect human activity (including a decline in deforestation),* *and, in part, it is the result of increased uptake by vegetation largely due to the positive effect of CO_2 on plant growth. The range of estimates is an indication of the substantial uncertainty about this carbon fertilization effect and land-use change and their evolution under a changing climate.*

- *GHG concentrations are projected to rise substantially over the century under reference scenarios. By 2100, CO_2 concentrations range from about 700 to 900 ppmv, up from 370 ppmv in 2000. Projected CH_4 concentrations range from 2000 to 4000 ppbv, up from 1750 ppb in 2000; projected N_2O concentrations range from about 375 to 500 ppbv, up from 317 ppbv in 2000.*

- *The resultant increase in radiative forcing ranges from 6.5 to 8.5 W/m^2 relative to preindustrial levels (zero by definition) and compares to approximately 2 W/m^2 in the year 2000, with non-CO_2 GHGs accounting for about 20 to 30% of this at the end of the century.*

5.2.2. Stabilization Scenarios

Important assumptions underlying the stabilization cases involve the flexibility that exists in a policy design, and as represented in the model simulation, to seek out least cost abatement options regardless of where they occur, what substances are abated, or when they occur. It is a set of conditions 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 special circumstances lead to least cost abatement. Each model applied an economic instrument that priced GHGs in a manner consistent with their interpretation of “where,” “what” and “when” flexibility. The economic results 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, (2) the marginal cost of abatement rises over time reflecting different interpretations and approaches among the modeling teams of “when” flexibility, and (3) the radiative forcing targets were achieved by combining control of all greenhouse gases – with differences, again, in how modeling teams compared them and assessed the implications of “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 these results to be a realistic estimate of costs would require, among other things, the assumption that a negotiated international agreement include these features. Failure in that regard would have a substantial effect on the difficulty of achieving any of the targets studied. For example, a delay of many years in the participation of some large countries would require a much greater effort by the others, and policies that impose differential burdens on different sectors can result in a many-fold increase in the cost of any environmental gain. Therefore, it is important to view these result as scenarios 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 on given interactions with existing taxes, technology spillovers, or other non-market externalities.

If the developments projected in these reference scenarios were to occur, concerted efforts to reduce GHG emissions would be required to meet the stabilization targets analyzed here. 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 are modeled in this exercise. Nevertheless, some general conclusions are possible.

- *Stabilization efforts are made more challenging by the fact that in two of the modeling teams' formulations, both terrestrial and ocean CO_2 uptake decline as the stringency of emissions mitigation increases.*

- *Stabilization of radiative forcing at the levels examined in this study will require a substantially different energy system globally, and in the U.S., than what emerges in the reference scenarios in the absence of climate change considerations. The degree and timing of change in the global energy system depends on the level at which radiative forcing is stabilized.*

- *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. Importantly, end-use energy consumption is lower. Carbon dioxide capture and storage is widely deployed because each model assumes that the technology can be successfully developed and that concerns about storing large amounts of carbon do not impede its deployment. Removal of this assumption would make the stabilization levels much more difficult to achieve and, if not restrained for reasons of safety and proliferation concerns, a much greater demand for nuclear power.*

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

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

- *Increased use is made of biomass energy crops whose contribution is ultimately limited by competition with agriculture and forestry. One model examined the importance of valuing terrestrial carbon similarly to the way fossil fuel carbon is valued in stabilization scenarios. It found that in stabilization scenarios important interactions between large-scale deployment of commercial bioenergy* *crops and land use occurred to the detriment of unmanaged ecosystems when no economic value was placed terrestrial carbon.*

- *The lower the radiative forcing limit, 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. The bulk of emissions reductions take place in the second half of the century in all the stabilization scenarios. But near-term emissions reductions occurred in all models in all stabilization scenarios.*

- *The 2100 time horizon of the study limited examination of the ultimate requirements of stabilization. However, it is the case that atmospheric stabilization at any of the levels studied requires human emissions of* CO_2 *in the very long run to be essentially halted altogether because, as the ocean and terrestrial biosphere approach equilibrium with the target concentration level, their rate of uptake falls toward zero. Only capture and storage of* CO_2 *could allow continued burning of fossil fuels. Higher radiative forcing limits can delay this requirement beyond the year 2100 horizon, but further reductions after 2100 would be required in any of the cases studied here.*

Fuel sources and electricity generation technologies change substantially, both globally and in the U.S., under 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, renewable energy forms, and carbon dioxide capture and storage all play important roles in stabilization scenarios. The contribution of each can vary, depending on assumptions about technological improvements, the ability to overcome obstacles such as intermittency, and the policy environment surrounding them, for example, the acceptability of nuclear power.*

- *By the end of the century, electricity produced by conventional fossil technology, where* CO_2 *from the combustion process is emitted freely, is reduced from the reference scenarios in the stabilization scenarios. The level of production from these sources varies substantially with the stabilization level; in the lowest stabilization level, production from these sources is reduced toward zero.*

The economic effects of stabilization could be substantial although much of this cost is borne later in the century if the mitigation paths assumed in these scenarios are followed. As noted earlier, each of the modeling teams assumed that a global policy was implemented beginning after 2012, with universal participation by the world's nations, and that the time path of reductions approximated a "cost-effective" solution. These assumptions of “where” and “when” flexibility lower the economic consequences of stabilization relative to what they might be with other implementation approaches:

- *Across the stabilization scenarios, the carbon price follows a pattern that, in most cases, gradually rises over time, providing an opportunity for the energy system to change gradually. Two of the models show prices $10 or below per ton of carbon at the outset for the less stringent cases, with their prices rising to $100 per ton in 2020 for the 450 ppmv case. IGSM shows higher initial carbon prices in 2020, ranging from around $20 for 750 ppmv to over $250 for the 450 ppmv target.*

- *While the general shape of the carbon value trajectory is similar across the models, the specific carbon prices required vary substantially for reasons that reflect the underlying uncertainty about the effort that would be required. Differences among the reference cases has the main effect to mid-century while differences among models in assumptions about the cost and performance of future technologies have the greatest effect in subsequent decades. Other differences modeling approach also contribute to the inter-model variation.*

- *Non-CO_2 gases play an important role in shaping the degree of change in the energy system. Scenarios that assume relatively better performance of non-CO_2 emissions mitigating technologies require less stringent changes in the energy system to meet the same radiative forcing goal.*

- *These differences in carbon prices and other model features lead to a wide range of the cost of the various stabilization targets. For example, for the 450-ppmv scenario estimates of the reduction in Gross World Product (aggregating country figures using market exchange rates) in mid-century from around 1% in two of the models to approximately 5% in the third, and in 2100 from less than 2% in two of the models to over 16% in the third. This difference among models is a product of the variation in model structure and reference case assumptions noted earlier. At mid-century the difference in projected cost is mainly attributable to variation in the reference scenario, whereas late in the century the model estimates depart primarily because of differences in assumptions about technology change. As noted earlier, the overall cost levels are strongly influenced by the burden-sharing conditions that all models imposed, the assumption of “where” flexibility, and an efficient pattern of increasing stringency over time. Any variation in assumptions regarding these conditions would lead to higher cost. Also, the use of exchange rates based on purchasing power parity could lead to different global results. Thus, these scenarios should not be interpreted as applying beyond the particular conditions assumed.*

- *Such carbon constraints would also affect fuel prices. Generally, the producer price for fossil fuels falls as demand for them is depressed by the stabilization measures. Users of fossil fuels pay for the fuel plus a carbon price if the CO_2*

emissions were freely released to the atmosphere, so consumer costs of energy rise with more stringent stabilization targets.

Achieving stabilization of atmospheric GHGs poses a substantial technological and policy challenge for the world. It would require important transformations of the global energy system. Assessments of the cost and feasibility of such a goal depends importantly on judgments about how technology will evolve to overcome existing limits and barriers to adoption and on the efficiency and effectiveness of the policy instruments for achieving stabilization. These scenarios provide a means to gain insights into the challenge of stabilization and the implications of technology.

5.3. Application of the Scenarios In Further Analysis

These scenarios, supported by the accompanying database[1], can be used as the basis of further analysis of these stabilization cases and the underlying reference scenario. There are a variety of possible applications. For example, the scenarios could be used as the basis for analysis of the climate implications. Such studies might begin with the radiative forcing levels of each, with the individual gas 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 be made to approximate the emissions (or concentrations) of the reflecting and absorbing aerosols. This could be done by the use of sub-models linked to the energy use by fuel calculated in each of the models applied here.

The scenarios could also be used as a jumping off point for partial equilibrium analysis of technology penetration. Because these models compute the prices of fossil fuels under the various scenarios, the results can be used for analysis of the target cost performance of new technologies and to serve as a basis for analysis of rates of market penetration. Differences in results between the three models 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 study, but information is provided that could form a basis for such analysis, e.g., the potential effects on the U.S. and the globe of implied volumes of CCS and biomass production, or of nuclear expansion that results in some of the scenarios.

Of course, the scenarios can also be used in comparative mode. That is, just as many lessons were learned by comparing the differences between the three modeling teams' scenarios, still more could be learned by extending the comparison to scenarios that pre-date these or come after, including scenarios developed using entirely different

---

[1] This data archive will be made available upon completion of the final draft of this report.

approaches. Some scenario exercises do not apply an economic model with detailed analysis of energy markets of the type used here. Rather, they build up estimates from engineering descriptions of particular technologies and assumptions about low- or no-cost emissions reductions that result from market failures of one kind or another. These scenarios provide descriptions of energy-market behavior and, in particular, of energy prices that can be used as a structure for assessing and calibrating scenarios developed by other means.

Finally, we could imagine the scenarios being used to analyze of the welfare effects of the different stabilization targets. Such work was beyond the scope of the analysis specified in the Prospectus. However, the results do contain information that can be used to calculate indicators of consumer impact in the U.S., e.g., by using the changes in prices and quantities of fuels in moving from one stabilization level to another.

5.4. Moving Forward

As noted earlier, this work is neither the first nor the last of its kind. Throughout the report, a number of limitations to the approach and the participating models have been highlighted. All would benefit from further research and model development and this section suggests some of the more productive paths to pursue.

5.4.1. Technology Sensitivity Analysis

The importance of future technology development is clear in this report, and sensitivity testing of key assumptions. For example, what if, in the model that constrained nuclear because of policy considerations, nuclear were allowed to penetrate solely on economic grounds? What were the various cost assumptions underlying different technologies, and, implicitly, if nuclear, wind, natural gas combined cycle generation, biomass were somewhat more or less expensive, how would that affect penetration or policy cost? If costs of these technologies were different, would that affect the conclusion that fossil fuels remained very dominant in the reference? Interest was also expressed in creating conditions wherein the behavior of the three models could be compared under more controlled circumstances. What if they each made the same assumptions about population and GDP growth—would the results be very similar or very different?

5.4.2. Consideration of Less Optimistic Policy Regimes

The discussion above emphasizes that the estimate of the difficulty of the stabilization task 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 here, is limited. This question, seemingly an obvious one to answer, depends critically on how the economic burden of emissions reduction is shared among countries. If the U.S. and other developed countries take disproportionate emissions cuts then, even with a cost-effective instrument like emissions trading, the cost will be very high in the U.S. because we will purchase emissions allowances from elsewhere in the world.

The results also depend importantly on international trade and changes in the terms of trade, and so some allocations of allowances can lead to the U.S. benefiting from the policy. Not so surprisingly, a carbon policy would suppress energy use around the world and that means that the world price of oil would fall. The result is that carbon policy can be an instrument by which the world appetite for oil is held back and, as a result, the U.S. would gain substantially by being able to import oil at much less cost than it otherwise would. In some cases, this gain can be greater than the direct cost of the emissions reductions in the U.S. Of course, this result depends on other countries actually reducing emissions, which is an assumption that calls into question the simple case we have constructed in which all countries join and act together in 2015.

Equally important, the highly stylized policy—with a broad cap and trade system with international flexibility, and approximated or applied with “when” flexibility—represents no policy that has actually been proposed by any legislature that has seriously taken up the issue of GHG mitigation. Some sectors are inevitably exempted, others enter through a cumbersome crediting system, and still other policies, such as renewable portfolio standards for electricity or higher fuel efficiency standards for automobiles, are inevitably part of the policy mix. Some of this mix of policy or exemptions may make sense, correcting other problems in the economy or reflecting the fact that measuring and monitoring very small sources of emissions may involve great cost per unit of reduction likely in those sectors. Thus, realistic estimates of costs for the U.S. need to address these realistic aspects of the formulation of real policies, and would require multiple scenarios to illustrate clearly why one approach looked inexpensive and another expensive. The simple policy architecture assumed here, with U.S. costs dependent as they are on the allocation of burden among regions, leads to cost estimates that by themselves are likely to be misleading rather than helpful.

5.4.3. Expansion/Improvement of the Land Use Components of the Models

A significant weakness in this analysis 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. Even more so than for energy, the idea of a broad cap and trade system applied to agriculture and forest sinks seems particularly unrealistic because no legislation anywhere has proposed such a system. Instead, incentives for agriculture and forest sinks have been proposed as a crediting system or through more traditional agriculture and forestry programs. The efficacy and effectiveness of such policies and the potential contribution from forestry and agriculture deserve greater attention than was possible here.

5.4.4. Inclusion of other Radiatively-Important Substances

There are obviously a number of cautions and limitations to any scenario analysis. In this case, the focus has been on the relatively long-lived GHGs. Tropospheric ozone and aerosols also have strong climatic effects, but inclusion of these substances was beyond the scope of the scenarios specified for this study.

5.4.5. 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 and how a policy might reduce the odds of extremely bad outcomes. One would like to compare the expected benefits of a policy against the expected cost of achieving that reduction. By focusing only on emission paths that would lead to stabilization, we are able to report the costs of achieving that goal without an assessment of the benefits. Moreover, given the direction provided in the Prospectus, the focus was on scenarios and not an 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. The task is an important one, but beyond the scope of the study carried out here.