CCSP Synthesis and Assessment Product 2.1, Part A: Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations

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ES. EXECUTIVE SUMMARY: SCENARIOS OF GREENHOUSE GAS EMISSIONS AND ATMOSPHERIC CONCENTRATIONS: CCSP PRODUCT 2.1 A

ES.1. Background

The *Strategic Plan for the U.S. Climate Change Science Program* (CCSP 2003) noted that “sound, comprehensive emissions scenarios are essential for comparative analysis of how climate might change in the future, as well as for analyses of mitigation and adaptation options.” The *Plan* included Product 2.1, which consists of two parts: *Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations* and *Review of Integrated Scenario Development and Application*. This report presents the results from the scenario development component; the review of scenario methods is the subject of a separate report. Guidelines for producing these scenarios were set forth in a Prospectus (CCSP 2005), which specified that the new scenarios focus on alternative levels of atmospheric stabilization of the radiative forcing from the combined effects of a suite of the main anthropogenic greenhouse gases (GHGs). The Prospectus also set forth criteria for the analytical facilities to be used in the analysis, and the results from three models that met these conditions, and that were used to develop the new scenarios, are reported here.

Scenarios such as those developed here serve as one of many inputs to public and private discussions regarding the threat of climate change and what to do about it. The goal of this report is to contribute to the ongoing and iterative process of developing improved scenarios to serve as inputs for decision making and analysis. The intended audience includes decision-makers, analysts, and members of the public who may be concerned with the energy system and economic effects of policies leading to stabilization. For example, these scenarios may provide a point of departure for further studies of mitigation and adaptation options, or enhance the capability for studies by the U.S. Climate Change Technology Program (CCTP) of alternative patterns of technology development.

Each of the three participating analytical models was used to develop a “no climate policy” or reference scenario to serve as baseline for comparing the scenarios with emissions control, and then each model was applied to an exploration of emissions pathways that led to stabilization of radiative forcing at four alternative levels. Results of these calculations were selected to provide insight into questions such as the following:

- *Emissions trajectories*. What emissions trajectories over time are consistent with meeting the four stabilization levels? What are the key factors that shape the emissions trajectories that lead toward stabilization?

- *Energy systems*. What energy system characteristics are consistent with each of the four stabilization levels? How might these characteristics differ among stabilization levels?

- *Economic implications*. What are the possible economic implications of meeting each of the four stabilization levels?

Although each of the models simulates the world as a set of interconnected nations and multi-nation regions, as specified in the Prospectus, the results in this report focus on the U.S. and world totals.

With the exception of the stabilization targets themselves and a common hypothesis about international burden-sharing, there was no direct coordination among the modeling groups either in the assumptions underlying the no-policy reference or the precise path to stabilization. Furthermore, the scenarios were not designed to span the full range of possible futures and no explicit uncertainty analysis was called for. Nonetheless, the results among the three models do vary, a reflection of the unavoidable uncertainty that attends projections many decades into the future.

This report should in no way be perceived as a cost benefit analysis of climate policy. The focus is exclusively on the nature and costs of the mitigation required to meet various stabilization levels. No attempt has been made to assess the damages avoided by adopting a particular stabilization level or ancillary benefits that may be realized (e.g., in air pollution reduction). Although the information contained in the report should provide a useful input to policy deliberations, it provides an incomplete guide to decisions on particular policy measures.

A scenario exercise such as this continues a tradition of research and analysis that has gone on for over 20 years. This work will necessarily be continued and refined as the field advances, new information becomes available, and decision-makers raise new questions and issues. Similar work is being conducted by modeling teams in Europe and Asia. The new scenarios developed here add to this larger body of scholarship and should be viewed as one additional piece of information in an ongoing and iterative process of scenario development.

ES.2. Models Used in the Scenario Exercise

The Prospectus set out the following criteria for participating models: they must (1) be global in scale, (2) be capable of producing global emissions totals for designated GHGs, (3) represent multiple regions, (4) be capable of simulating the radiative forcing from these GHGs and substances, (5) have technological resolution capable of distinguishing among major sources of primary energy (e.g., renewable energy, nuclear energy, biomass, oil, coal, and natural gas) as well as between fossil fuel technologies with and without carbon capture and storage systems, (6) be economics-based and capable of simulating macroeconomic cost implications of stabilization, and (7) look forward at least to the end of the twenty-first century. In addition, modeling teams were required to have a track record of publications in professional, refereed journals, specifically in the use of their models for the analysis of long-term GHG emission scenarios.

Application of these criteria led to the selection of three models:

- The Integrated Global Systems Model (IGSM) of the Massachusetts Institute of Technology's Joint Program on the Science and Policy of Global Change
- The MiniCAM Model of the Joint Global Change Research Institute, which is a partnership between the Pacific Northwest National Laboratory and the University of Maryland
- 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.

Each of these models has been used extensively for climate change analysis. The roots of each extend back more than a decade, during which time features and details have been refined, modified and added. Results of each have appeared widely in peer-reviewed publications.

ES.3. Approach

As directed by the Prospectus, a total of 15 separate scenarios were developed, 5 from each of the three modeling teams. First, reference scenarios were developed on the assumption that no climate policy would be implemented beyond the set of policies currently in place (e.g., the Kyoto Protocol and the U.S. carbon intensity target, each terminating in 2012 because targets beyond that date have not been identified). Each modeling team developed its own reference scenario. The Prospectus required only that each scenario be based on assumptions believed by the participating modeling teams to be "meaningful" and "plausible." Each of the three reference scenarios provided a different view of how the future might unfold without additional climate policies.

Each team then produced four stabilization scenarios by constraining the models to achieve four alternative radiative forcing targets. Stabilization was defined in terms of the total long-term radiative impact of a suite of GHGs including carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), hydrofluorocarbons (HFCs), perfluorocarbons

(PFCs), and sulfur hexafluoride (SF_6). These are the gases enumerated in the U.S. goal to reduce the intensity of GHG emissions relative to GDP as well as the Kyoto Protocol. Other substances with radiative impact, such as the gases controlled under the Montreal Protocol, carbon monoxide (CO), ozone (O_3), and aerosols were not included in the scenario design.

The four stabilization scenarios were developed so that the increased radiative forcing from these gases was constrained to no more than 3.4 W/m^2 for Level 1, 4.7 W/m^2 for Level 2, 5.8 W/m^2 for Level 3, and 6.7 W/m^2 for Level 4. These levels were defined as increases above the preindustrial level, so they include the roughly 2.2 W/m^2 increase that had already occurred as of the year 2000. See Table ES.1.

Table ES.1: Greenhouse gas concentrations & forcing. The change in concentration levels for the gases of interest from 1750 to the present and the estimated increase in radiative forcing.

	Preindustrial Concentration (1750)	Current Concentration (2000)	Increased Forcing W/m^2 (1750-2000)
CO2	280 ppmv	369 ppmv	1.52
CH4	700 ppbv	1760 ppbv	0.517
N2O	270 ppbv	316 ppbv	0.153
HFCs	0	various	0.005
PFCs	0	various	0.014
SF6	0	4 ppt	0.0025
Total	--	--	2.21

To facilitate comparison with previous work focused primarily on CO_2 stabilization, these levels were chosen so that the associated CO_2 concentrations, accounting for radiative forcing from the non-CO_2 GHGs, would be roughly 450 ppmv, 550 ppmv, 650 ppmv, and 750 ppmv. See Table ES.2.

Table ES.2: Radiative Forcing Stabilization Levels (Wm^{-2}) and Approximate CO_2 Concentrations (ppmv). The stabilization levels were constructed so that the CO_2 concentrations resulting from stabilization of total radiative forcing, after accounting for radiative forcing from the non-CO_2 GHGs, would be roughly 450 ppmv, 550 ppmv, 650 ppmv, and 750 ppmv.

	(1) W/m^2 from Preindustrial (1750)	(2) W/m^2 from 2000 Levels	(3) Approximate long-term CO_2 Level (ppmv)	(4) Increase in CO_2 from Preindustrial (ppmv)	(5) Increase in CO_2 from 2000 Levels (ppmv)
Level 1	3.4	1.2	450	172	81
Level 2	4.7	2.5	550	272	181
Level 3	5.8	3.5	650	372	281
Level 4	6.7	4.5	750	472	381

ES.4. Results

Findings are summarized first for the no climate policy or reference scenarios, and then for the twelve stabilization scenarios, one from each model for the four stabilization levels.

ES.4.1. Reference Scenarios

The difficulty in achieving any specified level of atmospheric stabilization depends heavily on the emissions that would occur absent actions to address greenhouse gas emissions. In other words, the reference strongly influences the stabilization cases. If the reference case 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 improvements in technology. 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 strongly influence 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. Figures ES.1-4 summarize the results for primary energy production both globally and for the U.S. Results are presented for the entire energy sector as well as for the electric sector. Although the electric sector is but one of the major sources of GHG emissions, it is highlighted here because it may offer an increasing part of the solution for meeting a particular stabilization target over the long-term.

Insert Figure ES.1-4 as four separate pages

Global primary energy production rises substantially in all three reference scenarios, from about 400 EJ/y in 2000 to between roughly 1275 and 1500 EJ/y in 2100. U.S. primary energy production also grows substantially, about 1¼ 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 60% to 75% between 2000 and 2100 across the three reference scenarios.

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 provide 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 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 in 2100 range from 250 EJ to 450 EJ—between roughly half to one and one half times total global 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, 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 in the reference scenarios ranges from an increase of around 50% over current levels, if political considerations constrain its growth as is the case in one reference scenario, to an expansion of almost an order of magnitude assuming economically driven growth otherwise unconstrained.

In the reference case, oil and natural gas prices rise through the century relative to year 2000 levels whereas coal and electricity prices are projected to remain relatively stable. It should be emphasized, however, that 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 multi-year averages.

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 22.5 and 24 GtC/y in 2100; that is, from three to three and one-half times current levels. See Figure ES.5.

Insert Figure ES.5.

It is instructive to see how emissions are divided between industrialized countries (Annex 1) and developing countries (Non-Annex1). Figure ES.6 shows that developing country emissions overtake those of developed countries somewhere in the 2020 to 2030 timeframe in the reference scenarios. This suggests the difficulty of stabilizing radiative forcing without developing country participation. Indeed, even if developed countries were to reduce their emissions to zero, global involvement will still be necessary for stabilization.

Insert Figure ES.6.

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 GtC/y in 2000, rising to about 5 to 11 GtC/y by 2100. The three ocean models behave more similarly in the stabilization scenarios.

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. There remains substantial uncertainty about this carbon fertilization effect and land-use change and their evolution under a changing climate.

Although this Executive Summary tends to focus on the most important anthropogenic greenhouse gas, CO_2, the models include a number of other greenhouse gases—CH_4 , N_2O SF_6, PFCs, and HFCs—which 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 views of technological opportunities and different assumptions 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 concentrations and radiative forcing. This increase is moderated by natural biogeochemical removal processes. As a result, GHG concentrations rise substantially over the century in the reference scenarios. By 2100, CO_2 concentrations range from about 700 to 900 ppmv, up from 370 ppm 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 about 320 ppbv in 2000.

As a result, radiative forcing in 2100 ranges from 6.4 to 8.6 W/m^2 relative to preindustrial levels. The non-CO_2 GHGs account for about 20 to 25% of the forcing at the end of the century. See Figure ES.7.

Insert Figure ES. 7.

ES.4.2. Stabilization Scenarios

Important assumptions underlying the stabilization scenarios include 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 ("where" flexibility), (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 the resulting abatement costs to be realistic estimates of actual abatement costs would require, among other things, 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 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 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 as reflected in the discussion below.

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. The degree and timing of change in the global energy system depends on the level at which radiative forcing is stabilized. See Figures ES.8 and ES.9.

Insert Figures ES.8 and ES.9.

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 models differ in the degree to which these technologies are deployed. 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 more difficult to achieve and would lead to greater demand for low-carbon sources such as renewable energy and, if not restrained for reasons of safety and proliferation concerns, 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.

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 on terrestrial carbon.

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. See Figure ES.10.

Insert Figure ES.10.

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 emissions reductions occurred in all models in the first half of the century in every stabilization scenario.

The 2100 time horizon of the study limited examination of the ultimate requirements of stabilization. However, 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, despite the fact that much of the carbon emissions will eventually find its way into oceans and terrestrial sinks, some will remain in the atmosphere for thousands of years. 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. See Figures ES.11 and ES.12.

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 that freely emits CO_2 is reduced in the stabilization scenarios relative to reference scenario levels. 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 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:

Table ES.3: Carbon Prices at various Points in Time for the Stabilization Scenarios

	2020 ($/tonne C)			2030 ($/tonne C)		
Stabilization Level	IGSM	MERGE	MiniCAM	IGSM	MERGE	MiniCAM
Level 4	$18	$1	$1	$26	$2	$2
Level 3	$30	$2	$4	$44	$4	$7
Level 2	$75	$8	$15	$112	$13	$26
Level 1	$259	$110	$93	$384	$191	$170

	2050 ($/tonne C)			2100 ($/tonne C)		
Stabilization Level	IGSM	MERGE	MiniCAM	IGSM	MERGE	MiniCAM
Level 4	$58	$6	$5	$415	$67	$54
Level 3	$97	$11	$19	$686	$127	$221
Level 2	$245	$36	$69	$1,743	$466	$420
Level 1	$842	$574	$466	$6,053	$609	$635

Across the stabilization scenarios, the carbon price follows a pattern that, in most cases, gradually rises over time as shown in Table ES.3., providing an opportunity for the energy system to change gradually. Two of the models show prices of $10 or below per ton of carbon in 2020 for the less stringent cases, with their prices rising to roughly $100 per ton in 2020 for the most stringent stabilization level. A third model 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.

Although 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 in cumulative emissions over the century and models in assumptions about the cost and performance of future technologies, especially in the second half of the century, are major contributors to these differences. Other aspects of the modeling approaches also contribute to the inter-model variation.

These differences in carbon prices and other model features lead to a wide range of the cost of the various stabilization targets. For example, in the most stringent scenarios, estimates of the reduction in Gross World Product (aggregating country figures using market exchange rates) in mid-century range from around 2% in two of the models to approximately 5% in the third, and in 2100 from less than 2% in two of the models to 16% in the third. This difference among models is a product of the variation in model structure, technology assumptions, and reference case assumptions noted earlier. This discussion is reflected in Figure ES.13 which shows the relationship between carbon price and abatement for the three models in 2050 and 2100 for the various stabilization levels.

Insert Figure ES.13.

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 increasing stringency over time, and integrated reductions in emissions of the different GHGs. Less efficient assumptions regarding these conditions would lead to higher cost. 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, on the other hand, 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.

Table ES.4. Relationship Between a $100/ton Carbon Tax and Fuel Prices

Fuel	Base Cost ($2005)	Added Cost ($)	Added Cost (%)
Crude Oil ($/bbl)	$60.0	$12.2	20%
Regular Gasoline ($/gal)	$2.39	$0.26	11%
Heating Oil ($/gal)	$2.34	$0.29	12%
Wellhead Natural Gas ($/tcf)	$10.17	$1.49	15%
Residential Natural Gas ($/tcf)	$15.30	$1.50	10%
Utility Coal ($/short ton)	$32.6	$55.3	170%
Electricity (c/kWh)	9.6	1.76	18%

Source: Bradley et al. (1991), updated with US average prices for the 4th quarter of 2005 as reported by US DOE, EIA, Short-Term Energy and Winter Fuels Outlook October 10th, 2006 Release

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. Differences in the gas concentrations among the three models reflect differences in assumed mitigation opportunities for non-CO_2 GHGs relative to CO_2. For example, lower CH_4 and N_2O emissions exhibited by one of the models reflects a greater market penetration of technologies that reduce CH_4 and N_2O emissions with positive profits even in the reference scenario, and significant abatement in the stabilization scenarios. With lower levels of CH_4 and N_2O than is the case with the other two models, higher levels of CO_2 are still consistent with the overall radiative forcing targets. See Figure ES. 14.

Insert Figure ES.14.

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 improve costs and performance and 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.

ES.5. Using the Scenarios and Future Work

The review process for this scenario product started a dialogue among scenario-developers and the user community that has already led to suggestions of the need for better-quantified estimates of uncertainty and further sensitivity studies to help understand differences among the models and the affects of different factors on outcomes. Requests stem from the particular interest of users and in general require extensions of the present work in a variety of new directions.

Nonetheless, these scenarios as they presently stand can be used as the basis of further analysis. For example, they could be applied as the basis for assessing the climate implications of alternative stabilization levels. Such studies might begin with radiative forcing levels from the scenarios, with the individual gas concentrations or with the emissions, augmenting the results provided here with assumptions about the reflecting and absorbing aerosols. Applications of this type could be made directly in climate models that do not incorporate a three-dimensional atmosphere and detailed biosphere model. For the more complete models some approximation would need to be imposed to allocate the short-lived gases by latitude or grid cell.

The scenarios could also provide a basis for partial equilibrium analysis of technology penetration with the prices of fossil fuels under the various scenarios used to study the target cost performance of new technologies. Differences in results among the three models provide a variety of conditions for assessing the range of cost and performance characteristics for new technologies to compete in global energy markets, or subsidy levels needed to affect early introduction. Such studies might include the non-climate environmental implications of implementing potential new energy sources at a large scale.

Finally, these scenarios can serve as an input to a more complete analysis of the welfare effects of the different stabilization targets. For example, the results contain information that can be used to calculate indicators of consumer impact in the U.S. ***The reader is reminded, however, that these effects do not include the benefits that alternative stabilization levels might yield in reduced climate change risk or ancillary effects (e.g., on air pollution).***

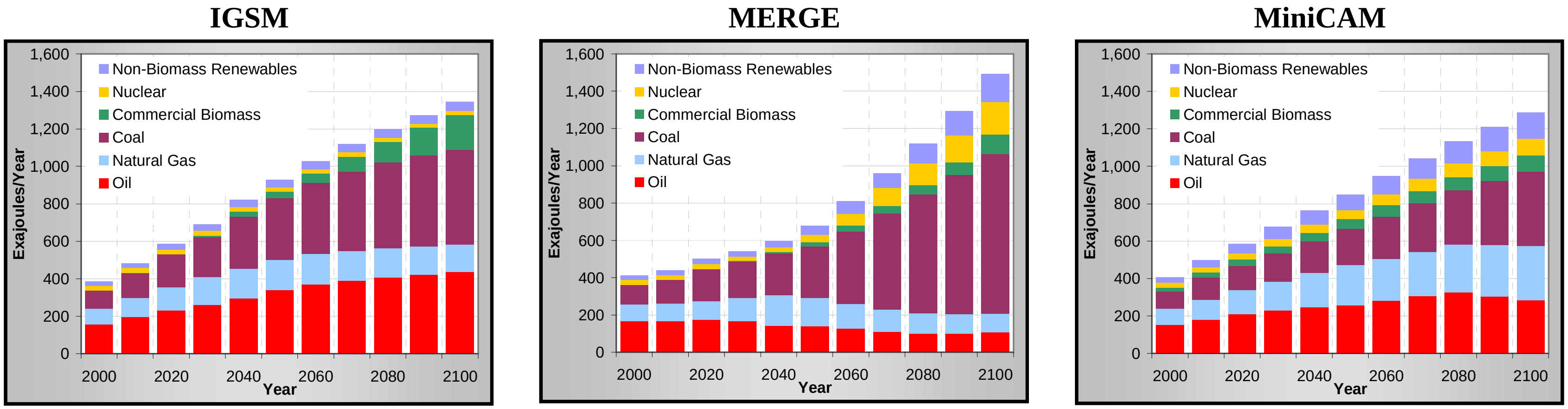
This effort is but one step in a long process of research and assessment, and the scenarios and their underlying models will benefit from further work. The review process has identified at least five different areas that hold the promise of potentially fruitful research: (1) technology sensitivity analysis, (2) consideration of non-idealized policy architectures, (3) expansion and improvement of the land use and terrestrial carbon cycle linkages to the energy and economic model components, (4) inclusion of other radiatively-important substances such as emissions affecting tropospheric ozone and aerosols, and (5) decision-making under uncertainty. These and other needs for additional research and analyis are elaborated in Chapter 5.

ES.6. References

CCSP [Climate Change Science Program]. 2003 (updated July 2004). *Strategic Plan for the U.S. Climate Change Science Program*. http://www.climatescience.gov/Library/stratplan2003/final/default.htm

CCSP [Climate Change Science Program]. 2005. *Final Prospectus for synthesis and assessment product 2.1*. http://www.climatescience.gov/Library/sap/sap2-1/sap2-1Prospectus-final.htm

Figure ES.1: Global primary energy consumption (EJ/yr): Global primary energy consumption rises in all three reference scenarios, from about 400 EJ/y in 2000 to between between roughly 1275 EJ/y to 1500 EJ/y in 2100. There is a gradual reduction in the dependence on conventional oil resources. However, 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 70% to 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/y to 450 EJ/y— between roughly half and one and one half times global energy consumption today.



IGSM MERGE MiniCAM

Figure ES.2: U.S. primary energy consumption (EJ/yr): U.S. primary energy production rises in all three reference scenarios. Growth is in the range of 1¼ to 2½ times present levels by 2100. This growth occurs despite continued improvements in the efficiency of energy use and production: U.S. energy intensity declines 60 to 75% between 2000 and 2100.

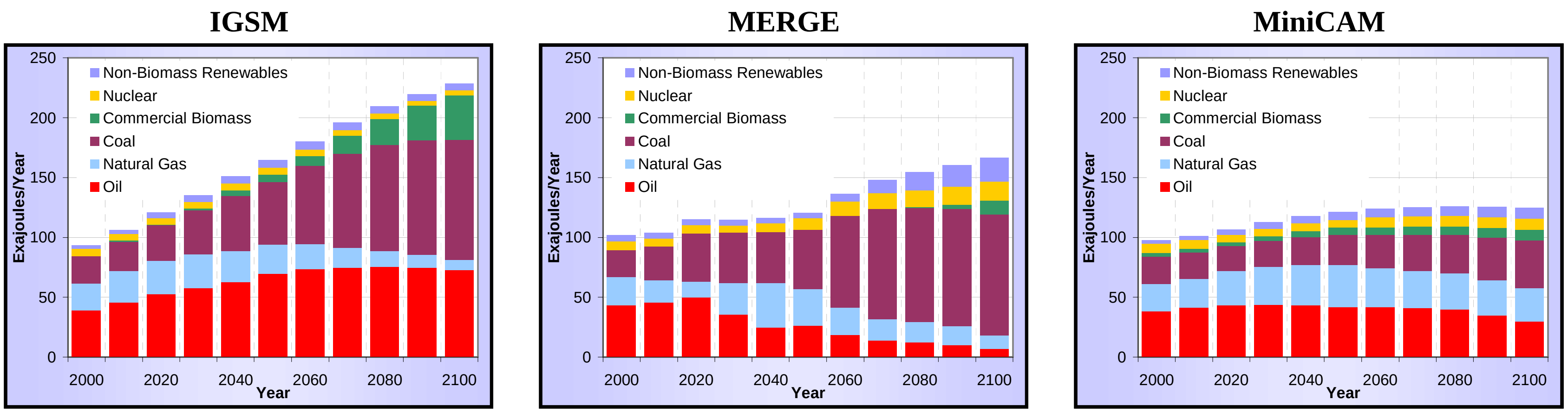
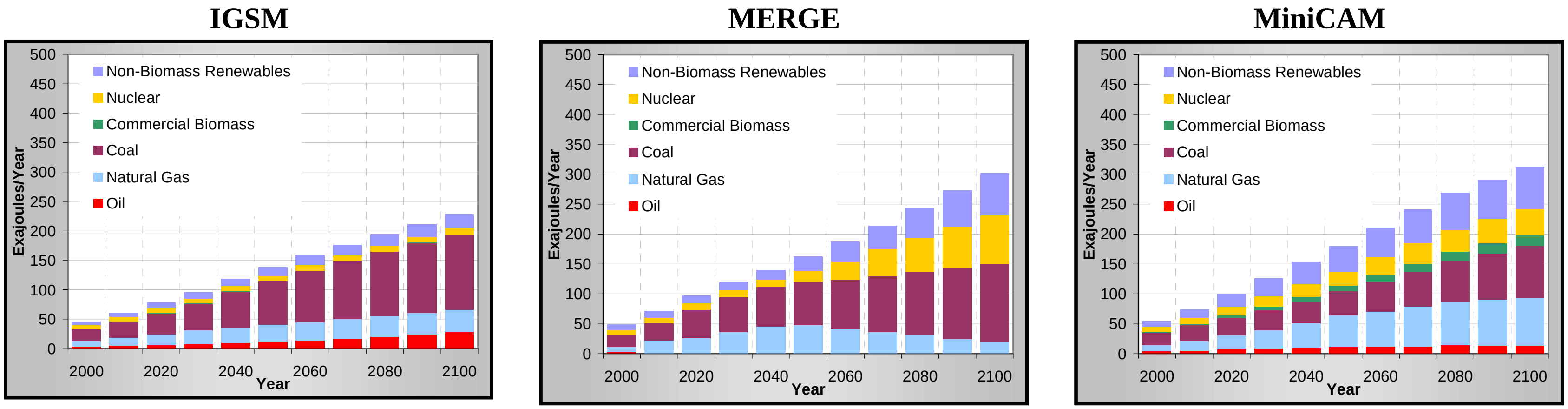


Figure ES.3: Global electricity production (EJ/yr): Global electricity production grows to over four times production in 2000 in all the reference scenarios. Global electricity production shows continued reliance on coal although this contribution varies among the reference scenarios. The contribution 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 in the reference scenarios ranges 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.



IGSM

MERGE

MiniCAM

Figure ES.4: U.S. electricity production (EJ/yr): Continued dependence on coal for electricity generation is a feature of the reference case, with the degree of dependence varying among scenarios. Differences in nuclear power reflect assumptions about public acceptability of nuclear power, and the ability to site and construct new plants.

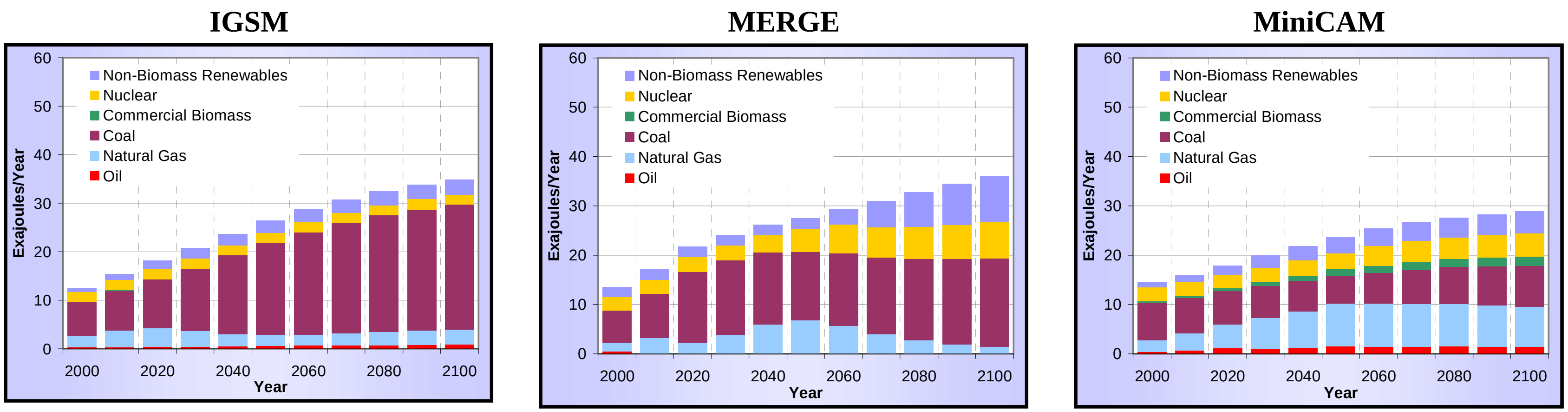


Figure ES.5: Global Emissions of CO_2 from Fossil Fuels and Industrial Sources [CO2 from land use change excluded] across Reference Scenarios (GTC/Year). Global emissions of CO_2 from fossil fuel combustion and other industrial sources, mainly cement production, increase over the century in all three reference scenarios. By 2100 emissions reach 22.5 GtC/yr to 24 GtC/y. Note that CO_2 from land use change is excluded from this figure.

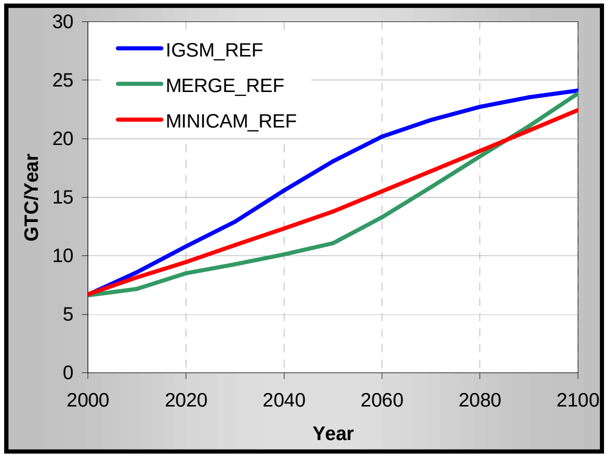
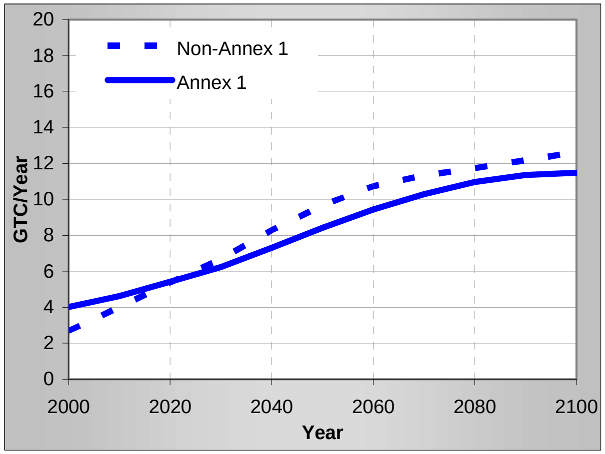


Figure ES.6: Global Emissions of Fossil Fuel and Industrial CO_2 by Annex I and Non-Annex I Countries across Reference Scenarios (GtC/y). Emissions of fossil fuel and industrial CO_2 in the reference scenarios show Non-Annex I emissions exceeding Annex I emissions for in all three reference scenarios by 2030 or earlier. Two reference scenarios show continued relative rapid growth in emissions in Non-Annex I regions after that so that their emissions are on the order of twice the level of Annex I by 2100. The third does not show continued divergence, due in part to relatively slower economic growth in Non Annex I regions, and faster growth in Annex I than the other models, and also increased emissions in Annex I as they become producers and exporters of shale oil, tar sands, and synthetic fuels from coal.

IGSM



MERGE **MiniCAM**

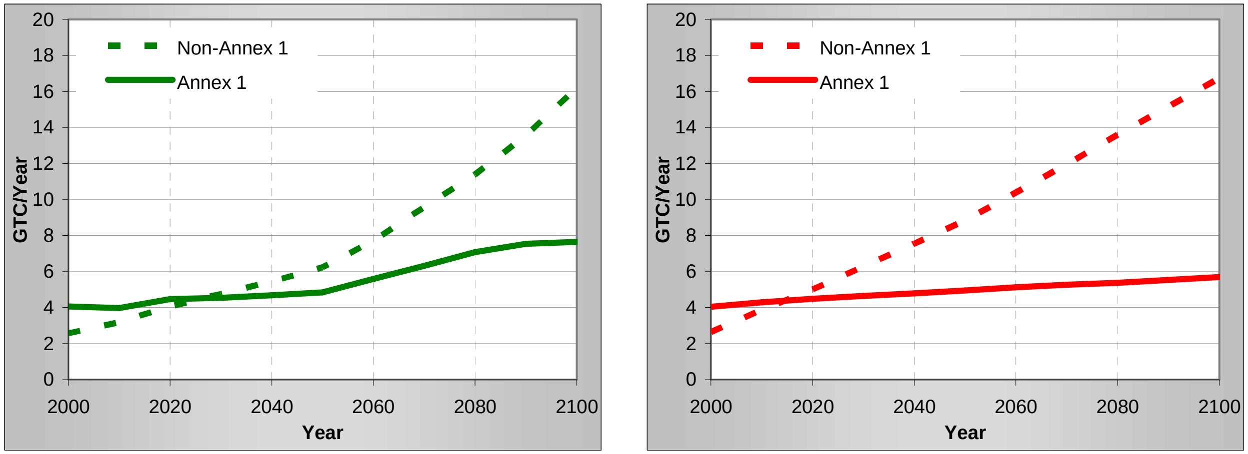
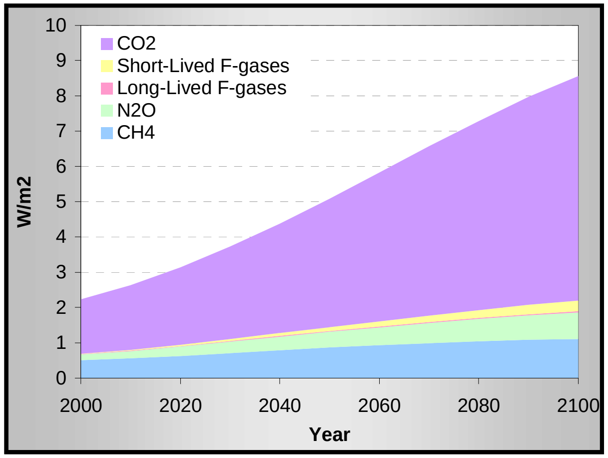
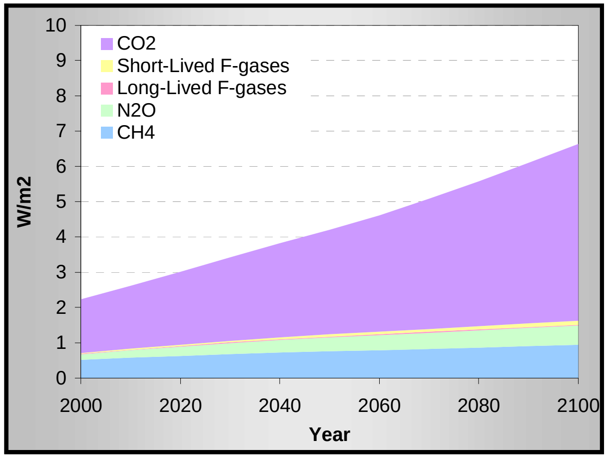


Figure ES.7: Radiative Forcing by Gas across Reference Scenarios (W/m^2). The contribution of different greenhouse gases to increased radiative forcing through 2100 show CO_2 accounting for 75% to 80% percent of the increased forcing from preindustrial for all 3 models. The total increase ranges from about 6.4 to 8.6 W/m^2 above pre-industrial levels.

IGSM



MERGE



MiniCAM

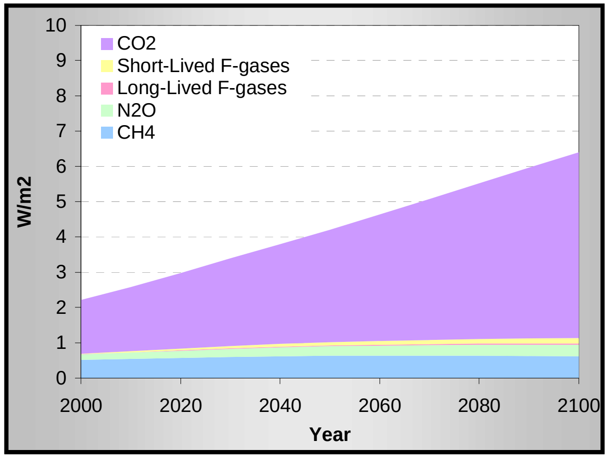
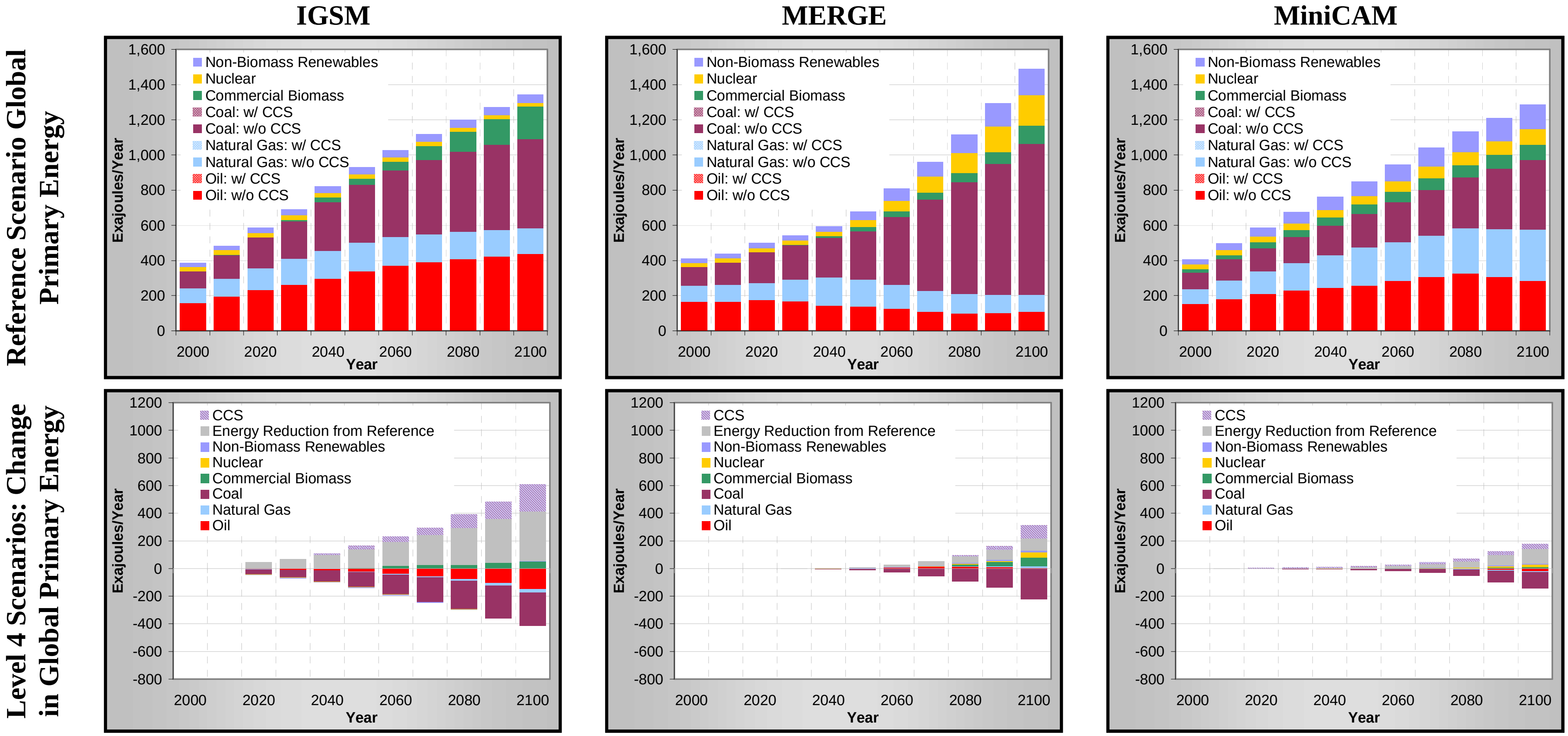


Figure ES.8: Change in Global Primary Energy by Fuel across Stabilization Scenarios, relative to Reference Scenarios (Exajoules/Year): Energy consumption changes from the reference scenario to the stabilization scenarios show significant transformation of the energy system for all three models. The transformation begins later under the Level 3 and Level 4 targets, but would need to continue into the following century. The transformation includes reduction in energy use, increased use of carbon-free sources of energy (biomass, other renewables, nuclear), and addition of carbon capture and sequestration. The contribution of each varies among the models reflecting different assessments of the economic viability, policy assumptions, and resource limits.



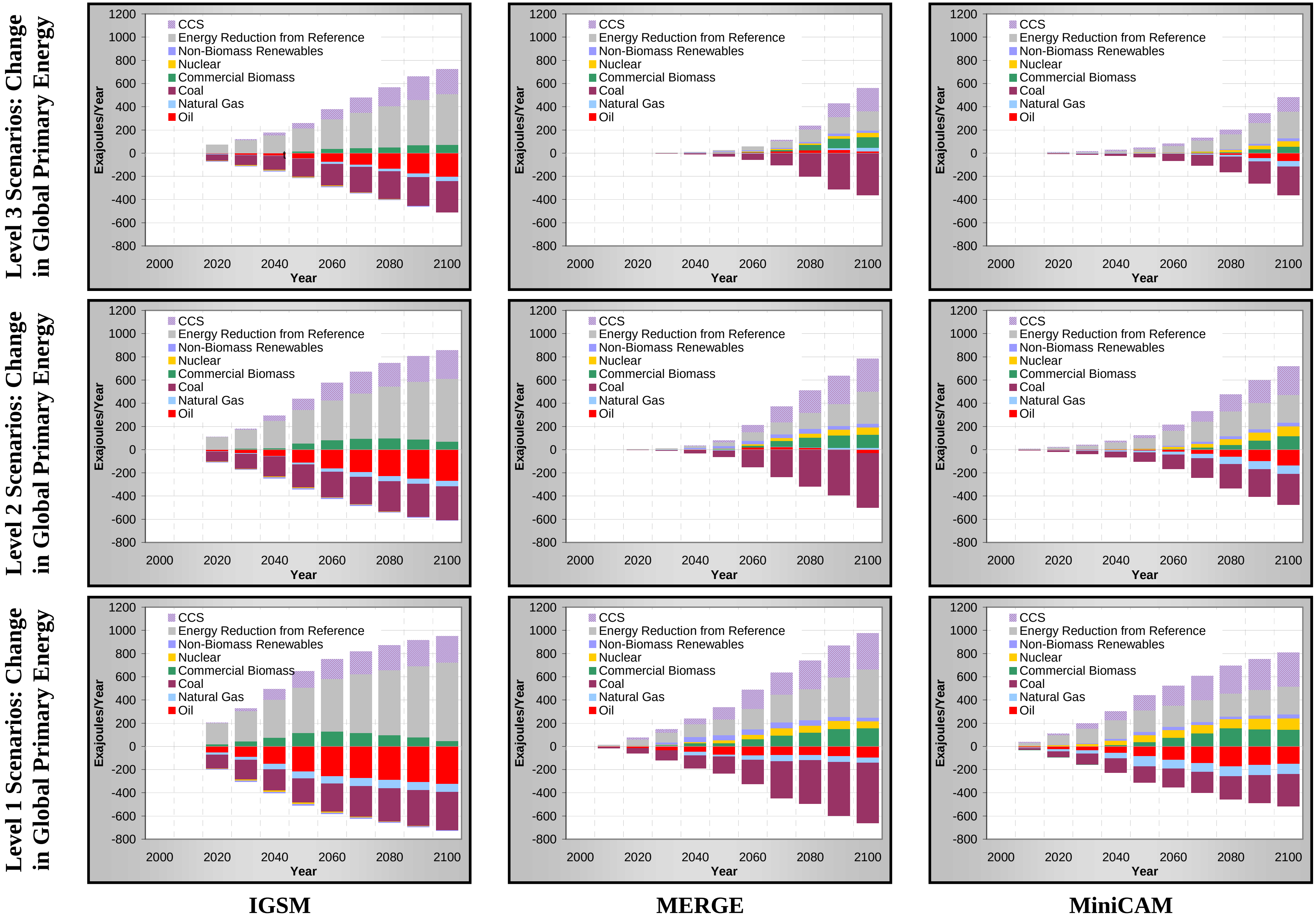
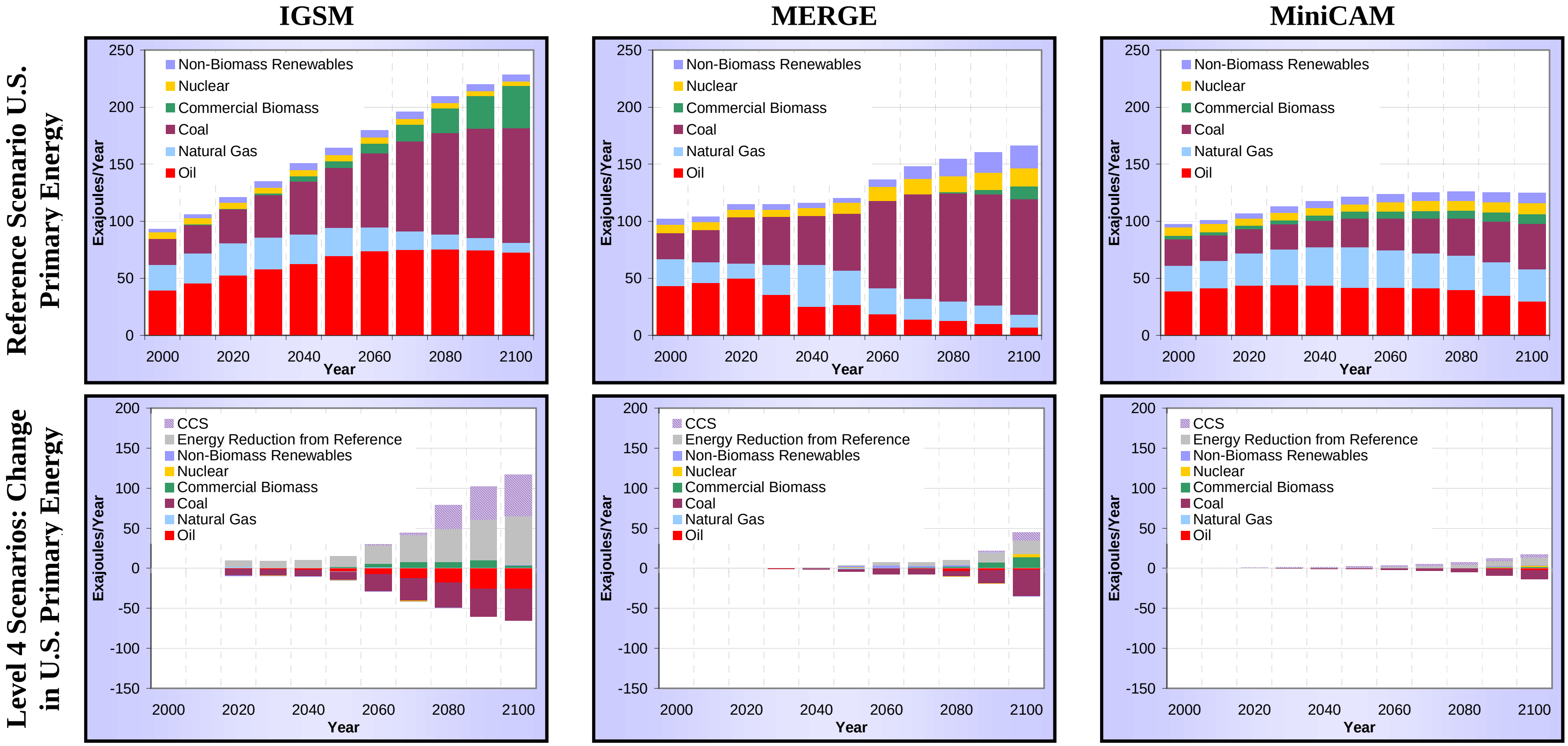

Level 3 Scenarios: Change in Global Primary Energy
Level 2 Scenarios: Change in Global Primary Energy
Level 1 Scenarios: Change in Global Primary Energy
IGSM
MERGE
MiniCAM
CCS
Energy Reduction from Reference
Non-Biomass Renewables
Nuclear
Commercial Biomass
Coal
Natural Gas
Oil
Exajoules/Year
Year
1200
1000
800
600
400
200
0
-200
-400
-600
-800
2000
2020
2040
2060
2080
2100

Figure ES.9: Change in U.S. Primary Energy by Fuel across Stabilization Scenarios, relative to Reference Scenarios (Exajoules/Year): The United States energy system in the reference scenarios, and the changes needed under the stabilization scenarios involve transformations similar to those for the global energy system. One difference not obvious from these primary fuel data is the transformation from conventional oil and gas to synthetic fuel production derived from shale oil or coal. One model (IGSM) includes heavy use of shale oil in the reference with some coal gasification, whereas another (MERGE) includes primarily synthetic liquid and gaseous fuels derived from coal.



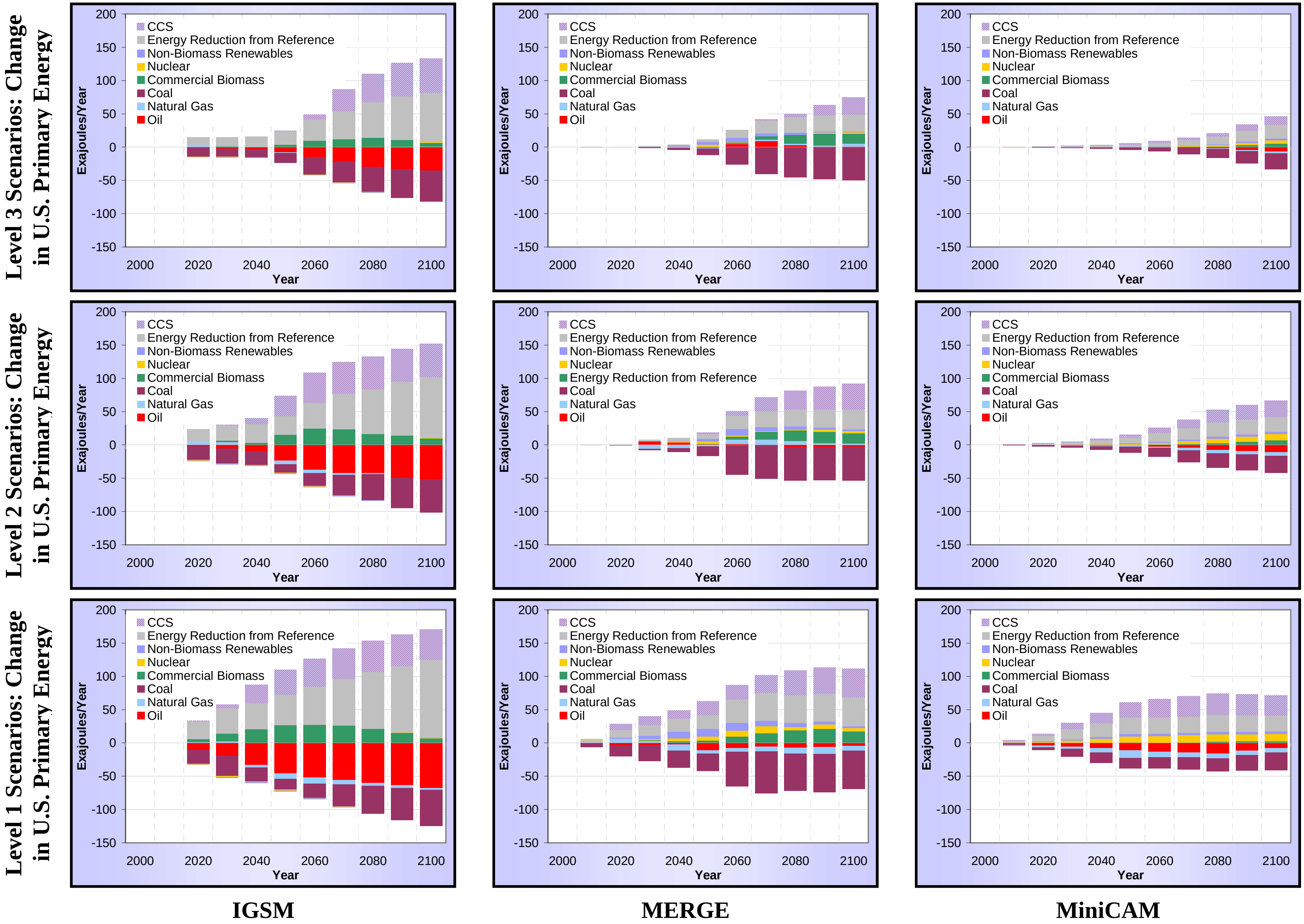

Level 3 Scenarios: Change in U.S. Primary Energy
Level 2 Scenarios: Change in U.S. Primary Energy
Level 1 Scenarios: Change in U.S. Primary Energy
CCS
Energy Reduction from Reference
Non-Biomass Renewables
Nuclear
Commercial Biomass
Coal
Natural Gas
Oil
CCS
Energy Reduction from Reference
Non-Biomass Renewables
Nuclear
Energy Reduction from Reference
Coal
Natural Gas
Oil
Exajoules/Year
200
150
100
50
0
-50
-100
-150
2000
2020
2040
2060
2080
2100
Year
IGSM
MERGE
MiniCAM

Figure ES.10: Carbon emissions **(GtC/y) in the reference and stabilization scenarios.** The tighter the constraint on the stabilization level the faster the rate at which carbon emissions must decline from the baseline. This is because the stabilization level defines a long-term carbon budget; that is the remaining amount of carbon that can be emitted in the future. The gradual deflection of the emissions from the reference reflects the assumption of “when”flexibility, with carbon prices rising gradually. The most stringent scenarios require global emissions to begin to fall absolutely from the start of the policy, whereas the other cases allow for some further increase.

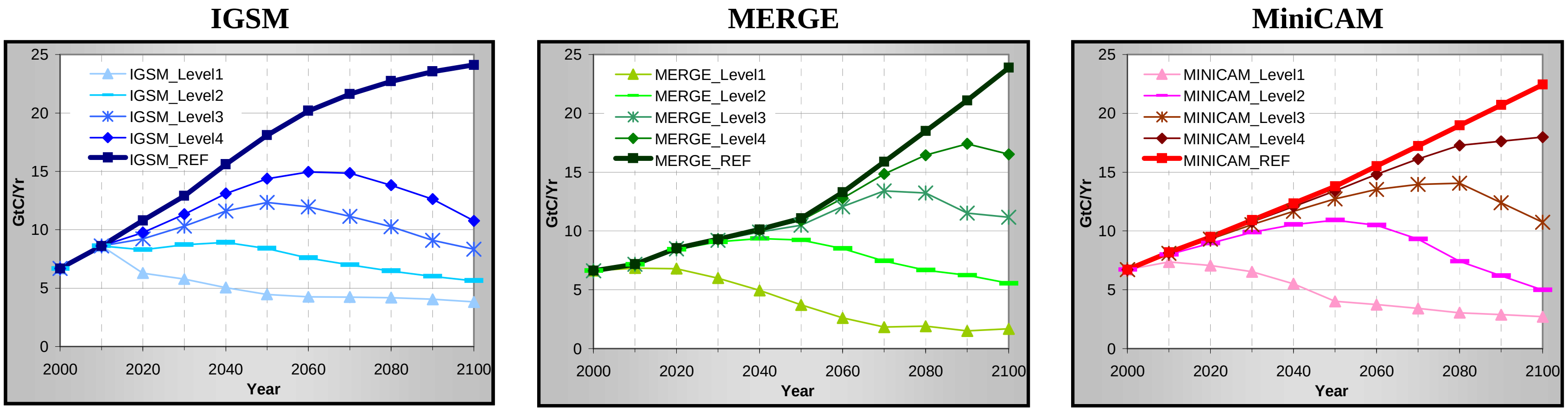
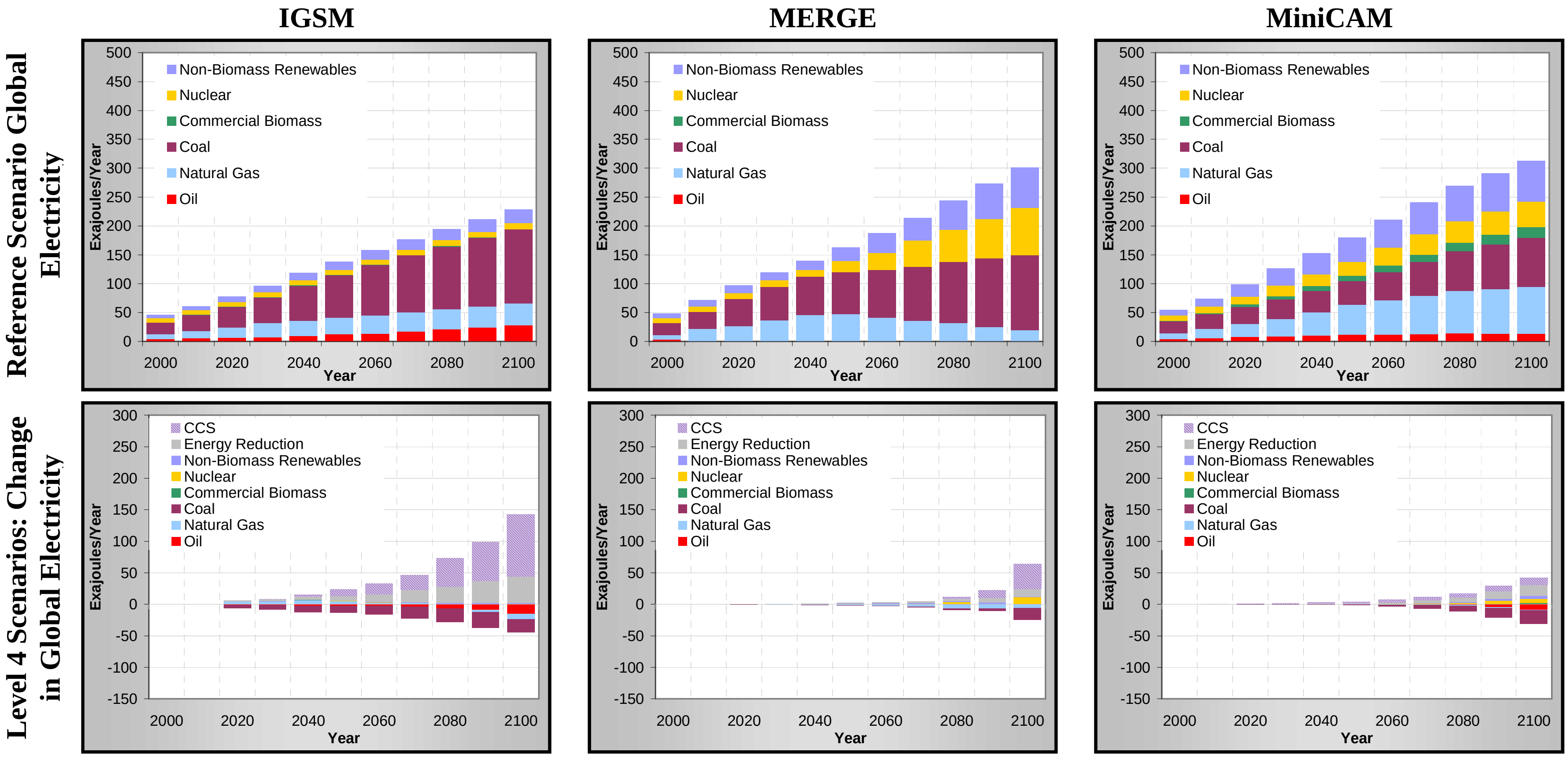


Figure ES.11: Change in Global Electricity by Fuel across Stabilization Scenarios, relative to Reference Scenarios (EJ/y): Various electricity technology options could be competitive in the future, and different assessments of their relative economic viability, reliability, and resource availability lead to considerably different projections for the global electricity sector in reference and stabilization scenarios across the models. One reference scenario (IGSM) includes relatively little change in the electricity sector in the reference, with continued reliance on coal. The other two reference scenarios include large transformations from current in the reference. In all cases, large changes from reference are required to meet the stabilization targets.



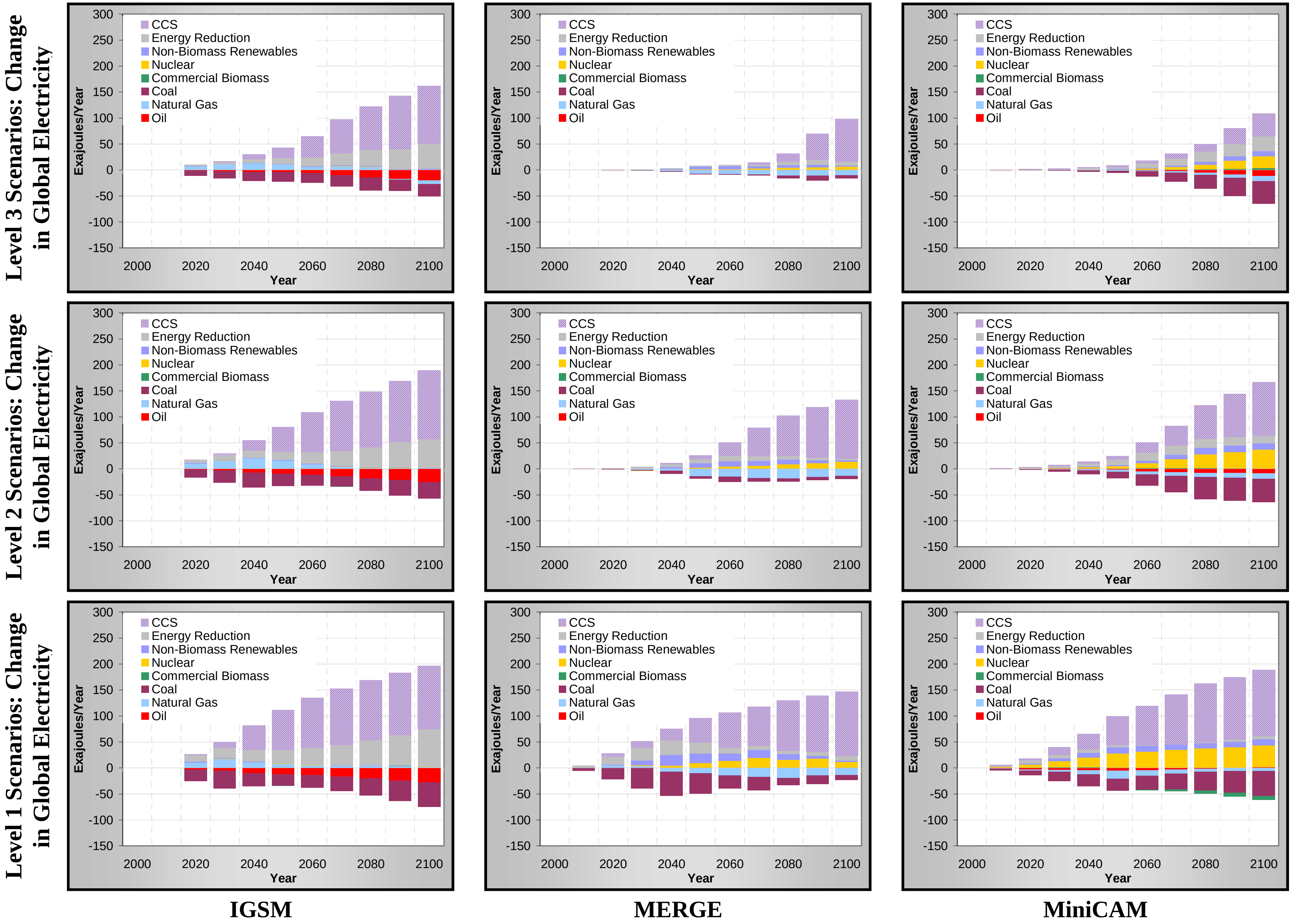
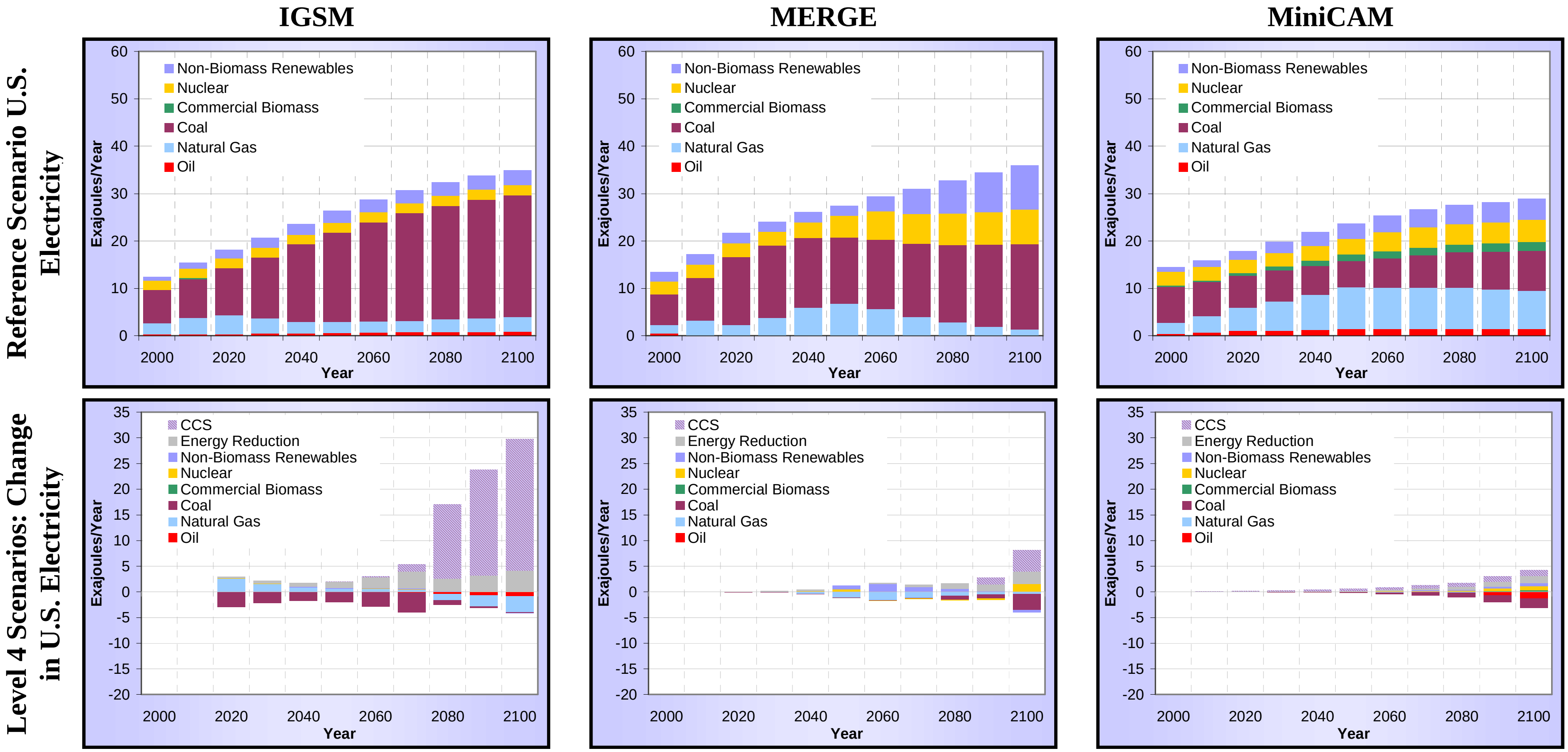

Level 3 Scenarios: Change in Global Electricity
Level 2 Scenarios: Change in Global Electricity
Level 1 Scenarios: Change in Global Electricity
CCS
Energy Reduction
Non-Biomass Renewables
Nuclear
Commercial Biomass
Coal
Natural Gas
Oil
Exajoules/Year
300
250
200
150
100
50
0
-50
-100
-150
2000
2020
2040
2060
2080
2100
Year
IGSM
MERGE
MiniCAM

Figure ES.12: Change in U.S. Electricity by Fuel across Stabilization Scenarios, relative to Reference Scenarios (Exajoules/Year): United States electricity generation sources and technologies will need to be substantially transformed to meet stabilization targets. Carbon capture and sequestration figure in all three models under stabilization scenarios, but the contribution of other sources and technologies and the total amount of electricity used differ substantially.



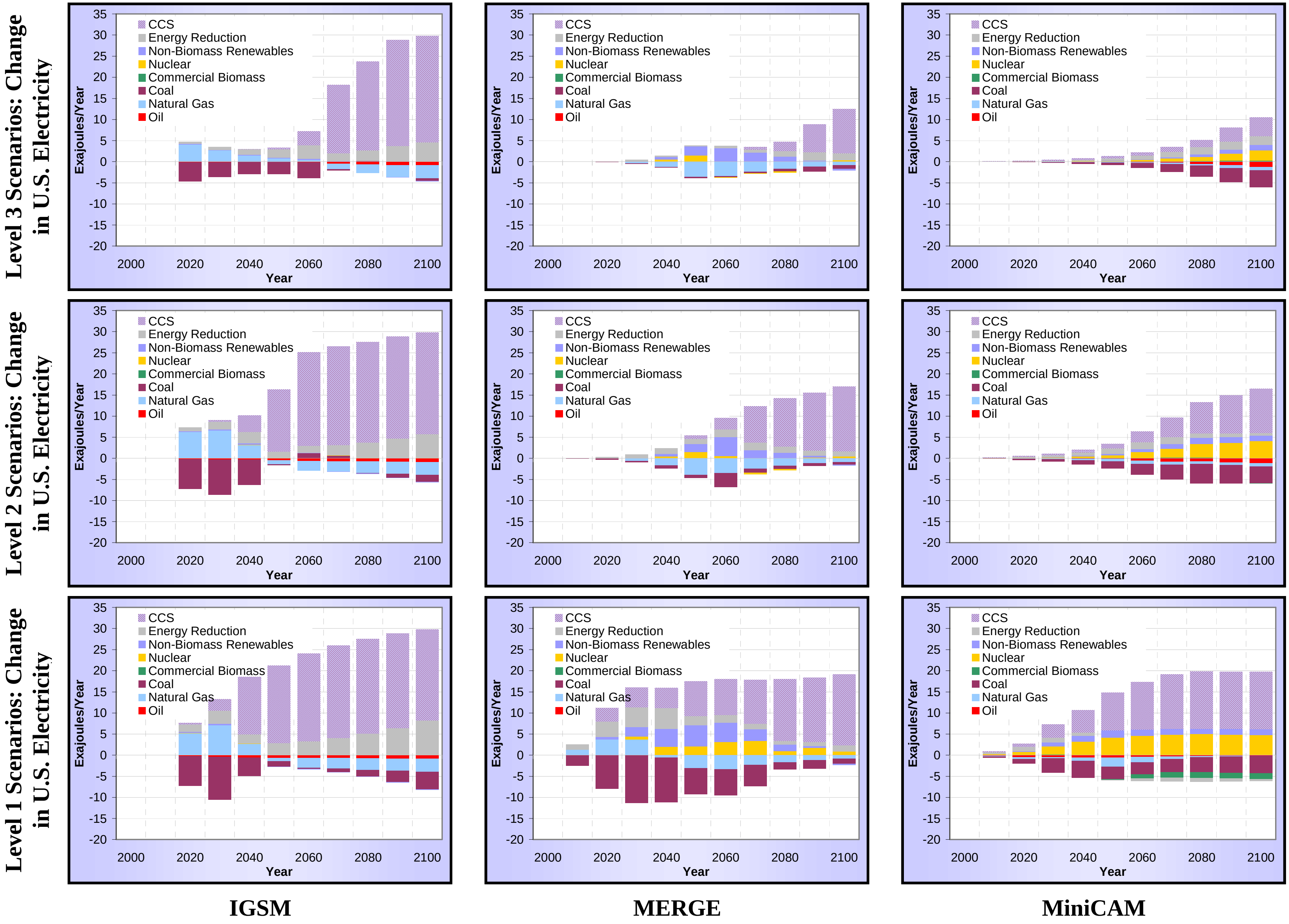
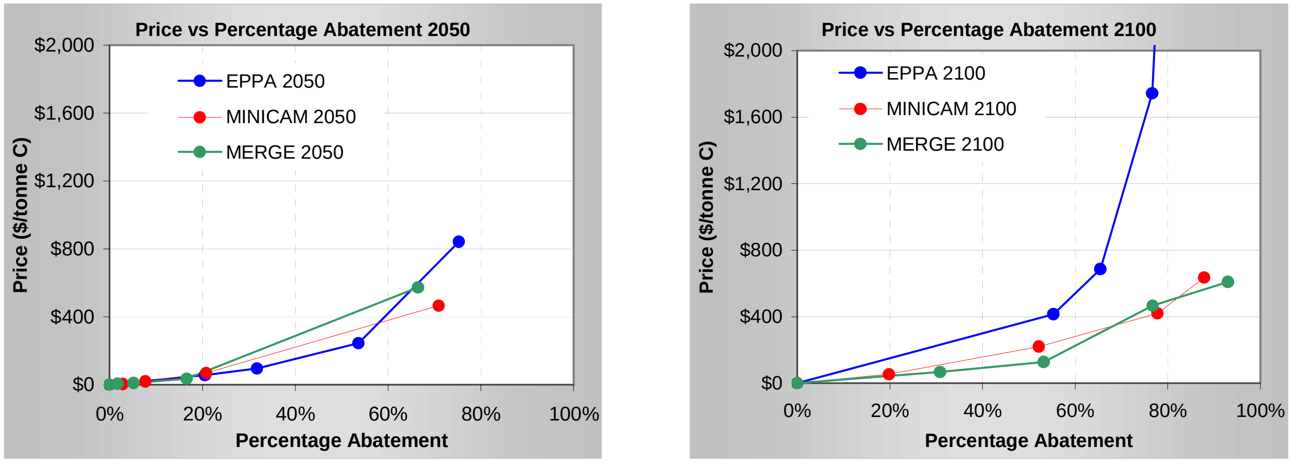
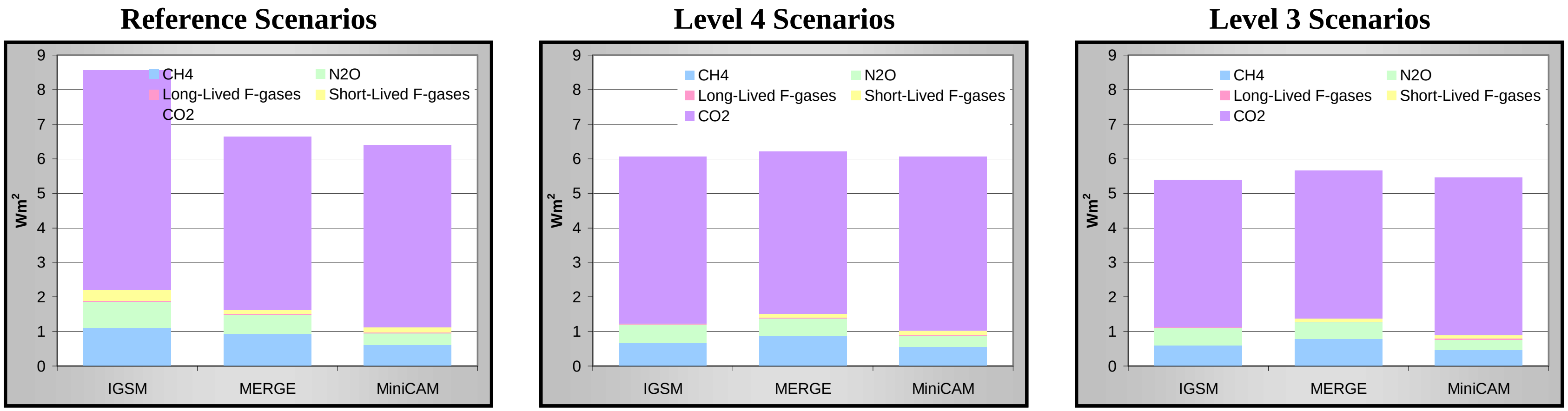

Level 3 Scenarios: Change in U.S. Electricity
Level 2 Scenarios: Change in U.S. Electricity
Level 1 Scenarios: Change in U.S. Electricity
IGSM
MERGE
MiniCAM
CCS
Energy Reduction
Non-Biomass Renewables
Nuclear
Commercial Biomass
Coal
Natural Gas
Oil
Exajoules/Year
35
30
25
20
15
10
5
0
-5
-10
-15
-20
Year
2000
2020
2040
2060
2080
2100

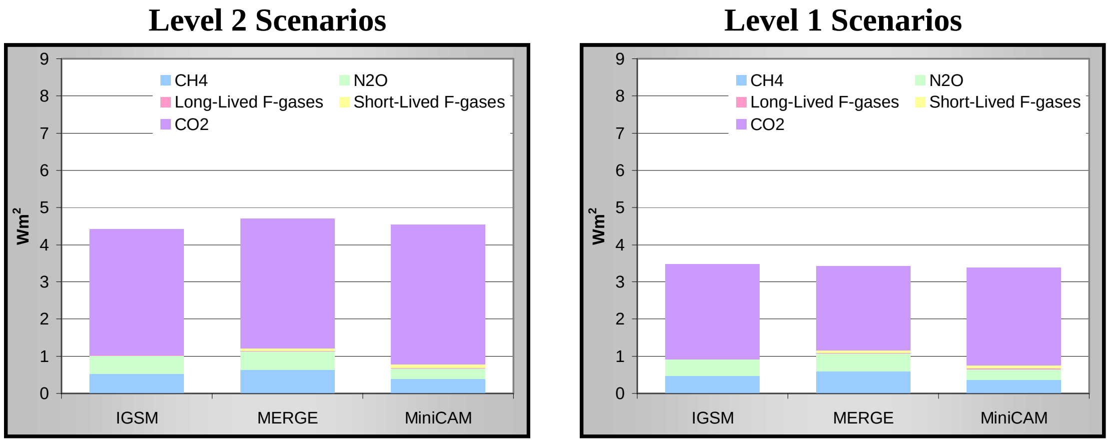
Figure ES.13: Ratio of Relationship Between Carbon Price and Percentage Abatement in 2050 and 2100: The relationship between carbon price and percentage abatement very similar among the models in 2050. In 2100, the relationship between carbon price and abatement diverges across the models, due in large part to different assumptions regarding the technologies available to facilitate emissions reductions late in the century.


2050

2100

Figure ES.14: Total Radiative Forcing in 2100 across Scenarios (W/m^2 relative to preindustrial): Results for radiative forcing in the year 2100 by greenhouse gas show CO_2 to be the main contributor. Contributions from non-CO_2 gases are relatively higher in the reference in the IGSM scenarios, relatively lower in the MiniCAM scenarios, and intermediate for the MERGE scenarios.





1. INTRODUCTION AND OVERVIEW

1.1. Introduction

The *Strategic Plan for the U.S. Climate Change Science Program* (CCSP 2003) calls for the preparation of 21 synthesis and assessment products. Noting that "sound, comprehensive emissions scenarios are essential for comparative analysis of how climate might change in the future, as well as for analyses of mitigation and adaptation options," the plan includes Product 2.1, Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations and Review of Integrated Scenario Development and Application. This report presents the results from the scenario development component of this product; the review of scenario methods is the subject of a separate report. The guidelines for the development of these scenarios are set forth in the *Final Prospectus for Synthesis and Assessment Product 2.1* ("the Prospectus"; CCSP 2005).

This report discusses the overall design of scenarios (this chapter), describes the key features of the participating models (Chapter 2), presents the new scenarios that have been prepared and reports the main results comparatively (Chapters 3 and 4), and reflects in conclusion on emerging insights from these new scenarios, the uses and limitations of them, and avenues for further research (Chapter 5). Scenario details are available in a separate data archive.[1]

As set forth in the Prospectus, the primary purpose of these scenarios is to serve as one of many inputs to decision-making for climate change. Consistent with the Prospectus and the nature of the climate change issue, these scenarios were developed using long-term, century-scale models of global energy-agriculture-land-use-economy systems coupled to models of global atmospheric composition and radiation. The intended audience includes decision-makers and analysts who might benefit from enhanced understanding of the potential implications of stabilizing greenhouse gas concentrations at various levels. For example, technology planners such as those at the Climate Change Technology Program (CCTP) need to take account of the possible energy systems implications of stabilization

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

levels. The Prospectus for this product highlighted three areas in particular in which the scenarios might provide valuable insights:

1. Emissions Trajectories: What emissions trajectories over time are consistent with meeting the four stabilization levels, and what are the key factors that shape them?

2. Energy Systems: What energy system characteristics are consistent with each of the four alternative stabilization levels, and how do they differ from one another?

3. Economic Implications: What are the possible economic consequences of meeting the four alternative stabilization levels?

The scenarios may also serve as a point of departure for further CCSP and other analyses, such as exploring the implications for future climate or examining the costs and feasibility of mitigation and adaptation options. Finally, this effort will enhance the capabilities for future scenario analysis that might be conducted by the CCSP or related U.S. government offices such as the CCTP.

It should be emphasized that there are issues of climate change decision-making that these scenarios do not address. For example, they were not designed for use in exploring the role of aerosols in climate change. And they lack the level of detail that may be desired for local or regional decision-making, such as state or city planning or the decision-making of individual firms or members of the public. ***In addition, this report should in no way be perceived as a cost benefit analysis of climate policy. The focus is exclusively on the nature and costs of the mitigation required to meet various stabilization levels. No attempt has been made to assess the damages avoided by adopting a particular stabilization level or ancillary benefits that may be realized (e.g., in air pollution reduction). Although the information contained in the report should provide a useful input to policy deliberations, it provides an incomplete guide to decisions on particular policy measures.***

Three analytical models, all meeting the criteria set forth in the Prospectus, were used in preparing the new scenarios. As also directed in the Prospectus, fifteen scenarios are presented in this document, five from each of the three modeling teams. First, each team produced a unique reference scenario based on the assumption that no climate policy would be implemented either nationally or globally beyond the current set of policies in place (e.g., the Kyoto Protocol and the President's greenhouse gas emissions intensity target for the U.S.). These reference scenarios were developed independently by the modeling teams, so they provide three separate visions of how the future might unfold across the globe over the 21st century without additional climate policies.[2]

Each team then produced four additional stabilization scenarios, which are departures from each team's reference case. The Prospectus specified that stabilization levels,

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[2] Although there are many reasons to expect that the three reference scenarios would be different, it is worth noting that the modeling teams met periodically during the development of the scenarios to review progress and to exchange information. Thus, while not adhering to any formal protocol of standardization the three reference scenarios are not entirely independent.

common across the teams, be defined in terms of the total long-term radiative impact of the suite of greenhouse gases (GHGs) that includes carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). This radiative impact is expressed in terms of radiative forcing, which is a measure of the additional heat-trapped in the atmosphere by these six GHG's relative to preindustrial levels.

Although stabilization is defined in terms of radiative forcing, the Prospectus also directed that stabilization levels be chosen to provide results easily compared with those from previous scenario exercises based only on CO_2 concentrations. Radiative forcing levels were constructed so that the resulting CO_2 concentrations, after accounting for radiative forcing from the non-CO_2 GHGs, would be roughly 450 ppmv, 550 ppmv, 650 ppmv, and 750 ppmv. Based on this requirement, the four stabilization levels were chosen as 3.4 W/m^2 (Level 1), 4.7 W/m^2 (Level 2), 5.8 W/m^2 (Level 3), and 6.7 W/m^2 (Level 4). In comparison, radiative forcing relative to pre-industrial levels for this suite of gases stood at roughly 2.2 W/m^2 in 2000. Details of these stabilization assumptions are elaborated in Section 4.

The production of emissions scenarios consistent with these stabilization goals required analysis beyond study of the emissions themselves because of physical, chemical, and biological feedbacks within the Earth system. Scenarios focused only on emissions of GHGs and other substances generated by human activity (anthropogenic sources) can rely exclusively on energy-agriculture-economic models that project human activity and the emissions that result. However, relating emissions paths to concentrations of GHGs in the atmosphere requires models that account for both anthropogenic and natural sources as well as the sinks for these substances.

Models that attempt to capture these complex interactions and feedbacks must, because of computational limits, use simplified representations of individual components of the Earth system. These simplified representations are typically designed to mimic the behavior of more complex models but cannot represent all of the elements of these systems. Thus, while the scenario exercise undertaken here uses models that represent both the anthropogenic sources (the global energy-industrial-agricultural economy) and the Earth system processes (ocean, atmosphere, terrestrial systems), it is not intended to supplant detailed analysis of these systems using full scale, state-of-the-art models and analytic techniques. Rather, these scenarios provide a common point of departure for more complex analyses of individual components of the Earth’s system as it is affected by human activity. These might include, for example, detailed studies of sub-components of the energy sector, regional projections of climate change using three-dimensional general circulation models and further downscaling techniques, and assessment of the implications for economic activity and natural ecosystems of climate change under various stabilization goals.

The remainder of this chapter is organized into four sections. Section 1.2 provides an overview of scientific aspects of the climate issue as background for interpretation of these scenarios. Section 1.3 then presents the study design with a focus on the characteristics of the stabilization cases to be investigated in Chapter 4. Section 1.4

briefly discusses how scenarios of this type have been used to examine the climate change issue and the intended uses and limits of the new scenarios, focusing on interpretation of these scenarios under conditions of uncertainty. Section 1.5 provides a guide to the structure of the remaining chapters and the associated data archive.

1.2. Background: Human Activities, Emissions, Concentrations, and Climate Change

Materials that influence the Earth's radiation balance come in various forms, and most have natural as well as anthropogenic sources. Some are gases which remain in the atmosphere for periods ranging from days to millennia, trapping heat while they are there. They are known as GHGs because, while transparent to incoming short-wave radiation (the visible spectrum that people commonly perceive as light), they capture and reflect back to Earth long-wave radiation, thus increasing the temperature of the lower atmosphere from what it otherwise would be. These naturally occurring GHGs, plus clouds and the effect of water vapor (the most important GHG of all), are responsible for creating a habitable climate on Earth. Without them, the average temperature at the Earth's surface would be colder than it is today by roughly 55°F (31°C).

GHGs are not the only influences on the Earth's radiative balance. Other gases like oxides of nitrogen (NO_x) have no direct greenhouse effect, but they are components of the atmospheric chemistry that determine the lifetime of some of the heat-trapping GHGs and are involved in the reactions that produce tropospheric ozone, another GHG. Aerosols (non-aqueous particles suspended in air) may have positive or negative effects, depending on their relative brightness. Some present a white surface and reflect the sun's energy back to space; others are black and absorb solar energy, adding to the solar warming of the atmosphere. Aerosols also have an indirect effect on climate in that they influence the density and lifetime of clouds, which have a strong influence on the radiation balance and on precipitation. Humans also alter the land surface, changing its reflective properties, and these changes can have climate consequences with effects most pronounced at a local scale (e.g., urban heat islands) and regional levels (e.g., large-scale changes in forest cover). In addition, the climate itself has positive and negative feedbacks, such as the decrease in global albedo that would result from the melting land and sea ice or the potential release of GHGs such as methane from wetlands.

Climate policy concerns are driven by the fact that emissions from human activities (mainly combustion of fuels and biomass, industrial activities, and agriculture) are increasing the atmospheric concentrations of these substances. Climate policy discussions have focused heavily on CO_2, CH_4, N_2O, and a set of fluorine-containing industrial chemicals – SF_6 and two families of substances that do not exist naturally, hydrogenated halocarbons (including hydrochlorofluorocarbons [HCFCs] and HFCs)[3] and PFCs. Some of these substances remain in the atmosphere on the order of decades (CH_4, most HFCs), others for the order of 100 years (CO_2, N_2O) and some for thousands of years (PFCs, SF_6).

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[3] For simplicity, all hydrogenated halocarbons will be referred to as HFCs in the subsequent text. The greenhouse gas methyl chloroform is often also grouped along with HFCs and HCFCs.

Other naturally occurring substances whose levels have also been greatly enhanced by human activities remain in the atmosphere for days to months. With such short lifetimes they are not well mixed in the atmosphere and so their effects have a regional pattern as well as global consequences. These substances include aerosols such as black carbon and other particulate matter; sulfur dioxide, which is the main precursor of the reflecting aerosols; and other gases such as volatile organic compounds, nitrogen dioxide, other oxides of nitrogen, and carbon monoxide. All are important components of atmospheric chemistry.

This suite of substances with different radiative potency and different lifetimes in the atmosphere presents a challenge in defining what is meant by atmospheric “stabilization.” Specification in terms of quantities of the gases themselves is problematic because there is no simple way to add them together in their natural units such as tons or parts per million by volume. Thus, a meaningful metric is needed in order to combine the effects of different GHGs.

One approach is to define stabilization in terms of some ultimate climate measure, such as the change in the global average temperature. One drawback of such measures is that they interject large uncertainties into the consideration of stabilization because the ultimate climate system response to added GHGs is uncertain. Climate models involve complex and uncertain interactions and feedbacks, such as increasing levels of water vapor, changes in reflective polar ice, cloud effects of aerosols, and changes in ocean circulation that determine the ocean’s uptake of CO_2 and heat.

For the design of these scenarios, the Prospectus called for an intermediate, less uncertain measure of climate effect, the direct heat-trapping impact of a change in the concentrations of the six categories of GHGs listed earlier. It is constructed to represent the change in the net balance of the Earth with the sun (energy in *vs*. energy out) where the units are watts per square meter (W/m^2) of the Earth’s shell. Generally referred to as radiative “forcing” (see Box 1.1), a positive value means a warming influence. This measure is widely used to compare the climate effects of different substances, although calculation of the net forcing of a group of gases, where there may be chemical interaction among them or saturation of the infrared spectrum, requires specialized models of atmospheric chemistry and radiation.

--- BOX 1.1: RADIATIVE FORCING ---

Most of the Sun’s energy that reaches the Earth is absorbed by the oceans and land masses and radiated back into the atmosphere in the form of heat or infrared radiation. Some of this infrared energy is absorbed and re-radiated back to the Earth by atmospheric gases, including water vapor, CO_2, and other substances. As concentrations of these so-called greenhouse gases (GHGs) increase, the warming effect is augmented. The National Research Council (2005) defines direct radiative forcing as an effect on the climate system that directly affects the radiative budget of the Earth’s climate which may result from a change in concentration of radiatively active gases, a change in solar radiation reaching the Earth, or changes in surface albedo. The increase is called radiative “forcing” and is typically measured in watts per square meter (W/m^2). Increases in radiative forcing influence global temperature by indirect effects and feedback from a variety of processes, most of which are subject to considerable uncertainty. Together, they affect, for example, the level of water vapor, the most important of the GHGs.

--- END BOX 1.1 ---

Figure 1.1 shows estimates of how increases in GHGs and aerosols and other changes have influenced radiative forcing since 1850. The GHGs considered in these scenarios are collected in the left-most bar and together they have had the biggest effect, with CO_2 being the largest of this group. Increased tropospheric ozone has also had a substantial warming effect. The reduction in stratospheric ozone has had a slight cooling effect. Changes in aerosols have had both warming and cooling effects. Aerosol effects are highly uncertain because they depend on the nature of the particles, how the particles are distributed in the atmosphere, and their concentrations, which are not as well understood as the GHGs. Land-use change and its effect on the reflectivity of the Earth's surface, jet contrails and changes in high-level (cirrus) clouds, and the natural change in intensity of the sun have also had effects.

Figure 1.1: Estimated Influences of Atmospheric Gases on Radiative Forcing, 1850-present

Another important aspect of the climate effects of these substances, not captured in the W/m^2 measure, is the persistence of their influence on the radiative balance—a characteristic discussed in Box 1.2. The W/m^2 measure of radiative forcing accounts for only the effect of a concentration in the atmosphere at a particular instant. The GHGs considered here have influences that may last from a decade or two (e.g., the influence of CH_4) to millennia, as noted earlier.

--- BOX 1.2: ATMOSPHERIC LIFETIMES OF GREENHOUSE GASES ---

The atmospheric lifetime concept is more appropriate for CH_4, N_2O, HCFCs, PFCs, and SF_6 than it is for CO_2. These non-CO_2 gases are destroyed via chemical processes after some time in the atmosphere. In contrast, CO_2 is constantly cycled between pools in the atmosphere, the surface layer of the ocean, and vegetation, so it is (for the most part) not destroyed. Very slow processes lead to some removal of carbon from oceans, vegetation, and atmosphere as calcium carbonate; also, over long geological periods, carbon from vegetation was stored as fossil fuels, which is a permanent removal process as long as they are not burned to produce energy.

Although the "lifetime" concept is not strictly appropriate for CO_2 (see Box 2.2 in Chapter 2), the molecules in a kilogram of emissions can be thought of as residing in the atmosphere, exercising their radiative effect, for around 100 years. This approximation allows a rough comparison with the other gases: CH_4 at 12 years, N_2O at 114 years, and SF_6 at 3200 years. Hydrogenated halocarbons, such as HCFCs and HFCs, are a family of gases with varying lifetimes from less than a year to over 200 years; those predominantly in use now have lifetimes mostly in the range of 10 to 50 years. Similarly, the PFCs have various lifetimes, ranging from 2,600 to 50,000 years.

The lifetimes are not constant, as they depend to some degree on other Earth system processes. The lifetime of CH_4 is the most affected by the levels of other pollutants in the atmosphere.

--- END BOX 1.2 ---

An important difference between GHGs and most of the other substances in Figure 1.1 is their long lifetime. In contrast to GHGs, aerosols remain in the atmosphere only for a few days to a couple of weeks. Once an aerosol emission source is eliminated, its effect on radiative forcing disappears very quickly. Tropospheric ozone lasts for a few months. Moreover, relatively short-lived substances are not well-mixed in the atmosphere. Levels are very high near emissions sources and much lower in other parts of the world, so their climate effect has a different spatial pattern than that of long-lived substances. The regional differences and much shorter lifetimes of non-GHG substances make comparisons among them more difficult than among GHGs. The radiative effects of these substances also subject to more uncertainty, as shown in Figure 1.1.

1.3. Study Design

The broad elements of the study design for these scenarios are set forth in the Prospectus, including (1) selection of models, (2) guidance to the model teams for development of a reference scenario, and (3) guidance for the development of stabilization scenarios.

1.3.1. Model Selection

The Prospectus sets forth the model capabilities required to carry out the desired stabilization analyses. As stated in the Prospectus, participating models must

1. Be global in scale
2. Be capable of producing global emissions totals for, at a minimum, CO_2, N_2O, CH_4, HFCs, PFCs, and SF_6, that may serve as inputs to global general circulation models (GCMs), such as the National Center for Atmospheric Research (NCAR) Community Climate System Model (CCSM) and the Geophysical Fluid Dynamics Laboratory (GFDL) climate model
3. Be capable of simulating the radiative forcing from these GHGs
4. Represent multiple regions
5. Have technological resolution capable of distinguishing among major sources of primary energy (e.g., renewable energy, nuclear energy, biomass, oil, coal, and natural gas) as well as between fossil fuel technologies with and without carbon capture and storage systems
6. Be economics-based and capable of simulating macroeconomic cost implications of stabilization
7. Look forward to the end of the century or beyond.

In addition, the Prospectus required that the modeling teams have a track record of publications in professional, refereed journals, specifically in the use of their models for the analysis of long-term GHG emission scenarios.

Selection by these criteria led to the three models used in this exercise: (1) The Integrated Global Systems Model (IGSM) of the Massachusetts Institute of Technology's Joint Program on the Science and Policy of Global Change; (2) the MiniCAM Model of the Joint Global Change Research Institute, which is a partnership between the Pacific Northwest National Laboratory and the University of Maryland; and (3) the Model for Evaluating the Regional and Global Effects [of greenhouse gas reduction policies] (MERGE), developed jointly at Stanford University and the Electric Power Research Institute.

Each of these models has been used extensively for climate change analysis. The roots of each extend back more than a decade, during which time features and details have been added. Results of each have appeared widely in peer-reviewed publications. The features of the models are described in Chapter 2 with references to the publications and reports that provide complete documentation.

These models fall into a class that has come to be known as Integrated Assessment Models (IAMs). There are many ways to define IAMs and to characterize the motivations for developing them (IPCC 1996). However, a particularly appropriate definition of their primary purposes, provided by Parson and Fisher-Vanden (1997), is "evaluating potential responses to climate change; structuring knowledge and characterizing uncertainty; contributing to broad comparative risk assessments; and contributing to scientific research."

1.3.2. Development of Reference Scenarios

As required by the Prospectus, each participating modeling team first produced a "reference" scenario that assumes no policies specifically intended to address climate change beyond the implementation of any existing policies to their end of their commitment periods. The Kyoto Protocol and the policy of the United States to reduce greenhouse gas emissions intensity by 18% by 2012 are both existing policies. For purposes of the reference scenario (and for each of the stabilization scenarios), it was assumed that these policies are successfully implemented through 2012 and their goals are achieved. (This assumption could only be approximated within the models because their time steps did not coincide exactly with the period from 2002 to 2012. However, such approximation is a minor consideration as slight differences in emissions for a few years will have little impact on long term concentrations.) As directed by the Prospectus, after 2012, these existing climate policies expire and are not renewed or replaced. This is not a prediction but a scenario designed to provide a clearly defined case to serve as a basis for illuminating the implications of alternative stabilization goals. The paths toward stabilization are implemented to start after 2012 as discussed further in the following section. The reference scenarios and assumptions underlying them are detailed in Chapter 3.

The reference scenarios serve two main purposes. First, they provide insight into how the world might evolve without additional efforts to constrain greenhouse gas emissions, given various assumptions about principal drivers of the economy, energy use, and emissions. These assumptions include those concerning population increase, land and labor productivity growth, technological options, and resource endowments. These forces govern the supply and demand for energy, industrial goods, and agricultural products—the production and consumption activities that lead to GHG emissions. The reference scenarios are a thought experiment in that they assume that even as emissions increase and climate changes nothing is done to reduce emissions. The specific levels of GHG emissions and concentrations are not predetermined but result from the combination of assumptions made.

Second, the reference scenarios serve as points of departure for analysis of the changes by stabilization, and the underlying assumptions have a large bearing on the characteristics of the stabilization cases. For example, all other things being equal, the lower the economic growth and the higher the availability and competitiveness of low-carbon energy technologies in the reference scenario, the lower will be the GHG emissions and the easier it will be to reach stabilization. On the other hand, if a reference scenario assumes that fossil fuels are abundant, and fossil-fuel technologies will become cheaper over time while low- or zero-carbon alternatives remain expensive, the scenario will show consumers having little reason to conserve, adopt more efficient energy-equipment, or switch to non-fossil sources. Under such a reference scenario, emissions will grow rapidly, and stronger economic incentives will be required to achieve stabilization.

Finally, the Prospectus specified that the modeling teams develop their reference scenarios independently, applying “plausible” and “meaningful” assumptions for key drivers.[4] Similarities and differences among the reference scenarios are useful in illustrating the uncertainty inherent in long-run treatment of the climate challenge. At the same time, with only three participating models, the range of scenario assumptions produced is unlikely to span the full range of possibilities.

1.3.3. Development of the Stabilization Scenarios

Although the model teams were required to independently develop their modeling assumptions, the Prospectus required that a common set of four stabilization targets be used across the participating models. Also, whereas much of the literature on atmospheric stabilization focuses on concentrations of CO_2 only, an important objective of this exercise was to expand the range of coverage to include other GHGs. Thus the Prospectus required that the stabilization levels be defined in terms of the combined effects of CO_2, N_2O, CH_4, HFCs, PFCs, and SF_6 This suite of GHGs forms the basis for the U.S. GHG intensity reduction policy, announced by the President on February 14, 2002; it is the same set subject to control under the Kyoto Protocol. These gases are included in the left most bar of Figure 1.1, and thus the stabilization targets specified in the Prospectus explicitly omit the aerosol, ozone, land surface and other effects shown in other bars in Figure 1.1, which may be influenced by the measures taken to achieve the stabilization goal. Table 1.1 shows the change in concentration levels for these gases from 1750 to 2000. The left most bar in Figure 1.1 shows radiative forcing of nearly 2.5 Wm^{-2} compared with a sum of 2.2 Wm^{-2} in Table 1.1. The difference exists because

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[4] See footnote 2.

Figure 1.1 includes .25 to .3 Wm^{-2} of forcing from chlorofluorocarbons (CFCs) not in Table 1.1, and data in the figure extend only through 1998 (IPCC, 2001, Table 6.1) whereas the table extends through the year 2000. CFCs, important in the historical data, are already being phased out under the Montreal Protocol because of their stratospheric ozone-depleting properties, and so they are not expected to be a significant source of additional increased forcing in the future. The HFCs, which do not contribute to stratospheric ozone depletion, were developed as substitutes for the CFCs, but are of concern because of their radiative properties. Table 1.2 shows the specific radiative forcing targets chosen.

Table 1.1. Greenhouse Gas Concentrations and Forcing

Table 1.2. Radiative Forcing Stabilization Levels (W/m^2) and Approximate CO_2 Concentrations (ppmv)

As noted earlier, the Prospectus instructed that the stabilization levels be constructed so that the CO_2 concentrations resulting from stabilization of total radiative forcing, after accounting for radiative forcing from the non-CO_2 GHGs, would be roughly 450 ppmv, 550 ppmv, 650 ppmv, and 750 ppmv. This correspondence was achieved by (1) calculating the increased radiative forcing from CO_2 at each of these concentrations, (2) adding to that amount the radiative forcing from the non-CO_2 gases from 1750 to present, and then (3) adding an initial estimate of the change in radiative forcing from the non-CO_2 GHGs under each of the stabilization levels. Each of the models represents the emissions and abatement opportunities of the non-CO_2 gases somewhat differently, and takes a different approach to representation of the tradeoffs among them, so an exact correspondence between overall radiative forcing and CO_2 levels that would fit all three models was not possible. The approximated radiative forcing levels correspond very closely to CO_2 targets set out in the Prospectus for all three models.

The Prospectus also specified that, beyond the implementation of any existing policies, the stabilization scenarios should be based on universal participation by the world's nations. This guidance was implemented by assuming a climate regime with simultaneous global participation in emissions mitigation where the marginal costs of emission controls are equalized across countries and regions. Under this assumption, known as "where" flexibility, emissions will be reduced where it is cheapest to do so regardless of their geographical location. One important implication of this assumption is that the stabilization scenarios produce estimates of stabilization costs that are systematically lower than what might be expected in a world in which some major countries remain out of an emissions mitigation regime for an extended period of time, some economies use more costly regulatory mechanisms, or emissions mitigation regimes within nations are incomplete either in terms of greenhouse gas or sectoral coverage. On the other hand, possible ancillary benefits, tax interaction effects, or effects of carbon policies on technical change were not assessed which in some cases can lower costs. These issues are discussed in more detail in Chapter 4.

In addition, the Prospectus required that stabilization be defined as long-term. Because of the inertia in the Earth system, largely attributable to the ocean, perturbations to the climate and atmosphere have effects for thousands of years. Economic models have little credibility over such time-frames. The Prospectus, therefore, instructed that the participating modeling teams report scenario information only up through 2100. Each group then had to address how to relate the level in 2100 to the long-term goal. The chosen approaches were generally similar, but with some differences in implementation. This and other details of the stabilization scenario design are addressed more completely in Chapter 4.

1.4. Interpreting Scenarios: Uses, Limits, and Uncertainty

Emissions scenarios have proven to be useful aids to understanding climate change, and there is a long history of their use (see Box 1.3). Scenarios are descriptions of future conditions, often constructed by asking “what if” questions: i.e, what if events were to unfold in a particular way? Informal scenario analysis is part of almost all decision-making. For example, families making decisions about big purchases, like a car or a house, might plausibly construct a scenario in which changes in employment forces them to move. Scenarios developed for major public-policy questions perform the same purpose, helping decision-makers and the public to understand the consequences of actions today in the light of plausible future developments.

--- BOX 1.3: EMISSIONS SCENARIOS AND CLIMATE CHANGE ---

Emissions scenarios that describe future economic growth and energy use have been important tools for understanding the long-term consequences of climate change. They were used in assessments by the U.S. National Academy of Sciences in 1983 and by the Department of Energy in 1985 (NAS 1983, USDOE 1985). Previous emissions scenarios have evolved from simple projections that extrapolated a 1 percent per year increase in CO_2 emissions to scenarios that incorporate assumptions about population, economic growth, energy supply, and controls on GHG emissions and CFCs (Leggett et al. 1992, Pepper et al. 1992). They played an important role in the reports of the Intergovernmental Panel on Climate Change (IPCC 1991, 1992, 1996). The IPCC *Special Report on Emissions Scenarios* (Nakicenovic et al. 2000) was the most recent major effort undertaken by the IPCC to expand and update earlier scenarios. This set of scenarios was based on story lines of alternative futures, updated with regard to the variables used in previous scenarios, and with additional detail on technological change and land use.

The Energy Modeling Forum (EMF) has been an important venue for intercomparison of emissions and integrated assessment models. The EMF, managed at Stanford University, includes participants from academic, government, and other modeling groups from around the world. It has served this role for the energy-modeling community since the 1970s. Individual EMF studies run over a course of about two years, with scenarios designed by the participants to provide insight into the behavior of the participating models. Results are often published in the peer-reviewed literature. A recent study, EMF 21, focused on multi-gas stabilization scenarios (Weyant and de la Chesnaye 2005).

--- END BOX 1.3 ---

Models assist in creating scenarios by showing how assumptions about key drivers, such as economic and population growth or policy options, lead to particular levels of GHG emissions. Model-based scenario analysis is designed to provide quantitative estimates of multiple outcomes and to assure consistency among them that is difficult to achieve without a formal structure. Thus, a main benefit of such model simulation of scenarios is that they ensure basic accounting identities: the quantity demanded of fuel is equal to the quantity supplied; imports in one region are balanced by exports from other regions; cumulative fuel used does not exceed estimates of the resource available; and expenditures for goods and services do not exceed income. The approach complements other ways of thinking about the future, ranging from formal uncertainty analysis to narratives. Also, such model analyses offer a set of macro-projections that users can build on, adding more detailed assumptions about variables and decisions of interest to them.

Possible users of emissions scenarios include climate modelers and the science community; those involved in national public policy formulation; managers of Federal research programs; individual firms, farms, and members of the public; as well as state and local government officials who face decisions that might be affected by climate change and mitigation measures. A single scenario exercise cannot hope to provide the details needed by all potential users or address their specific questions. Thus these scenarios are an initial set offered to potential user communities. If successful, they will generate 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 more often demanding detail that can only be provided with other modeling and analysis techniques. As such, this effort is one step in the ongoing and iterative international process of producing and refining climate-related scenarios and scenario tools.

Although the required long-term perspective demands scenarios that stretch into the distant future, any such scenarios carry with them considerable uncertainty. Inevitably the future will hold surprises. Scientific advances will be made, new technologies will be developed, and the direction of the economy will change, making it necessary to reassess the issues examined here. The Prospectus called for development of a limited number of scenarios, without a formal treatment of likelihood or uncertainty, requiring as noted earlier only that the modeling teams use assumptions that they believe to be “plausible” and “meaningful”. Formal uncertainty analysis has much to offer and could be a useful additional follow-on or complementary exercise. Here, however, the range of outcomes from the different modeling teams help to illustrate, if incompletely, the range of possibilities.

The scenarios developed here take the best information available now and assess what that may mean for the future. Any such exercise, however, will necessarily be incomplete and will not foresee all possible future developments. The best planning must, of course, prepare for changes in course later as new information becomes available.

1.5. Report Outline

Chapter 2 of this report provides an overview of the three models used in development of the scenarios. Chapter 3 describes the assumptions about key drivers in each of the models and reports reference scenario results. Chapter 4 provides greater detail on the design of the stabilization scenarios and presents their results. Chapter 5 provides concluding observations, including possible avenues for additional research.

The chapters seek to show how the models differ and, to the degree possible, relate where these differences matter and how they shape the results. The models have their own respective strengths and each offers its own reasonable representation of the world. The authors have been at pains to distill general conclusions common to the scenarios generated by the three modeling teams, while recognizing that other plausible representations could well lead to quite different results. The major results are presented primarily in the figures. Associated with the report is a database with the quantitative results available for those who wish to further analyze and use these scenarios. A description of the database, directions for use, and its location can be found in the appendix.[5]

1.6. References

CCSP [Climate Change Science Program]. 2003 (updated July 2004). *Strategic Plan for the U.S. Climate Change Science Program*. http://www.climatescience.gov/Library/stratplan2003/final/default.htm

CCSP [Climate Change Science Program]. 2005. *Final Prospectus for synthesis and assessment product 2.1*. http://www.climatescience.gov/Library/sap/sap2-1/sap2-1Prospectus-final.htm

IPCC [Intergovernmental Panel on Climate Change]. 1991. *Climate Change: The IPCC Response Strategies*. Washington, DC: Island Press.

IPCC [Intergovernmental Panel on Climate Change]. 1992. *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment*, ed. J.T Houghton, B.A. Callander, and S.K. Varney. Cambridge, UK: Cambridge University Press.

IPCC [Intergovernmental Panel on Climate Change]. 1996. *Climate Change 1995: Economic and Social Dimensions of Climate Change*, ed. J. P. Bruce, H. Lee, and E.F. Haites. Cambridge, UK: Cambridge University Press.

IPCC [Intergovernmental Panel on Climate Change]. 2001. *Climate Change 2001: The Scientific Basis*, ed. J.T. Houghton, Y. Ding, D.J Griggs, N. Noguer, P.J. van der Linden, X. Dai, K. Maskell and C.A. Johnson. Cambridge, UK: Cambridge University Press.

Leggett, J., W.J. Pepper, and R.J. Swart. 1992. Emission scenarios for the IPCC: an update. In *Climate Change 1992: The Supplemental Report to the IPCC Scientific Assessment*, ed. J.T. Houghton, B.A. Callander, and S.K. Varney. Cambridge, UK: Cambridge University Press.

Nakicenovic, N. et al. 2000. *Special Report on Emissions Scenarios*. Cambridge, UK: Cambridge University Press.

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[5] This data archive and associated appendix will be made available upon completion of the final draft of this report.

National Academy of Sciences. 1983. *Changing Climate: Report of the Carbon Dioxide Assessment Committee*. Washington, DC: National Academy Press.

National Research Council 2005. *Radiative Forcing of Climate Change: Expanding the Concept and Addressing Uncertainties*. National Academies Press, Washington, D.C.

Parson, E.A., and K. Fisher-Vanden. 1997. Integrated assessment models of global climate change. *Annual Review of Energy and the Environment* 22, 589-628.

Pepper, W.J., J. Leggett, R.J. Swart, J. Wasson, J. Edmonds, and I. Mintzer. 1992. *Emissions Scenarios for the IPCC: An Update – Assumptions, Methodology, and Results*. Geneva: Intergovernmental Panel on Climate Change.

US DOE [United States Department of Energy]. 1985. *Atmospheric Carbon Dioxide and the Global Carbon Cycle*, ed. J.R. Trabalka. DOE/ER-0239. Washington, DC: Office of Energy Research.

Weyant, J.P., and F. de la Chesnaye. 2005. Multigas scenarios to stabilize radiative forcing. *Energy Journal*, Special Edition on Multigas Scenarios and Climate Change.

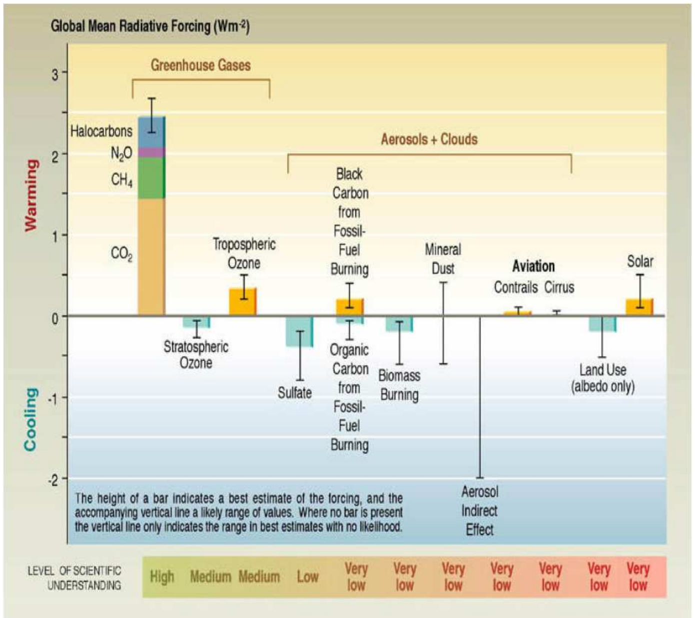
Table 1.1. Greenhouse Gas Concentrations and Forcing

	Preindustrial Concentration (1750)	Current Concentration (2000)	Increased Forcing W/m^2 (1750-2000)
CO_2	280 ppmv	369 ppmv	1.52
CH_4	700 ppbv	1760 ppbv	0.517
N_2O	270 ppbv	316 ppbv	0.153
HFCs	0	NA	0.005
PFCs	0	NA	0.014
SF_6	0	4 ppt	0.0025

Table 1.2. Radiative Forcing Stabilization Levels (W/m^2) and Approximate CO_2 Concentrations (ppmv). The stabilization levels were constructed so that the CO_2 concentrations resulting from stabilization of total radiative forcing, after accounting for radiative forcing from the non-CO_2 GHGs, would be roughly 450 ppmv, 550 ppmv, 650 ppmv, and 750 ppmv.

	(1) W/m^2 from Preindustrial (1750)	(2) W/m^2 from 2000 Levels	(3) Approximate long-term CO_2 Level (ppmv)	(4) Increase in CO_2 from Preindustrial (ppmv)	(5) Increase in CO_2 from 2000 Levels (ppmv)
Level 1	3.4	1.2	450	172	81
Level 2	4.7	2.5	550	272	181
Level 3	5.8	3.5	650	372	281
Level 4	6.7	4.5	750	472	381

Figure 1.1. Estimated Influences of Atmospheric Gases on Radiative Forcing, 1850-present



2. MODELS USED IN THIS STUDY

2.1. Overview of the Models

The analysis facilities used in this exercise are referred to as integrated assessment models (IAMs) in that they combine, in an integrated framework, the socio-economic and physical processes and systems that define the human influence on, and interactions with, the global climate. They integrate computer models of socio-economic and technological determinants of the emissions of greenhouse gases (GHGs) and other substances influencing the Earth's radiation balance with models of the natural science of Earth system response, including those of the atmosphere, oceans, and terrestrial biosphere. Although they differ in their specific design objectives and details of their mathematical structures, each of these IAMs was developed for the purpose of gaining insight into economic and policy issues associated with global climate change.

To create scenarios of sufficient depth, scope, and detail, a number of model characteristics were deemed critical for development of these scenarios. The criteria set forth in Chapter 1 led to the selection of three IAMs:

- The Integrated Global Systems Model (the IGSM) of the Massachusetts Institute of Technology's Joint Program on the Science and Policy of Global Change. The IGSM (Sokolov et al. 2005) is an Earth system model that comprises a multi-sector, multi-region economic component and a science component, including a two-dimensional atmosphere, a three-dimensional ocean, and a detailed biogeochemical model of the terrestrial biosphere. Because this study focuses on new emissions scenarios, results from the economic model component of the IGSM, the Emissions Prediction and Policy Analysis (EPPA) model (Paltsev et al. 2005), are featured in the discussion below. EPPA is a recursive-dynamic computable general equilibrium (CGE) model of the world economy and greenhouse-relevant emissions, solved on a five-year time step. Previous applications of the IGSM and its EPPA component system can be found at http://web.mit.edu/globalchange.

- The Model for Evaluating the Regional and Global Effects of GHG reduction policies (MERGE) was developed jointly at Stanford University and the Electric Power Research Institute. MERGE (Manne and Richels 2005) is an intertemporal general equilibrium model of the global economy in which the world is divided into nine-geopolitical regions. It is solved on a ten-year time step. MERGE is a hybrid model combining a bottom-up representation of the energy supply sector, together with a top-down perspective on the remainder of the economy.[1] Savings and investment decisions are modeled as if each region maximizes the discounted utility of its consumption, subject to an intertemporal wealth constraint. Embedded within this structure is a reduced-form representation of the physical Earth system. MERGE has been used to explore a range of climate-related issues, including multi-gas strategies, the value of low-carbon-emitting energy technologies, the choice of near-term hedging strategies under uncertainty, the impacts of learning-by-doing, and the potential importance of "when" and "where" flexibility. To support this analysis of stabilization scenarios, the multi-gas version has been revised by adjustments in technology and other assumptions. The MERGE code and publications describing its structure and applications can be found at http://www.stanford.edu/group/MERGE/.

- The MiniCAM is an integrated assessment model, (Brenkert et al. 2003) that combines a technologically detailed global energy-economy-agricultural-land-use model with a suite of coupled gas-cycle, climate, and ice-melt models, integrated in the Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC). MiniCAM was developed and is maintained at the Joint Global Change Research Institute, a partnership between the Pacific Northwest National Laboratory and the University of Maryland, while MAGICC was developed and is maintained at the National Center for Atmospheric Research. MiniCAM is solved on a 15-year time step. MiniCAM has been used extensively for energy, climate, and other environmental analyses conducted for organizations that include the U.S. Department of Energy (DOE), the U.S. Environmental Protection Agency (EPA), the Intergovernmental Panel on Climate Change (IPCC), and several major private sector energy companies. Its energy sector is based on a model developed by Edmonds and Reilly (1985). The model is designed to examine long-term, large-scale changes in global and regional energy systems, focusing on the impact of energy technologies. Documentation for MiniCAM can be found at http://www.globalchange.umd.edu/models/MiniCAM.pdf/.

These three are among the most detailed models of this type of IAM, and each has long history of development and application.

Because these models were designed to address an overlapping set of climate-change issues, they are similar in many respects. All three have social science-based components that capture the socio-economic and technology interactions underlying the emissions of GHGs, and each incorporates models of physical cycles for GHGs and other radiatively important substances and other aspects of the natural science of global climate. The

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[1] It differs from the pure "bottom-up" approach described in the Box 2.1 in that demands for energy are price-responsive.

differences among them lie in the detail and construction of these components and in the ways they are modeled to interact. Each was designed with somewhat different aspects of the climate issue as a main focus. IGSM includes the most detailed representation of the chemistry, physics, and biology of the atmosphere, oceans, and terrestrial biosphere; thus, its EPPA component is designed to provide the emissions detail that these natural science components require. MERGE has its origins in an energy-sector model that was initially designed for energy technology assessment. It was subsequently modified to explore the influence of expectations (and uncertainty regarding expectations) about future developments related to climate policy on the economics of current investment and the cost-minimizing allocation of emissions mitigation over time. Its focus requires a forward-looking structure, which in turn employs simplified non-energy components of the economy. MiniCAM is a technology rich IAM. It features detailed representations of energy technologies, energy systems, and energy markets, their interactions with demographics, the economy, agricultural technologies and markets land use, and the terrestrial carbon cycle.

Each of these IAMs thus has its unique strengths and areas of special insight. In this scenario study, the simultaneous application of different model structures is useful in revealing different aspects of the task of atmospheric stabilization. The differences among their results, presented in Chapters 3 and 4, are an indication of the limits of our knowledge about future GHG emissions and the challenges in stabilizing atmospheric conditions. Indeed, differences among the reference forecasts and in the implications of various stabilization targets are likely within the range that would be realized from an uncertainty analysis applied to any one of the three, as indicated by the analysis of the EPPA model by Webster et al. (2003).

Table 2.1 provides a cross-model overview of some of the key characteristics to be compared in the following sections of this chapter. Section 2.2 focuses on social science components, describing similarities and differences and highlighting the assumptions that have the greatest influences on the resulting scenarios. Section 2.3 does the same for the natural science sub-models of each IAM, which in this study make the connection between the emissions of GHGs and other radiatively important substances and the resulting atmospheric conditions.

Table 2.1. Characteristics of the Models

2.2. Socio-Economic and Technology Components

2.2.1. Equilibrium, Expectations, and Trade

As can be seen in Table 2.1, the models represent economic activity and associated emissions in a similar way; each divides the world economy into several regions, and further divides each region into economic sectors. In all three, the greatest degree of disaggregation is applied to the various components of energy supply and demand.

The models differ, however, in the representation of the equilibrium structure, the role of future expectations, and in the goods and services traded.

MERGE and the EPPA component of the IGSM are CGE models, which solve for a consistent set of supply-demand and price equilibria for each good and factor of production that is distinguished in the analysis. In the process, CGE models ensure a balance in each period of income and expenditure and of savings and investment for the economy, and they maintain a balance in international trade in goods and emissions permits. MiniCAM is a partial equilibrium model, solving for supply-demand and price equilibria within linked energy and agricultural markets. Other economic sectors that influence the demand for energy and agricultural products and the costs of factors of production in these sectors are represented through exogenous assumptions.

The models also differ in how expectations about the future affect current decisions. The EPPA component of the IGSM and MiniCAM are recursive-dynamic models, meaning they are solved one period at a time with economic agents modeled as responding to conditions in that period. This behavior is also referred to as “myopic” because these agents do not consider expected future market conditions in their decisions. The underlying behavioral assumption is that consumers and producers maximize their individual utilities or profits. In MiniCAM this process is captured through the use of demand and supply functions that evolve over time as a function of evolving economic activity and regional economic development; in IGSM explicit representative-agent utility and sector production functions ensure that consumer and producer decisions are consistent with welfare and profit maximization. In both of these models, the patterns of emissions mitigation over time in the scenarios that stabilize radiative forcing are imposed through assumptions intended to capture the features of a strategy that, as explained in Section 2.4, would be cost-efficient. MERGE, on the other hand, is an intertemporal optimization model where all periods are solved simultaneously such that resources and mitigation effort are allocated optimally over time as well as among sectors. Intertemporal models of this type are often referred to as “forward-looking” or “perfect foresight” models because actors in the economy base current decisions not only on current conditions but on future ones which are assumed to be known with certainty. Simultaneous solution of all periods ensures that agents’ expectations about the future are realized in the model solution. MERGE’s forward-looking structure allows it to explicitly solve for cost-minimizing emissions pathways, in contrast to MiniCAM and IGSM which exogenously prescribe emissions mitigation policies over time.

Although all three models also represent international trade in goods and services and include exchange in emissions permits, they differ in the combinations of goods and services traded. In IGSM, all goods and services represented in the model are traded, with electricity trade limited to geographically contiguous regions to the extent that it occurs in the base data. MiniCAM models international trade in oil, coal, natural gas, agricultural goods, and emission permits. MERGE models trade in oil and natural gas, emissions permits, energy-intensive industrial goods, and a single non-energy good representing all other tradeable goods and services.

2.2.2. Population and Economic Growth

A projected increase in the overall scale of economic activity is among the most important drivers of GHG emissions. However, economic growth depends, in part, on growth in population, which in all three models is an exogenously determined input. Although economic activity is a projected output of the models, its level is largely determined by assumptions about labor productivity and labor force growth, which are also model inputs. Policies to reduce emissions below those in the reference scenarios also affect economic activity, which may be measured as changes in Gross Domestic Product (GDP) or in national consumption. (See Chapter 4, which provides a discussion of the interpretation and limitations of GDP and other welfare measures.)

In MiniCAM, labor productivity and growth in the labor force are the main drivers of GDP growth. GDP is calculated as the product of labor force and average labor productivity modified by an energy-service cost feedback elasticity. The labor force and labor productivity are both exogenous inputs to MiniCAM, but were developed for these scenarios from detailed demographic analysis. Starting with the underlying population scenario, the labor force was estimated from age and gender-specific labor force participation rates applied to the relevant cohorts, and then summed and adjusted by a fixed unemployment rate. Trends were explicitly considered, such as the increasing rate of labor force participation by females in the U.S. economy, the aging of the "baby boomers," and evolving labor participation rates in older cohorts, reflecting the consequences of changing health and survival rates. Labor force productivity growth rates vary over time and across region to represent these evolving demographics.

In MERGE and the EPPA component of the IGSM the labor force and its productivity, while extremely important, are not the only factors determining GDP. Savings and investment and productivity growth in other factors (e.g., materials, land, labor, and energy) variously contribute as well. IGSM and MERGE use population directly as a measure of the labor force and apply assumptions about labor productivity change that are appropriate for that definition.

2.2.3. Energy Demand

In all three models, energy demands are represented regionally and driven by regional economic activity. As a region's economic activity increases, its corresponding demand for energy services rises. Energy demand is also affected by assumptions about changes in technology, in the structure of the economy, and in other economic conditions (see Section 2.2.5). Similarly, all the models represent the way demand will respond to changes in price. The formulation of price response is particularly important in the construction of stabilization scenarios because the imposition of a constraint on carbon emissions will require the use of more expensive energy sources with lower emissions and will, therefore, raise the consumer price of all forms of energy.

The demand for energy is derived from demands for other goods and services in all three IAMs. However, the models differ in the way they derive their energy demands. In the

IGSM each good- or service-producing sector demands energy. The production sector is an input-output structure where every industry (including the energy sector) supplies its outputs as inputs to intermediate production in other industries and for final consumption. Households have separate demands for automobile fuel and for all other energy services. Each final demand sector can use electricity, liquid fuels (petroleum products or biomass liquids), gas, and coal; fuel for automobiles is limited to liquids. MiniCAM is similar in that each MiniCAM sector demands energy. Energy is demanded by both final consumers and transforming sectors. In MiniCAM there are three final energy consumption sectors: buildings, industry and transport which consume electricity and refined energy products (coal, biomass, refined liquid fuels, methane and hydrogen). In addition energy is demanded by energy producing and refining sectors, power generators, and hydrogen producers, whose demands in turn are derived from the demands arising in the final energy consumption sectors. MERGE is similar to the IGSM except that its inter-industry transactions are aggregated into a single non-energy production sector for each region from which demands for fuels (oil, gas, coal and bioenergy) and electricity are derived. The power generation sector’s demands for energy are derived from the economy’s demand for electricity.

2.2.4. Energy Resources

The future availability of energy resources, particularly of exhaustible fossil fuels, is an important determinant of energy use and emissions, so the models provide explicit treatments of the underlying resource base. All three include empirically based estimates of in-ground resources of oil, coal, and natural gas that might ultimately be available, along with a model of the costs of extraction. The levels of detail in the different models are shown in Table 2.1. Each of the models includes both conventional and unconventional sources in its resource base and represents the process of exhaustion of resources by an increasing cost of exploitation. That is, lower-cost resources are utilized first so that the costs of extraction rise as the resources are depleted. The models differ, however, in the way they represent the increasing costs of extraction. MiniCAM divides the resource base for each fossil fuel into discrete grades with increasing costs of extraction, along with an exogenous technical change that lowers resource extraction costs over time. MERGE has similar differential grades for oil and gas, but assumes that the coal base is more than sufficient to meet potential demand and that exogenous technological improvements in extraction will be minimal. For these reasons, MERGE represents coal as having a constant cost over time irrespective of utilization. IGSM models resource grades with a continuous function, separately identifying conventional oil, shale oil, natural gas, and coal. Fuel-producing sectors are subject to economy-wide technical progress (e.g., increased labor productivity growth), which partly offsets the rise in extraction costs. The models all incorporate tar sands and unconventional gas (e.g., tight gas, coal-seam gas) in the grade structure for oil and natural gas, and each also includes the potential development of shale oil.

The models seek to represent all resources that could be available as technology and economic conditions vary over time and across simulations. Thus, they reflect judgments that technology will advance to the point where currently unused resources can be economically exploited. Generally, then, they define a resource base that is more expansive than, for example, that of the U.S. Geological Survey, which estimates technological and economic feasibility only at current technology and prices. However, differences exist in the treatments of potentially available resources. MiniCAM includes a detailed representation of the nuclear power sector, including Uranium and Thorium resources, nuclear fuel fabrication, reactor technology options, and associated fuel-cycle cycles, including waste, storage, and fuel reprocessing. IGSM and MERGE assume that the uranium resources used for nuclear power generation are sufficient to meet likely use and, therefore, do not explicitly model their depletion.

The treatment of wind and solar resources also differs among the models. IGSM represents the penalty for intermittent supply by modeling wind and solar as imperfect substitutes for central station generation, where the elasticity of substitution implies a rising cost as these resources supply a larger share of electricity supply. Land is also an input, and the regional cost of wind/solar is based on estimates of regional resource availability and quality. MERGE represents these resources as having a fixed cost that improves over time, but it applies upper limits on the proportion of these resources, representing limits on the integration of these resources into the grid. MiniCAM represents wind and solar technologies as extracting power from graded, regional, renewable resource bases. Variation in resource availability across diurnal and annual cycles affects market penetration of these technologies. As wind and solar technologies achieve larger fractions of the total power generation system, storage and ancillary power production capacity are required in MiniCAM, which in turn affects the cost of power generation and technology choice.

IGSM and MiniCAM model biomass production as competing for agricultural land. Increasing production leads to an increasing land rent, representing the scarcity of agricultural land, and, thus, to an increasing cost of biomass as production expands. MiniCAM also has a separate set of regional supply functions for biomass supplied from waste and residue sources. MERGE places an upper limit on the amount of biomass energy that might supply the electric and non-electric energy sectors, but otherwise assumes a fixed cost for biomass energy and allows biomass to compete unhindered in the market.

2.2.5. Technology and Technological Change

Technology is the broad set of processes covering know-how, experience and equipment, used by humans to produce services and transform resources. In the three models participating in this study the relationship between things that are produced and things that are used in the production process are represented mathematically. In the jargon of the models, the relationship between things that are produced and things that are used in the production process is referred to as a production function.

The three modeling teams differed substantially in their representation of technology depending on their overall design objectives and because data limitations and computational feasibility force tradeoffs between the inclusion of engineering detail and the representation of the interaction among the segments of a modern economy that determines supply, demand, and prices (see Box 2.1).

Though all three of the models applied here follow a “hybrid” approach to the representation of energy technology, involving substantial detail in some areas and more aggregate representations in others, some of the choices that flow from the distinct design of each can be seen in Table 2.1. They represent energy demand, as described in Section 2.2.3, with the application of an autonomous energy efficiency improvement (AEEI) factor to represent non-price-induced trends in energy use. However, AEEI parameter values are not directly comparable across the models because each has a unique representation of the processes that together explain the multiple forces that have contributed historically to changes in the energy intensity of economic activity. In IGSM and MERGE, the AEEI captures non-price changes (including structural change not accounted for in the models) that can be energy-using rather than energy-saving. MERGE represents the AEEI as a function of GDP growth in each region. MiniCAM captures shifts among fuels through differing income elasticities, which change over time, and separately represents AEEI efficiency gains.

--- BOX 2.1: TOP-DOWN, BOTTOM-UP, AND HYBRID MODELING ---

The models used in energy and environmental assessments are sometimes classified as either top-down or bottom-up in structure, a distinction that refers to the way they represent technological options. A top-down model uses an aggregate representation of how producers and consumers can substitute non-energy inputs for energy inputs, or relatively energy-intensive goods for less energy-intensive goods. Often, these tradeoffs are represented by aggregate production functions or by utility functions that describe consumers’ willingness and technical ability to substitute among goods. The bottom-up approach begins with explicit technological options, and fuel substitution or changes in efficiency occur as a result of a discrete change from one specific technology to another. The bottom-up approach has the advantage of being able to represent explicitly the combination of outputs, inputs, and emissions of types of capital equipment used to provide consumer services (e.g., a vehicle model or building design) or to perform a particular step in energy supply (e.g., a coal-fired powerplant or wind turbine). However, a limited number of technologies are typically included, which may not well represent the full set of possible options that exist in practice. Also, in a pure bottom-up approach, the demands for particular energy services are often characterized as fixed (unresponsive to price), and the prices of inputs such as capital, labor, energy and materials are exogenous. On the other hand, the top-down approach explicitly models demand responsiveness and input prices, which usually require the use of continuous functions to model at least some parts of the available technology set. The disadvantage of the latter approach is that production functions of this form will poorly represent switch points from one technology to another—as from one form of electric generation to another, or from gasoline to biomass blends as vehicle fuel. In practice, the vast majority of models in use today, including those applied in this study, are hybrids in that they include substantial technological detail in some sectors and more aggregate representations in others.

--- END BOX ---

Other areas shown in the table where there are significant differences among the models are in energy conversion—from fossil fuels or renewable sources to electricity, and from solid fossil fuels or biomass to liquid fuels or gas. In the IGSM, discrete energy technologies are represented as energy supply sectors contained within the input-output structure of the economy. Those sources of fuels and electricity that now dominate supply are represented as production functions with the same basic structure as the other sectors of the economy. Technologies that may play a large role in the future (e.g., power plants with carbon capture and storage or oil from shale) are introduced using this same structure, calibrated to current engineering estimates of required inputs. They are subject to economy-wide productivity improvements (e.g., labor, land, and energy productivity), whose effect on cost depends on the share of each factor in the technology production function. MERGE and MiniCAM characterize energy-supply technologies in terms of discrete technologies. In MERGE, technological improvements are captured by allowing for the introduction of more advanced technologies in future periods; in MiniCAM, the cost and performance of technologies are assumed to improve over time and new technologies become available in the future. Similar differences among the models hold for other conversion technologies, such as coal gasification or liquefaction or liquids from biomass.

The entry into the market of new sources and their levels of production by region are determined endogenously in all three models and depend on the relative costs of supply. It should be emphasized that the models do not explicitly represent the research and development (R&D) process and how it leads to technical change through, for example, public and private R&D, spillovers from innovation in other economic sectors, and learning-by-doing. A number of recent efforts have been made to incorporate such processes and their effects as an endogenous component of modeling exercises. However, generally these studies have not been applied to models of the complexity needed to meet the requirements of this scenario product.

Because of the differences in structure among these models, there is no simple technology-by-technology comparison of performance and cost across particular sources of supply or technical options. This situation exists for a variety of reasons. First, cost is an output of the three models and not an input. In the three models here technologies are defined not in terms of some exogenously specified cost, but rather in terms of a set of parameters to a production function. The three models differ in many regards. Each model defines the scope of a technology differently. Sectoral definitions, technology definitions, and data sources all vary across the three models. For example, one model has a service sector while another has a buildings sector. There is then, no common definition for technologies, technology descriptors and hence for a set of comparable costs. Readers interested in understanding detailed technology assumptions employed by the two models are encouraged to consult the detailed scenario documentation for each of the three modeling teams: [Insert references].

The influence of differing technology specifications and assumptions is evident in the results shown in Chapters 3 and 4, with several of these features being particularly notable. In the absence of any greenhouse gas policy, motor fuel is drawn ever more heavily from high-emitting sources—for example, oil from shale comes in under IGSM's resource and technology assumptions, but liquids from coal enter in MERGE and MiniCAM. Furthermore, because each model assumes market mechanisms operate efficiently, the marginal cost of reducing greenhouse gas emissions—that is the cost of reducing the last ton of greenhouse gas—is equal to the price of carbon in every technology employed in every sector and in every country of the world. When stabilization conditions are imposed, all models show carbon capture and storage taking a key role over the study period. Nuclear power contributes heavily in MERGE and in MiniCAM, whereas the potential role of this technology is overridden in the IGSM results by a scenario assumption of political restraints on expansion. Finally, although differences in emissions in the no-policy scenario contribute to variation in the projected difficulty of achieving stabilization, alternative assumptions about rates of technical change in supply technologies also play a prominent role.

2.2.6. Land Use and Land Use Change

The models used in this study were developed originally with a focus on energy and fossil carbon emissions. The integration of the terrestrial biosphere, including human activity, into the climate system is less highly developed. Each model represents the global carbon cycle, including exchanges with the atmosphere of natural vegetation and soils, the effects of human land-use and responses to carbon policy, and feedbacks to global climate. None represents all of these possible responses and interactions, and the level of detail varies substantially among the models. For example, they differ in the handling of natural vegetation and soils and in their responses to CO_2 concentration and changed climate. Furthermore, land-use practices (e.g., low- or no-till agriculture, or biomass production) and changes in land use (e.g., afforestation, reforestation, or deforestation) that influence GHG emissions and the sequestration of carbon in terrestrial systems are handled at different levels of detail. Indeed, improved two-way linking of global economic and climate analysis with models of physical land use (land use responding to climate and economic pressures and to climate response changes in the terrestrial biosphere) is the subject of ongoing research in these modeling groups.

In IGSM, land is an input to agriculture, biomass production, and wind/solar energy production. Agriculture is a single sector that aggregates crops, livestock and forestry. Biomass energy production is modeled as a separate sector, which competes with agriculture for land. Markets for agricultural goods and biomass energy are international, and demand for these products determines the price of land in each region and its allocation among uses. In other sectors, returns to capital include returns to land, but the land component is not explicitly identified. Anthropogenic emissions of GHGs (importantly including CH_4 and N_2O) are estimated within the IGSM model as functions of agricultural activity and assumed levels of deforestation. The response of terrestrial vegetation and soils to climate change and CO_2 increase is captured in the Earth system component of the model, which provides a detailed treatment of biogeochemical and land-surface properties of terrestrial systems. However, the biogeography of natural ecosystems and human uses remains unchanged over the simulation period, with the area of cropland fixed to the pattern of the early 1990s. Balance in the carbon cycle between ocean uptake, land-use and land-use change, and anthropogenic emissions is achieved in the IGSM with an adjustment factor to assure that the recent trend in atmospheric CO_2 increase is replicated. This adjustment factor is best interpreted as what carbon uptake due to forest regrowth must have been given the representation of terrestrial and ocean systems in the IGSM. The need for such an adjustment factor reflects the continuing scientific uncertainty in the carbon cycle; i.e., with fossil emissions and concentrations relatively well-known, the total uptake is known but the partitioning of the uptake between terrestrial and ocean systems is uncertain (e.g. see Sabine *et al.*, 2004). IGSM does not simulate carbon price-induced changes in carbon sequestration (e.g., reforestation, tillage) and change among land-use types in EPPA is not fed to the terrestrial biosphere component of the IGSM.

The version of MERGE used here incorporates a neutral terrestrial biosphere across all scenarios. That is, it is assumed that the net CO_2 exchange with the atmosphere by natural ecosystems and managed systems—the latter including agriculture, deforestation, afforestation, reforestation and other land-use change—sums to zero.

MiniCAM includes a model that allocates the land area in a region among various components of human use and unmanaged land—with changes in allocation over time in relation to income, technology and prices—and estimates the resulting CO_2 emissions (or sinks) that result. Land conditions and associated emissions are parameterized for a set of regional sub-aggregates. The supply of primary agricultural production (four food crop types, pasture, wood, and commercial biomass) is simulated regionally with competition for a finite land resource based on the average profit rate for each good potentially produced in a region. In stabilization scenarios, the value of carbon stored in the land is added to this profit, based on the average carbon content of different land uses in each region. This allows carbon mitigation policies to explicitly extend into land and agricultural markets. The model is solved by clearing a global market for primary agricultural goods and regional markets for pasture. The biomass market is cleared with demand for biomass from the energy component of the model. Exogenous assumptions are made for the rate of intrinsic increase in agricultural productivity although net productivity can decrease in the case of expansion of agricultural lands into less productive areas (Sands and Leimbach 2003). Unmanaged land can be converted to agro-forestry, which in general results in net CO_2 emissions from tropical regions in the early decades. Emissions of non-CO_2 GHGs are tied to relevant drivers, for example, with CH_4 from ruminant animals related to beef production. MiniCAM thus treats the effects on carbon emissions of gross changes in land use (e.g., from forests to biomass production) using an average emission factor for such conversion. The pricing of carbon stocks in the model provides a counterbalance to increasing demand for biomass crops in stabilization scenarios.

2.2.7. Emissions of CO_2 and Non-CO_2 Greenhouse Gases

In all three models, the main source of CO_2 emissions is fossil fuel combustion, which is computed on the basis of the carbon content of each of the underlying resources: oil, natural gas, and coal. Special adjustments are made to account for emissions associated with the additional processing required to convert coal, tar sands, and shale sources into products equivalent to those from conventional oil. Other industrial CO_2 emissions also are included, primarily from cement production.

As required for this study, all three models also include representations of emissions and abatement of CH_4, N_2O, HFCs, PFCs, and SF_6 (plus aerosols and other substances not considered in this study). The models use somewhat different approaches to represent abatement of the non-CO_2 GHGs. The IGSM includes the emissions and abatement possibilities directly in the production functions of the sectors that are responsible for emissions of the different gases. Abatement possibilities are represented by substitution elasticities (i.e., the degree to which one factor of production can be substituted for another) in a nested structure that encompasses gas emissions and other inputs, benchmarked to reflect bottom-up studies of abatement potential. This construction is parallel to the representation of fossil fuels in production functions, where abatement potential is similarly represented by the substitution elasticity between fossil fuels and other inputs, with the specific set of substitutions governed by the nest structure. Abatement opportunities vary by sector and region.

In MERGE, methane emissions from natural gas use are tied directly to the level of natural gas consumption, with the emissions rate decreasing over time to represent reduced leakage during the transportation process. Non-energy sources of CH_4, N_2O, HFCs, PFCs, and SF_6 are based largely on the guidelines provided by the Energy Modeling Forum (EMF) Study No. 21 on Multi-Gas Mitigation and Climate Change (Weyant and de la Chesnaye 2005). The EMF developed baseline projections from 2000 through 2020. For all gases but N_2O and CO_2, the baseline for beyond 2020 was derived by extrapolation of these estimates. Abatement cost functions for these two gases are also based on EMF 21, which provided estimates of the abatement potential for each gas in each of 11 cost categories in 2010. These abatement cost curves are directly incorporated in the model and extrapolated after 2010 following the baseline. There is also an allowance for technical advances in abatement over time.

MiniCAM calculates emissions of CH_4, N_2O, and seven categories of industrial sources for HFCs, PFCs, and SF_6. Emissions are determined for over 30 sectors, including fossil fuel production, transformation, and combustion; industrial processes; land use and land-use change; and urban emissions. For details, see Smith (2005) and Smith and Wigley (2006). Emissions are proportional to driving factors appropriate for each sector, with emissions factors in many sectors decreasing over time according to an income-driven logistic formulation. Marginal abatement cost (MAC) curves from the EMF-21 exercise are applied, including shifts in the curves for methane due to changes in natural gas prices. Any “below zero” reductions in MAC curves are assumed to apply in the reference scenario.

2.3. Earth Systems Component

The Earth system components of the models serve to compute the response of the atmosphere, ocean, and terrestrial biosphere to emissions and increasing concentrations of GHGs and other substances. Representation of these processes, including the carbon cycle (see Box 2.2, is necessary to determine emissions paths consistent with stabilization because these systems determine how long each of these substances remains in the atmosphere and how it interacts in the modification of the Earth's radiation balance. Each of the models includes such physical-chemical-biological components, but differs from the other models in the level of detail incorporated. The most elaborated Earth system components are found in the IGSM (Sokolov et al. 2005), which falls in a class of models classified as Earth System Models of Intermediate Complexity, or EMICs (Claussen et al. 2002) These are models that fall between the full three-dimensional atmosphere-ocean general circulation models (AOGCMs) and energy balance models with a box model of the carbon cycle. The Earth system components of MERGE and MiniCAM fall in the class of energy balance/carbon cycle box models. Table 2.1 shows how each of the models treat different components of the Earth systems.

--- BOX 2.2: THE CARBON CYCLE ---

Although an approximate atmospheric "lifetime" is sometimes calculated for CO_2, the term is potentially misleading because it implies that CO_2 put into the atmosphere by human activity always declines over time by some stable removal process. In fact, the calculated concentration of CO_2 is not related to any mechanism of destruction, or even to the length of time an individual molecule spends in the atmosphere, because CO_2 is constantly exchanged between the atmosphere and the surface layer of the ocean and with vegetation. Instead, it is more appropriate to think about how the quantity of carbon that the Earth contains is partitioned between stocks of in-ground fossil resources, the atmosphere (mainly as CO_2), surface vegetation and soils, and the surface and deep layers of the ocean. When stored CO_2 is released into the atmosphere, either from fossil or terrestrial sources, atmospheric concentrations increase, leading to disequilibrium with the ocean, and more carbon is taken up than is cycled back. For land processes, vegetation growth may be enhanced by increases in atmospheric CO_2, and this change could augment the stock of carbon in vegetation and soils. As a result of the ocean and terrestrial uptake, only about half of the carbon currently emitted remains in the atmosphere and over millennial time scales oceans would continue to remove carbon until a large fraction, presently about 80 percent, would ultimately be removed to the oceans leaving about 20 percent as a permanent increase in the atmospheric CO_2 concentration. But this large removal only occurs because current levels of emissions lead to substantial disequilibrium between atmosphere and ocean. Lower emissions would lead to less uptake, as atmospheric concentrations come into balance with the ocean and interact with the terrestrial system. Rising temperatures themselves will reduce uptake by the ocean, and will affect terrestrial vegetation uptake, processes that the models in this study variously represent.

An important policy implication of these carbon-cycle processes as they affect stabilization scenarios is that stabilization of emissions at anything like today's level will not lead to stabilization of atmospheric concentrations. CO_2 concentrations were increasing in the 1990s at just over 3 ppmv per year, an annual increase of 0.8 percent. Thus, even if societies were able to stabilize emissions at current levels, atmospheric concentrations of CO_2 would continue to rise. As long as emissions exceed the rate of uptake, even very stringent abatement will only slow the rate of increase.

--- END BOX ---

The IGSM has explicit spatial detail, resolving the atmosphere into multiple layers and by latitude, and includes a terrestrial vegetation model with multiple vegetation types that are also spatially resolved. A version of the IGSM with a full three-dimensional ocean model was used for this study, and it includes temperature dependent uptake of carbon. The IGSM models atmospheric chemistry, resolved separately for urban (i.e., heavily polluted) and background conditions. Processes that move carbon into or out of the ocean and vegetation are modeled explicitly. IGSM also models natural emissions of CH_4 and N_2O, which are weather/climate-dependent. The model includes a radiation code that computes the net effect of atmospheric concentrations of the GHGs studied in the scenarios considered below. Also included in the global forcing is the effect of changing ozone and aerosol levels, which result from projected emissions of methane and non-GHGs, such as NO_x and volatile organic hydrocarbons, SOx, black carbon, and organic carbon from energy, industrial, agricultural, and natural sources.

MERGE's physical Earth system component is embedded in the intertemporal optimization framework, thus allowing solution of an optimal allocation of resources through time, accounting for damages related to climate change, or optimizing the allocation of resources with regard to other constraints such as concentrations, temperature, or radiative forcing. In this study, the second of these capabilities is applied, with a constraint on radiative forcing (see Chapter 4). In contrast, the IGSM and MiniCAM Earth system models are driven by emissions as simulated by the economic components. In that regard, they are simulations rather than optimization models.

The carbon cycle in MERGE relates emissions to concentrations using a convolution ocean carbon-cycle model and assuming a neutral biosphere (i.e., no net CO_2 exchange). It is a reduced-form carbon cycle model developed by Maier-Reimer and Hasselmann (1987). Carbon emissions are divided into five classes, each with different atmospheric lifetimes. The behavior of the model compares favorably with atmospheric concentrations provided in the IPCC's Third Assessment Report (2001) when the same SRES scenarios of emissions are simulated in the model (Nakicenovic et al. 2000). MERGE models the radiative effects of GHGs using relationships consistent with summaries by the IPCC, and applies the median aerosol forcing from Wigley and Raper (2001). The aggregate effect is obtained by summing the radiative forcing effect of each gas.

MiniCAM uses the MAGICC model (Wigley and Raper 2001, 2002) as its biophysical component. MAGICC is an energy-balance climate model that simulates the energy inputs and outputs of key components of the climate system (sun, atmosphere, land surface, ocean) with parameterizations of dynamic processes such as ocean circulations. It operates by taking anthropogenic emissions from the other MiniCAM components, converting these to global average concentrations (for gaseous emissions), then determining anthropogenic radiative forcing relative to pre-industrial conditions, and finally computing global mean temperature changes. The carbon cycle is modeled with both terrestrial and ocean components: the terrestrial component includes CO_2 fertilization and temperature feedbacks; the ocean component is a modified version of the Maier-Reimer and Hasselmann (1987) model that also includes temperature effects on CO_2 uptake. Net land-use change emissions from the MiniCAM's land-use change component are fed into MAGICC so that the global carbon cycle is consistent with the amount of natural vegetation. Reactive gases and their interactions are modeled on a global-mean basis using equations derived from results of global atmospheric chemistry models (Wigley and Raper 2002).

In MiniCAM, global mean radiative forcing for CO_2, CH_4, and N_2O are determined from GHG concentrations using analytic approximations. Forcings for other GHGs are taken to be proportional to concentrations. Forcings for aerosols (for sulfur dioxide and for black and organic carbon) are taken to be proportional to emissions. Indirect forcing effects, such as the effect of CH_4 on stratospheric water vapor, are also included. Given radiative forcing, global mean temperature changes are determined by a multiple box model with an upwelling-diffusion ocean component. The climate sensitivity is specified as an exogenous parameter. MAGICC's ability to reproduce the global mean temperature change results of atmosphere-ocean general circulation models has been demonstrated (Cubasch et al. 2001, Raper and Gregory 2001).

Although aerosols and ozone are not included in the computation of the radiative forcing targets that are the focus of these scenarios they are nonetheless included in the simulations as noted above. That is, the target radiative forcing levels identified in Table 1.2, and the radiative forcing levels reported in subsequent chapters, account for only that part of radiative forcing due to those GHGs covered by the target. The models can simulate total radiative forcing including additional positive forcing from ozone and dark aerosols and negative forcing from sulfate aerosols. As shown by Prinn *et al.* (2006), even for very large changes in emissions related to these substances the temperature effect is small, in large part because aerosols and ozone have offsetting cooling and warming effects. To the extent temperature is affected by these substances, however, they have a small, indirect influence on the results because trace gas cycles are climate-dependent. For example, climate affects vegetation and ocean temperature and thus carbon uptake, and natural emissions of CH_4 and N_2O and the lifetime of CH_4 also depend on climate. Because the net effect of these substances on temperature is small, the feedback effect on trace gas cycles also is very small. However, to the extent these feedbacks are represented in the models as discussed above, they are included in the calculation of required emissions reduction because the temperature paths, while not reported here, are simulated in the models and affect the reported carbon and other gas concentrations. By the same token, the Montreal gases, which are being phased out, are nonetheless included in these models and exert some influence on temperature.

We note here that while the models have capabilities to evaluate to varying degrees climate change effects, the Prospectus limited the focus of this report to emissions scenarios. Additional CCSP products will focus on the climate consequences of changing concentrations and the attendant impacts of changing climate on ecosystems and the economy. One aspect of this division of the problem is that the three models employed in this exercise are not fully closed. With few exceptions, these three models do not include the consequences of such feedback effects as temperature on heating and cooling degree days, local climate change on agricultural productivity, a CO_2 fertilization effect on agricultural productivity (though a CO_2 fertilization effect is included in the terrestrial carbon cycle models employed by IGSM and MiniCAM), climate effects of water availability for applications ranging from crop growing to power plant cooling. We leave such improvements to future research.

2.4. References

Brenkert, A., S. Smith, S. Kim, H. Pitcher. 2003. *Model Documentation for the MiniCAM*. Pacific Northwest National Laboratory, Technical Report PNNL-14337.

Claussen, M., L.A. Mysak, A.J. Weaver, M. Crucifix, T. Fichefet, M.-F. Loutre, S.L. Weber, J. Alcamo, V.A. Alexeev, A. Berger, R. Calov, A. Ganopolski, H. Goosse, G. Lohman, F. Lunkeit, I.I. Mokhov, V. Petoukhov, P. Stone, and Zh. Wang. 2002. Earth system models of intermediate complexity: Closing the gap in the spectrum of climate system models. *Climate Dynamics* 15, 579-586.

Cubasch, U., Meehl, G. A., Boer, G. J., Stouffer, R. J., Dix, M., Noda, A., Senior, C. A., Raper, S., Yap, K. S., 2001: Projections of future climate change. In IPCC, 2001: *Climate Change 2001: The Scientific Basis*. Cambridge, UK. 525–582.

Edmonds, J., and J. Reilly. 1985. *Global Energy: Assessing the Future*. New York: Oxford University Press.

IPCC (Intergovernmental Panel on Climate Change), 2001. *Climate Change 2001: The Scientific Basis – Contribution of Working Group 1 to the third assessment report of the IPCC*. Cambridge, UK.

Maier-Reimer, E., and K. Hasselmann. 1987. Transport and storage of CO_2 in the ocean —An inorganic ocean-circulation carbon cycle model. *Climate Dynamics* 2: 63–90.

Manne, A. and Richels, R. 2005. “MERGE-A Model for Global Climate Change.” In *Energy and Environment* eds. Loulou, R. Waaub, J. and Zaccour, G. Springer.

Nakicenovic, N., J. Alcamo, G. Davis, B. de Vries, J. Fenhann, S. Gan, K. Gregory, A. Grubler, T. Y. Jung, T. Kram, E. L. L. Rovere, L. Michaelis, S. Mori, T. Morita, W. Pepper, H. Pitcher, L. Price, K. Riahi, A. Roehrl, H.-H. Rogner, A. Sankovski, M. Schlesinger, P. Shukla, S. Smith, R. Swart, S. van Rooijen, N. Victor, and Z. Dadi. 2000. *Special Report on Emissions Scenarios*. Cambridge, UK: Cambridge University Press.

Paltsev, S., J.M. Reilly, H.D. Jacoby, R.S. Eckaus, J. McFarland, M. Sarofim, M. Asadoorian, and M. Babiker. 2005. *The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Version 4*. Report 125. Cambridge, MA: MIT Joint Program on the Science and Policy of Global Change**.**

Prinn, R., J. Reilly, M. Sarofim, C. Wang and B. Felzer. 2006. Effects of air pollution control on climate.” In: Integrated Assessment of Human-induced Climate Change [M. Schlesinger, ed.], Cambridge University Press (in press)

Raper and Gregory. 2001. {NEED TO COMPLETE THIS CITATION}

Sabine, C.L., M. Heiman, P. Artaxo, D.C. Bakker, C.-T. Chen, C.B. Field, N. Gruber, C. LeQuéré, R.G. Prinn, J.E. Richey, P. Romero-Lankao, J. Sathaye and R. Valentini, 2004. Current status and past trends of the carbon cycle. In: *The Global Carbon Cycle, SCOPE Project 62*, C.B. Field and M.R. Raupach (eds.), Island Press, Washington DC, pgs 17-44.

Sands, R.D., and M. Leimbach. 2003. Modeling agriculture and land use in an integrated assessment framework, *Climatic Change* 56: 185–210.

Smith, S.J., and T.M.L. Wigley. 2006. Multi-gas forcing stabilization with the MiniCAM. (accepted for publication in the *Energy Journal*).

Smith, S. J. 2005. Income and pollutant emissions in the OBJECTS MiniCAM model. *Journal of Environment and Development* 14:1, 175–196.

Sokolov, A.P., C.A. Schlosser, S. Dutkiewicz, S. Paltsev, D.W. Kicklighter, H.D. Jacoby, R.G. Prinn, C.E. Forest, J. Reilly, C. Wang, B. Felzer, M.C. Sarofim, J. Scott, P.H. Stone, J.M. Melillo & J. Cohen. 2005. 124. *The MIT Integrated Global System Model (IGSM) Version 2: Model Description and Baseline Evaluation.* Report 124. Cambridge, MA: MIT Joint Program on the Science and Policy of Global Change.

Webster, M.D., M. Babiker, M. Mayer, J.M. Reilly, J. Harnisch, R. Hyman, M.C. Sarofim and C. Wang. 2003. Uncertainty in emissions projections for climate models, *Atmospheric Environment* 36(22): 3659-3670.

Weyant, J.P., and F. de la Chesnaye. 2005. Multigas scenarios to stabilize radiative forcing. *Energy Journal*, Special Edition on Multi-gas Scenarios and Climate Change.

Wigley, T.L.M. and Raper. 2002. Reasons for Larger Warming Projections in the IPCC Third Assessment Report, *Nature*, 357, 293-300.

Wigley, T.L.M. and Raper. 2001. Interpretation of High Projections for Global-mean Warming, *Science*, 293, 451-454.

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Table 2.1 Characteristics of the Integrated Assessment Models

Feature	**IGSM & EPPA economics component**	**MERGE**	**MiniCAM**
Regions	16	9	14
Time Horizon, Time Steps	2100, 5-year steps	2200, 10-year steps	2095, 15-year steps
Model Structure	General Equilibrium	General Equilibrium	Partial Equilibrium
Solution	Recursive Dynamic	Intertemporal Optimization	Recursive Dynamic
Final Energy Demand Sectors in Each Region	Households, private transportation, commercial transportation, service sector, agriculture, energy intensive industries, other industry	A single non-energy production sector	Buildings, transportation, industry (including agriculture)
Capital Turnover	Five vintages of capital with a depreciation rate	A "putty clay" approach wherein the input-output coefficients for each cohort are optimally adjusted to the future trajectory of prices at the time of investment	Vintages with constant deprecation rate for all electricity-sector capital; capital structure not explicitly modeled in other sectors
Goods in International Trade	All energy and non-energy goods, emissions permits	Energy, energy intensive industry goods, emissions permits, representative tradeable good.	Oil, coal, natural gas, biomass, agricultural goods, emissions permits
Emissions	CO_2, CH_4, N_2O, HFCs, PFCs, SF_6, CO, NOx, SOx, NMVOCs, BC, OC, NH_3	CO_2, CH_4, N_2O, long-lived F-gases, short-lived F-gases, SOx	CO_2, CH_4, N_2O, CO, NOx, SO_2, NMVOCs, BC, OC, HFC245fa, HFC134a, HFC125, HFC143a, SF_6, C_2F_6, CF_4
Land use	Agriculture (crops, livestock, forests), biomass land use, land use for wind/solar	Reduced-form emissions from land-use. No explicit land use sector. Assume no net terrestrial emissions of CO_2	Agriculture (crops, pasture, forests) & biomass land use and unmanaged land. The agriculture-land-use module directly determines land-use change emissions and terrestrial carbon stocks.
Population	Exogenous	Exogenous	Exogenous
GDP Growth	Exogenous productivity growth assumptions for labor, energy, land; exogenous labor force growth determined from population growth; endogenous capital growth through savings and investment	Exogenous productivity growth assumptions for labor, energy; exogenous labor force growth determined from population growth; endogenous capital growth through savings and investment	Exogenous productivity growth assumptions for labor; exogenous labor force growth based on population demographics
Energy Efficiency Change	Exogenous	Proportional the rate of GDP growth in each region	Exogenous

Energy Resources	Oil (including tar sands), shale oil, gas, coal, wind/solar, land (biomass), hydro, nuclear fuel	Conventional oil, unconventional oil (coal-based synthetics, tar sands and shale oil), gas, coal, wind, solar, biomass, hydro, nuclear fuel	Conventional oil, unconventional oil (including tar sands and shale oil), gas, coal, wind, solar, biomass (waste/residues, & crops), hydro, nuclear fuel (Uranium and Thorium) including a full representation of the nuclear fuel cycle.
Electricity Technologies	Conventional fossil (coal, gas, oil); nuclear, hydro, natural gas combined cycle w/ & w/o capture, integrated coal gasification with capture, wind/solar, biomass	Conventional fossil (coal, gas, oil); nuclear, hydro, natural gas combined cycle integrated coal gasification with capture, wind, solar, biomass, fuel cells	Conventional fossil (coal, gas, oil) w/ & w/o capture; IGCCs w/ & w/o capture; natural gas combined cycle (NGCC) w/ & w/o capture; Gen II, III, and IV reactors and associated fuel cycles, hydro, wind, solar, biomass (traditional & modern commercial)
Conversion Technologies	Oil refining, coal gasification, bio-liquids	Oil refining, coal gasification and liquefaction, bio-liquids, electrolysis	Oil refining, natural gas processing, natural gas to liquids conversion, coal, and biomass conversion, to synthetic liquids and gases. Hydrogen production using liquids, natural gas, coal, biomass, electrolysis including direct production from wind and solar, and nuclear thermal conversion.
Atmosphere- Ocean	2-Dimensional Atmosphere w/ a 3 Dimensional Ocean General Circulation Model, resolved at 20 minute time steps, 4° latitude, 4 surface types, 12 vertical layers in the atmosphere.		Global multi-box energy balance model with upwelling-diffusion ocean heat transport.
Carbon Cycle	Biogeochemical models of terrestrial and ocean processes, depend on climate/atmospheric conditions with 35 terrestrial ecosystem types		Globally balanced carbon-cycle with separate ocean and terrestrial components, with terrestrial response to land-use changes
Natural Emissions	CH_4, N_2O,weather/climate dependent as part of biogeochemical process models		Fixed natural emissions over time
Atmospheric fate of GHGs, pollutants	Process models of atmospheric chemistry resolved for urban & background conditions		Reduced form models for reactive gases and their interactions
Radiation Code	Radiation code accounting for all significant GHGs and aerosols		Reduced form, top of the atmosphere forcing including indirect forcing effects

3. REFERENCE SCENARIOS

Reference scenarios for all three models show significant growth in energy use and continued reliance on fossil fuels, leading to an increase in CO_2 emissions 3½ times the present level by 2100. When combined with increases in the non-CO_2 greenhouse gases and net uptake by the ocean and terrestrial biosphere, the result is that radiative forcing at the end of the century is 6.4 to 8.6 W/m^2 above the pre-industrial level.

3.1. Introduction

This chapter introduces the reference scenarios developed by the three modeling groups. These scenarios are plausible future paths, not predictions, for by the very nature of their construction they lack the features of “best-guess” forecasts. For example, they assume that in the post-2012 period existing measures to address climate change expire and are never renewed or replaced–an unlikely occurrence. Rather, they have been developed as points of departure to highlight the implications for energy use and other human activities of the stabilization of radiative forcing. Each of the modeling teams could have created a range of other plausible reference scenarios by varying assumptions about rates of economic growth, the cost and availability of alternative energy options, assumptions about non-climate environmental regulations, and so forth.

Other than to standardize reporting conventions and greenhouse gas (GHG) emissions mitigation policies (or lack thereof), the three modeling teams developed their reference scenarios independently as each judged appropriate. As noted in Chapter 2, the three models were developed with somewhat different original design objectives. They differ in (a) their inclusiveness, (b) their specifications of key aspects of economic structure, and (c) their choice of values for key parameters. These choices then lead to different characterizations of the underlying economic and physical systems that these models represent.

Moreover, even if the models were identical in structure the independent choice of key assumptions should lead to differences among scenarios. For example, as will be discussed, the reference scenarios differ in their specification of the technical details of virtually every aspect of the future global energy system, ranging from the cost and availability of oil and natural gas to the prospects for nuclear power. These differences affect future reference emissions and the nature and cost of stabilization regimes.

Finally, the modeling teams did not attempt to harmonize assumptions about non-climate-related policies. Such differences matter both in the reference and stabilization scenarios. For example, the MiniCAM reference assumes a larger effect of methane emission-control technologies deployed for economic reasons, which results in lower reference scenario methane emissions than the other models. Similarly, the IGSM modeling team assumed that non-climate concerns would limit the deployment of nuclear power, while the MERGE and MiniCAM models assumed that nuclear power would be allowed to participate in energy markets on the basis of energy cost alone.

This variation in modeling approach and assumptions is one of the strengths of this exercise, for the resulting differences across scenarios can help shed light on the implications of differing assumptions about the way key forces may evolve over time. It also provides three independent starting points for consideration of stabilization goals.

Although there are many reasons to expect that the three reference scenarios would be different, it is worth noting that the modeling teams met periodically during the study process, to review progress and to exchange information. Thus, while not adhering to any formal protocol of standardization, the three reference scenarios are not entirely independent either.

Development of a reference scenario involves the elaboration of one path from among a range of uncertain outcomes. Thus, it should be further emphasized that the three reference scenarios were not designed in an attempt to span the full range of potential future conditions or to shed light on the probability of the occurrence of future events. That is a much more ambitious undertaking than the one reported here.

The remainder of this chapter describes the reference scenarios developed by the three modeling teams working forward from underlying drivers to implications for radiative forcing. (Chapter 4, on the other hand, proceeds in the other direction, imposing the stabilization levels on radiative forcing and exploring the implications.) Section 3.2 begins with a summary of the underlying socio-economic assumptions, most notably for population and economic growth. Section 3.3 discusses the evolution of the global energy system over the twenty-first century in the absence of additional GHG controls and discusses the associated prices of fuels. The energy sector is the largest but not the only source of anthropogenic GHG emissions. Also important is the net uptake or release of CO_2 by the oceans and the terrestrial biosphere. Section 3.4 shows how the three models handle this aspect of the interaction of human activity with natural Earth systems. Section 3.5 then shows the estimates of anthropogenic emissions, taking into account both the energy sector and other sources, such as agriculture and various industrial activities. The section draws together all these various components to present reference scenarios of the consequences of anthropogenic emissions and the processes of CO_2 uptake and non-CO_2 gas destruction for the ultimate focus of the study: atmospheric concentrations and global radiative forcing.

3.2. Socio-Economic Assumptions

> *GHGs are a product of modern life. Population increase and economic activity are major determinants of the scale of human activities and ultimately of anthropogenic GHG emissions. The reference scenarios are similar in that both population and economic activity are assumed to continue to grow to the end of the century. Global population is projected to rise from 6 billion in the year 2000 to between 8.6 and 9.9 billion in 2100 in the three reference scenarios. Developed nations are assumed to continue to expand their economies at historical rates, and developing nations are assumed to make significant progress toward improved standards of living.*

Reference scenarios are grounded in a larger demographic and economic story. Each uses population as the basis for developing estimates of the scale and composition of economic activity for each region. For population assumptions, the IGSM modeling team adopted a regionally detailed U.N. projection for the period 2000-2050 (United Nations 2001) and then extended this projection to 2100 using information from a longer-term U.N. study (United Nations 2000). The MiniCAM assumptions are based on a median scenario by the United Nations (United Nations 2005) and a Millennium Assessment Techno-Garden Scenario from the International Institute for Applied Systems Analysis (O'Neal 2005). Near-term population assumptions for MERGE come from the Energy Information Administration's *International Energy Outlook*.

Table 3.1. Population by Region across Models, 2000-2100

Regional populations are given in Table 3.1. Population increases substantially across the reference scenarios by the end of the century, but all of the scenarios portray the population growth rate as slowing to near zero if not turning negative by the end of the century. As a result, by 2050 more than 75% of all the change between the year 2000 and 2100 has occurred. A demographic transition from high birth and death rates to low death rates and eventually to low birth rates is a feature of most demographic projections, reflecting assumptions that birth rates will decline to replacement levels or below. For some countries, birth rates are already below replacement levels, and just maintaining these levels will result in population decline for these countries. A key uncertainty in all demographic scenarios is whether a transition to less than replacement levels is a more or less permanent feature of those countries where it has occurred, and whether such a pattern will be repeated in other countries.

The differences among the scenarios lie in nuances of this pattern. The MiniCAM reference scenario exhibits a peak in global population around the year 2070 at slightly more than 9 billion people, after which the population declines to 8.6 billion. MERGE and IGSM, on the other hand, both employ demographic scenarios in which global population stabilizes but does not decline during this century. By 2100 populations range from 8.6 to 9.9 billion across the scenarios, an increase of 42 to 64% from the 6 billion on Earth in 2000. In total the difference between the demographic scenarios is relatively small: they differ by only 3% in 2030 and by less than 10% until after 2080.

Figure 3.1. World and U.S. Population across Reference Scenarios

The variation in population among the models is greater for the U.S. than for the globe. The U.S. population, in the right panel of Figure 3.1, increases from about 280 million in the year 2000 to between 335 million and 425 million by 2100. Although the MiniCAM global population is lowest of the three scenarios in 2100, it is the highest for the U.S. The higher U.S. population in MiniCAM compared to the other models can be traced to different assumptions about net migration.

As discussed in Chapter 2, gross domestic product (GDP), while ostensibly an output of all three models, is in fact largely determined by assumptions about labor productivity and labor force growth, which are model inputs. None of the three modeling teams began with a GDP goal and derived sets of input factors that would generate that level of activity. Rather, each began with assessments about potential growth rates in labor productivity and labor force and used these, through differing mechanisms, to compute GDP. In MiniCAM, labor productivity and labor force growth are the main drivers of GDP growth. In MERGE and IGSM, savings and investment and productivity growth in other factors (e.g., materials, land, and energy) contribute as well. All three models derive labor force growth from the underlying assumptions about population.

The alternative scenarios of population and productivity growth lead to differences among the three reference scenarios in U.S. GDP growth, as shown in Figure 3.2. There is relatively little difference among the three trajectories through the year 2020. After 2020, however, the scenarios diverge with the lowest scenario (MERGE) having US GDP roughly half of that of the highest scenario (IGSM) by the end of the century. The IGSM labor productivity growth assumptions for the U.S. were the highest of the three and its U.S. population was also relatively high, as seen in Figure 3.1. The relatively lower labor productivity growth assumptions used in the MERGE and MiniCAM reference scenarios lead to lower levels of GDP. The lower population growth assumptions employed in the MERGE reference scenario give it the lowest GDP level in 2100.

Figure 3.2. U.S. Economic Growth across Reference Scenarios

Table 3.2 shows GDP across regions in the three reference scenarios. The absolute levels of GDP increase are the result of relatively small differences in rates of per capita growth. Although difficulties arise in comparisons of GDP across countries (see Box 3.1), the growth rates underlying these scenarios are usefully compared with historical experience.

Table 3.3 presents long-term growth rates from reconstructed data showing that consistent rapid growth is a phenomenon of industrialization, starting in the 1800s in North America and Europe and gradually spreading to other areas of the world. By the end of the period 1950 to 1973, it appeared that the phenomenon of rapid growth had taken hold in all major regions of the world. Since 1973, it has been less clear to what degree that conclusion holds. Growth slowed in the 1970s in most regions, the important exceptions being China, India, and several South and East Asian economies. In Africa, Latin America, Eastern Europe, and the former Soviet Union, growth slowed in this period to rates more associated with pre-industrial times.

Table 3.2. Reference GDP for Key Regions

Table 3.3. Historical Annual Average Per Capita GDP Growth

--- BOX 3.1: Exchange Rates and Comparisons of Real Income among Countries ---
Models used in this type of exercise typically represent the economy in real terms, following the common assumption that inflation is a purely monetary phenomenon that does not have real effects, but issues occur in comparing income across regions in terms of what currency exchange rates are most appropriate. The models do not represent the factors that govern exchange rate determination and so cannot project changes. However, modeling international trade in goods requires either an exchange rate or a common currency. Rather than separately model economies in native currencies and use a fixed exchange to convert currencies for trade, the equivalent and simpler approach is to convert all regions to a common currency at average market exchange rates (MER) for the base year of the model.

At the same time, it is widely recognized that using market exchange rates to compare countries can have peculiar implications. Country A might start with a larger GDP than country B when converted to a common currency using that year’s exchange rates, and grow faster in real terms than B, yet could later have a lower GDP than B using exchange rates in that year. This paradoxical result can occur if A’s currency depreciates relative to B’s. Depreciation and appreciation of currencies by 20 to 50% over just a few years is common, so the example is not extreme. Interest in making cross-country comparisons that are not subject to such peculiarities has led to development of indices of international purchasing power. A widely used index is purchasing power parity (PPP), whose development was sponsored by the World Bank. PPP-type indices have the advantage of being more stable over time and are thought to better reflect relative living standards among countries than MER. Thus, analysts drawing comparisons among countries have found it preferable to use PPP-type indices rather than MER. Although the empirical foundation for the indices has been improving, the theory for them remains incomplete, and thus there is a limited basis on which changes in PPP can be projected into the future. Some hypothesize that differences close as real income gaps narrow, but the evidence for this outcome is weak, in part due to data limitations.

Controversy regarding the use of MER arose around the Special Report on Emissions Scenarios (SRES) produced by the IPCC (Nakicenovic and Swart, 2001) because they were reported to model economic convergence among countries, yet reported results in MER. Assessing convergence implies a cross-country comparison, but that would only be strictly meaningful if MER measures were corrected for a country's real international purchasing power. In developing the scenarios for this exercise, no assumptions were made regarding convergence. Growth prospects and other parameters for the world's economies were assessed relative to their own historical performance. The models are parameterized and simulated in MER, as this is consistent with modeling of trade in goods. To the extent GDP estimates are provided, readers are strongly cautioned against making international comparisons; for example, even global GDP for an historical period will differ if exchange rates of different years are used.

-- END BOX --

With this historical experience as background, the differences among the models in GDP growth can be explained. Demographic trends, slowing population and labor force growth, are responsible for a gradual slowing of overall GDP growth in all three models, and generally slower growth rates than in the last half of the twentieth century. With respect to the developed countries, the IGSM per capita income growth rate for the U.S. is about the average for North America for the period 1950-2000. The lower growth for the MiniCAM reference reflects an assessment that an aging population will lead to lower labor force participation, and the result of this demographic maturation is a lower future rate of per capita GDP growth compared to history. U.S. growth rates in the MERGE reference scenario are similar to those of MiniCAM.

GDP growth patterns for Western Europe and Japan are similar to one another within reference scenarios but vary across models. The IGSM reference scenario follows the post World War II trend in per capita GDP growth, but MiniCAM and MERGE anticipate a break from the trend with lower per capita growth in GDP as a consequence of changes in underlying demographic trends. As for the US, the MiniCAM results for other developed regions reflect a decline in average labor force participation as populations age, resulting in lower growth in per capita GDP compared to the IGSM reference scenario. The MERGE GDP growth pattern is similar to that of MiniCAM.

The scenarios for developing regions show greater differences from historical experience. Notably, all three modeling groups show consistent growth in many non-OECD regions at rates experienced by "industrializing" countries. However, growth rates are not homogeneous. Growth in China and India is generally higher than for regions such as Latin America and Africa, as it has been in recent decades. The IGSM results for non-OECD regions show somewhat less growth compared to the MiniCAM and MERGE scenarios. These are just one set of possible growth prospects from each modeling group and are not intended to be expressions of what the teams view as desirable performance. Clearly, more rapid growth in developing countries, if gains spread to lower income groups within these regions, could be the basis for improving the outlook for people in these areas.

3.3. Energy Use, Prices, and Technology

Global primary energy consumption expands dramatically over the century in all three reference scenarios, growing to between 3 and 4 times its 2000 level of roughly 400 EJ. This growth is the net result of a combination of forces including rising economic activity, increasing efficiency of energy use and changes in energy consumption patterns. Growth in per-capita energy consumption occurs despite a continuous decline in the energy intensity of economic activity. The improvement in energy intensity reflects, in part, assumptions of substantial technological change in all three reference scenarios.

Fossil fuels provided almost 90% of the energy supply in the year 2000 and remain the dominant energy source in all three scenarios throughout the twenty-first century despite a phase-out of conventional petroleum resources. In all three reference scenarios a range of alternative fossil resources is available to supply the bulk of the world's increasing demand for energy. Differing among the scenarios, however, is the mix of fossil fuels. The IGSM reference scenario has relatively more oil, derived from shale; the MERGE scenario has relatively more coal with a substantial amount of the increase used to produce liquid fuels; and the MiniCAM scenario has relatively more natural gas.

In all three cases, the production from non-fossil fuel resources grows substantially in comparison to today's levels, reaching levels roughly 65 to 100% of the total global level of energy consumption in 2000. The scenarios differ in the mix of non-fossil resources that emerges. In all reference scenarios, however, the growth in non-fossil fuel use does not forestall substantial growth in fossil fuel consumption.

3.3.1. The Evolving Structure of Energy Use

Energy production is closely associated with emissions of GHGs, particularly CO_2, because of the dominant role of fossil fuels. Figure 3.3 shows global primary energy use over the century and its composition by fuel type in the three reference scenarios. Not surprisingly, given the assumptions about economic growth, all of the reference scenarios show substantial growth in primary energy use: from approximately 400 EJ/y in the year 2000 to roughly between 1275 EJ/y and 1500 EJ/y by the end of this century. Combined with population growth, all three models project a growing per capita use of energy for the world (Figure 3.4). The per capita growth for the world is very similar for MiniCAM and the IGSM, with trends diverging somewhat late in the century. MERGE shows relatively slower growth in per capita use early in the century, with accelerated growth later. The U.S. results differ substantially on the other hand. U.S. per capita energy use in MERGE and the IGSM increases substantially, while in MiniCAM it declines gradually over the century.

Figure 3.3. Global and U.S. Primary Energy Consumption by Fuel across Reference Scenarios

Figure 3.4. Global and U.S. Primary Energy Consumption Per Capita across Reference Scenarios

The growth in total and per capita primary energy consumption arises despite substantial improvements in energy technology assumed in all three scenarios. Figure 3.5 displays the ratio of U.S. energy to GDP (energy intensity) computed for each of the three reference scenarios. The ratio declines throughout the century in all three. These patterns represent a continuation of changes in energy-intensity that have occurred in recent decades in the U.S. In 2100, each dollar of real GDP can be produced with only 40% of the energy used in 2000 in the MERGE reference scenario, and only 30% of the energy in the IGSM scenario, and only 25% in the MiniCAM scenario.

Figure 3.5. U.S. Primary Energy Intensity: Consumption per Dollar of GDP across Reference Scenarios

Globally and in the U.S., energy consumption over the century remains dominated by fossil fuels. In this sense the three reference scenarios tell a consistent story about future global energy, and all three run counter to the view that the world is running out of fossil fuels. Although reserves and resources of conventional oil and gas are limited in all three reference scenarios, the same cannot be said of coal and unconventional liquids and gases. All three reference scenarios project that, in the absence of constraints on GHG emissions, the world economy will move from current conventional fossil resources to increased exploitation of the extensive (if more costly) global resources of heavy oils, tar sands, and shale oil, and to synfuels derived from coal. The three scenarios exhibit a different mix of these sources. The IGSM reference scenario exhibits a relatively higher share of oil production (including unconventional oil); the MERGE reference scenario exhibits a relatively higher coal share; and the MiniCAM projects a higher share for natural gas.

The relative contribution of oil to primary energy supply differs across the reference scenarios, but all three include a decline in the share of conventional oil. Thus, these scenarios represent three variations on a theme of energy transition precipitated by limited availability of conventional oil and continued expansion of final demands for liquid fuels, mainly to fuel passenger and freight transport.

In the IGSM reference scenario, limits on the availability of conventional oil resources lead to the development of technologies to exploit unconventional oil, i.e., oil sands, heavy oils, and shale oil. These resources are large and impose no meaningful constraint on production during the twenty-first century. Thus, despite the fact that production costs are higher than for conventional oil, total oil production (conventional plus shale) expands throughout the century although oil as a primary energy source declines as a share of total energy with the passage of time.

The transition plays out differently in the MERGE reference. Although it begins the same way (that is, the transition is initiated by limits on conventional oil resources), declining production of conventional oil leads to higher oil prices and makes alternative fuels, especially those derived from coal liquefaction, economically competitive. Thus, there is a transition away from conventional oil (and gas) and a corresponding expansion of coal production. The large difference between MERGE and IGSM regarding primary oil thus reflects the role of coal liquefaction rather than a fundamentally different scenario of the need for liquid fuels.

The MiniCAM reference scenario depicts yet a third possible transition. Again, it begins with limited conventional oil resources leading to higher oil prices. Higher oil prices then lead to the development and deployment of technologies that access unconventional oil, such as oil sands, heavy oils, and shale oils. However, it also leads to expanded production of natural gas and (as in the MERGE scenario) to expanded production of coal to produce synthetic liquids.

Figure 3.3 also reflects assumptions about the availability of low-cost alternatives to conventional fossil fuels. In all three scenarios, non-fossil supplies increase both their absolute and relative roles in providing energy to the global economy, with their share growing to roughly 20 to 30% of total supply by 2100. In the IGSM scenario, which shows the lowest consumption of non-fossil resources, the magnitude of total consumption of these resources in 2100 is 65% the size of the total global primary energy production in 2000, which is more than a 500% increase in the level of production of non-fossil energy. In MERGE, which provides the scenario with the highest contribution from non-fossil resources, total consumption from these sources in 2100 exceeds total primary energy consumption in 2000. Despite this growth, the continued availability of relatively low-cost fossil energy supplies, combined with continued improvements in the efficiency with which they are used, results in fossil energy forms remaining competitive throughout the century.

The three reference scenarios tell different stories about non-fossil energy (much of which is covered below in the discussion of electricity generation). The IGSM reference scenario assumes political limits on the expansion of nuclear power, so it grows only to about 50% above of the 2000 level by 2100. However, growing demands for energy and for liquid fuels in particular lead to the development and expansion of bioenergy, both absolutely and as percentage of total primary energy.

In contrast, the MERGE scenario assumes that a new generation of nuclear technology becomes available and that societies do not limit its market penetration, so the share of nuclear power in the economy grows with time. In addition, renewable energy forms, both commercial biomass and other forms such as wind and solar, expand production during the century.

The MiniCAM reference scenario also assumes the availability of a new generation of nuclear energy technology that is both cost-competitive and unrestrained by public policy. Nuclear power, therefore, increases market share although not to the extent found in the MERGE scenario. Non-biomass renewable energy supplies become increasingly competitive as well. In MiniCAM, the expansion of bio-energy production in the reference scenario is predominantly recycled wastes, with a modest contribution from commercial biomass farming toward the end of the century.

The three scenarios for the U.S. are similar in character to the global ones, as also shown in Figure 3.3. The transition from inexpensive and abundant conventional oil to alternative sources of liquid fuels and electricity affects energy markets and patterns in the U.S. However, energy demands grow somewhat more slowly in the U.S. than in the world in general. As with the world total, the U.S. energy system remains dominated by fossil fuels in all three reference scenarios. MERGE and the IGSM have similar contributions from non-fossil energy, but for MERGE the sources are predominantly nuclear and other renewables while for the IGSM it is biomass. MiniCAM has smallest overall contribution from non-fossil sources split relatively evenly between nuclear, biomass, and other renewables.

3.3.2. Trends in Fuel Prices

Historically oil prices have been highly variable, with the volatility apparently often related to political events. Figure 3.6 plots oil prices from 1947 forward. Prices were in the \$15 to \$20 range (in the constant 2006 dollars shown in the figure) until the increases in the 1970s and early 1980s that were the result of disruptions in the Middle East. In inflation-adjusted terms, prices declined from peaks in the late 1970's to vary around the \$20 level in the latter half of the 1980s and 1990s. The period 2000 to 2005 has again seen rising prices of oil and other fossil energy sources, which suggests the possibility of a long-term trend toward rising prices. Depletion alone would suggest rising prices because of a combination of rents associated with a limited resource and the exhaustion of easily recoverable grades of oil. Global demand continues to grow, putting increasing pressure on supply. Opposing these forces toward higher prices has been improving technology that reduces the cost of recovering known deposits and facilitates discovery and that makes recovery of previously unrecoverable deposits economical.

Figure 3.6. Long-Term Historical Crude Oil Prices

The three models used for these scenarios employ time steps of 5 to 15 years (see Chapter 2) and thus are not set up to analyze short-term variability in prices. Their long-term trends are best interpreted as multi-year averages.

The three scenarios paint similar but by no means identical pictures of future energy prices. The price paths in the three models paint a picture that is a reflection of both energy resources and energy technologies. The price paths also shed light on the technology characterizations in the models and therefore about the technology assumptions employed in the three models. For example, the price of oil determines the marginal cost of bioenergy, which in turn is a reflection of the technology options assumed available for its production.

Figure 3.7 shows mine-mouth coal prices, electricity producer prices, natural gas producer prices for the U.S., and the world oil price. The scenarios by each model for all four energy markets – oil, natural gas, coal and electricity – are shaped by the supply of and demand for these commodities. These fuels also are interconnected because users can substitute one fuel for another, so thus higher prices in one fuel market will tend to increase demand for and the price of other fuels. Oil markets are driven by the rising cost of conventional oil and the transition to more expensive unconventional sources to supply a growing demand for liquid fuels, mainly for transportation. The oil price scenarios in the three models are thus the result of the interplay between increasing the demands for liquid fuels, the available technology, and the availability of liquids derived from these other sources.

Figure 3.7. Indices of Energy Prices across Reference Scenarios

Natural gas prices tell a similar story. Estimates of the ultimately recoverable natural gas resource vary, as does the cost structure of the resource, leading to differences among the models. Like the demand for oil, the demand for natural gas grows, driven by increasing population and per capita incomes. As is the case for oil, the price of gas tends to be driven higher in the transition from inexpensive conventional resources to less easily accessible grades of the resource and to substitutes, such as gas derived from coal or biological sources. The different degrees and rates of price escalation reflect different technology assumptions in the three reference scenarios.

Coal prices do not rise as fast as oil and natural gas prices in any of the three reference scenarios. The reason is the abundance of the coal resource base. The different patterns of coal price movement with time in the three scenarios reflect differences in assumptions about the rate of resource depletion, its grade structure, and improvements in extraction technology.

The stability of electricity prices compared with oil and natural gas prices is a reflection of the variety of technologies and of fuels available to produce electricity and their improvement over time, and the fact that fuel is just one component of the cost of electricity. The details underlying this electric sector development are reported next.

3.3.3. Electricity Production and Technology

Electricity production is projected to steadily increase in both the U.S. and the world although the scale and generation mix differ among the three scenarios (Figure 3.8). Here production is reported in units of electrical output—not units of energy input—by generation type in the U.S. and the world. All the scenarios depict a continued role for coal.. The IGSM scenario is dominated by coal, which accounts for more than half of all power production by the end of the twenty-first century, a result consistent with its limited growth in nuclear power. In contrast, the MERGE scenario projects that nuclear energy penetrates the market based on economic performance, and non-biomass renewable energy gains market share. Limited natural gas resources lead to a peak and decline in gas use in the first half of the century. In MiniCAM coal supplies the largest share of power, but natural gas is relatively abundant and provides a significant portion as well, as do nuclear and non-biomass renewable energy forms.

Figure 3.8. Global and U. S. Electricity Production by Source across Reference Scenarios

3.3.4. Non-Electric Energy Use

An important consideration in future energy projections are conversion losses as relatively lower grade resources are converted to higher grade fuels for use in final applications such as space conditioning, lighting, and to provide mechanical power. Figure 3.9 identifies the energy content of primary fuels for the U.S. in the year 2000 and where conversion losses occur. It shows the energy loss in the conversion from fuel to electricity to be 28.1 Quads (1 Quad is equal to 1.055 EJ) while the energy content of the electricity is 12.3 Quads. Other losses occur when fuels are used to create the mechanical power to, for example, propel vehicles, or when efficiency of conversion to heat, light, or mechanical energy is less that 100%. The potential for reducing such losses is one reason why energy intensity of the economy can continue to improve.

Figure 3.9. U.S. Energy Flow Diagram and Non-Electrical Energy Use for the Year 2000

However, in the future other fuel transformation activities may become important and fundamentally change energy-flow patterns, as higher grade resources are exhausted and lower grades that require more conversion are used.. As already discussed, the potential exists for coal and commercial biomass to be converted to liquids and gases—a technology thus far implemented only at a small scale. Furthermore, fuels and electricity may be transformed into hydrogen, creating fundamentally new branches of the system. Like electricity, these new branches will have conversion losses and those losses can be important.

Figure 3.10 shows non-electric energy use in the reference scenario, and it is important to realize that these patterns of non-electric use also can imply significant conversion losses. This prospect plays a strong role in the MERGE reference scenario, in which coal and biomass goes into liquefaction and gasification plants. To a lesser extent, these conversions are also present in the MiniCAM and IGSM scenarios. In addition, in the MiniCAM reference scenario some nuclear and renewable energy appears in non-electricity uses to produce hydrogen; and MERGE also includes some generation of hydrogen from renewables sources. In the IGSM and MiniCAM scenarios oil use is the largest single non-electric energy use, reflecting a continuing growth in demand for liquids by the transportation sectors. In the MERGE reference scenario, increasingly expensive conventional oil is supplanted by coal-based liquids. This phenomenon also has implications for energy intensity in that improvements in end-use energy intensity can be offset in part by losses in converting primary fuels to end-use liquids or gases.

Figure 3.10 Global and U.S. Primary Energy Consumed In Non-Electric Applications across Reference Scenarios

3.4. Land Use and Land-Use Change

The three reference scenarios take different approaches to emissions from land use and land-use change. The MERGE scenario assumes that the biosphere makes no net contribution to the carbon cycle. In the IGSM and MiniCAM scenarios the net contribution of the terrestrial biosphere is to remove carbon from the atmosphere, which results from the countervailing forces of land-use change emissions from deforestation and other human activities and the net uptake from unmanaged systems.

An important aspect of land use and land-use change in all three models is the production of biofuels for energy. Both IGSM and MiniCAM take account of the competition for scarce land resources. MERGE takes the availability of biofuels as an exogenous input based on extra-model analysis. Production of these crops is displayed in Figure 3.11. The IGSM and MiniCAM figures are based on somewhat different definitions, which account for the difference in 2000. IGSM models only the production of biomass energy beyond that now used, and does not explicitly model traditional use of biomass or, for example, the own-use of wood wastes for energy in the forest products industry. MiniCAM explicitly accounts for some current uses of biomass energy, such as that used in the pulp and paper industry, and separately considers the future potential for biofuels derived from wastes and residue along with energy crops grown explicitly for their energy content.

Figure 3.11 Global and U.S. Production of Biomass Energy across Reference Scenarios

Apparent differences among the models thus need to be considered in light of this differential accounting. The MiniCAM reference biomass production tends to be higher, especially in early years, because it is accounting waste and residue-derived biofuels explicitly. These waste and residue-derived biofuels account for all of the biomass production in the MiniCAM reference scenario in the early part of the century and the majority of all biomass production at the end of the century. The IGSM reference scenario exhibits a strongly growing production of biofuels beginning after the year 2020. The IGSM deployment is driven primarily by a world oil price that in the year 2100 is over 4.5 times the price in the year 2000. In contrast, MiniCAM, with its lower long-term world oil price, provides insufficient incentive to create a substantial market for bio-crops in the reference scenario. However, MiniCAM does utilize an increasing share of the potentially recoverable bio-waste as a source of energy.

Land use has implications for the carbon cycle as well. IGSM applies its component Terrestrial Ecosystem Model with a prescribed scenario of land-use, and this land-use pattern is employed in all scenarios. Thus in the IGSM scenarios commercial biomass production must compete with other agricultural activities for cultivated land, but the extent of cultivated land does not change from scenario to scenario. Because the land-use pattern is fixed in IGSM changes in the net flux of carbon to the atmosphere reflect the behavior of the terrestrial ecosystem in response to changes in CO_2 and climatic effects that are considered within the model's Earth-system component. Taken together, these effects lead to the negative net emissions from the terrestrial ecosystem shown in Figure 3.12, which contrasts with the neutral biosphere assumed by the MERGE model.

Figure 3.12. Global Net Emissions of CO_2 from Terrestrial Systems Including Net Deforestation across Reference Scenarios

MiniCAM uses the terrestrial carbon cycle model of MAGICC (Wigley 1993) to determine the aggregate net carbon flux to the atmosphere. However, unlike either IGSM or MERGE, MiniCAM determines the level of terrestrial emissions as an output from an integrated agriculture/land-use module rather than as the product of a terrestrial model with fixed land use. Thus, MiniCAM exhibits the same types of CO_2 fertilization effects as the IGSM, but it also represents interactions between the agriculture sector and the distribution of natural terrestrial carbon stocks.

3.5. Emissions, Concentrations, and Radiative Forcing

The growth in the global economy that is assumed in the reference scenarios and the changes in the composition of the global energy system lead to growing emissions of GHGs over the century. Emissions from fossil fuel burning and cement production more than triple over the study period in the reference scenarios. With growing emissions, GHG concentrations are projected to rise substantially over the twenty-first century, with CO_2 *concentrations increasing to 2-1/2 to over 3 times the pre-industrial concentration. Increases in the concentrations of the non-*CO_2 *GHGs vary more widely across the reference scenarios. The increase in radiative forcing ranges from 6.4 to 8.6* W/m^2 *from the year 2000 level with the non-*CO_2 *GHGs accounting for 20 to 25% of the instantaneous forcing in 2100.*

Moderating the effect on the atmosphere of anthropogenic CO_2 *emissions is the net uptake by the ocean and the terrestrial biosphere. As atmospheric* CO_2 *grows in the reference scenarios the rate of net uptake by the ocean increases as well. Also, mainly through the effects of* CO_2 *fertilization, increasing atmospheric levels of* CO_2 *spur plant growth and net carbon uptake by the terrestrial biosphere. Differences among scenarios of these effects are in part a reflection of variation in their sub-models of the carbon cycle.*

3.5.1. Greenhouse Gas Emissions

3.5.1.1. Calculating Greenhouse Gas Emissions

Emissions of CO_2 from fossil fuels are the sum of emissions from each of the different fuel types, and, for each type, emissions are the product of a fuel-specific emissions coefficient and the total combustion of that fuel. Exceptions to this treatment occur if a fossil fuel is used in a non-energy application (e.g., as a feedstock for plastic) or if the carbon is captured and stored in isolation from the atmosphere. All three of the models assume the availability of carbon capture and storage technologies and treat the leakage from such storage as zero during the study period, although they assume that technologies for capturing carbon do not capture 100 percent of the CO_2. Capture and storage incurs costs additional to the generation process with no attendant benefits absent actions to constrain carbon emissions, so they are not undertaken in the reference scenarios.

Although bioenergy such as wood, organic waste, and straw are hydrocarbons like the fossil fuels (only much younger), they are treated as if their use had no net carbon release to the atmosphere. Any fossil fuels used in their cultivation, processing, transport, and refining are accounted for. Nuclear and non-biomass renewables, such as wind, solar, and hydroelectric power, have no direct CO_2 emissions and are given a zero coefficient. Like bioenergy, emissions associated with the construction and operation of conversion facilities are accounted with the associated emitting source.

The calculation of net emissions from terrestrial ecosystems, including land-use change, is more complicated, and each model employs its own technique. The IGSM model employs the Terrestrial Ecosystem Model, which is a state-of-the-art terrestrial carbon-cycle model with a detailed, geographically disaggregated representation of terrestrial ecosystems and associated stocks and flows of carbon on the land. The IGSM scenario, therefore, incorporates fluxes to the atmosphere as a dynamic response of managed and unmanaged terrestrial systems to the changes in the climate and atmospheric composition.

MiniCAM builds its net terrestrial carbon flux by summing both emissions from changes in the stocks of carbon from human-induced land-use change and the natural system response, represented in the reduced-form terrestrial carbon module of MAGICC. As noted above, the MiniCAM model employs a simpler reduced-form representation of terrestrial carbon reservoirs and fluxes; however, its scenario is fully integrated with its agriculture and land-use module, which in turn is directly linked to energy and economic activity in the energy portion of the model. As noted above, MERGE assumes no net emissions from the terrestrial biosphere.

Differing approaches among the models are used to account for the non-CO_2 GHGs. They begin with a current inventory of these gases and link growth in emissions to relevant activity levels. Because emissions are associated with very narrow activities, in some cases below the sectoral resolution of the models, the reference growth in emissions may be benchmarked to more detailed forecasts of activities. Details of these methods are included in the referenced papers that document these models.

3.5.1.2. Reference Scenarios of Fossil Fuel CO_2 Emissions

All three reference scenarios foresee a transition from conventional oil production to some other source of liquid fuels based primarily on other fossil sources, either unconventional liquids or coal. As a consequence, carbon-to-energy ratios cease their historic pattern of decline, as can be seen in Figure 3.13. While the particulars of each model differ, none shows a dramatic reduction in carbon intensity over this century.

Figure 3.13. Global and U.S. CO_2 Emissions from Fossil Fuel Consumption and Industrial Sources Relative to Primary Energy Consumption

Substantial increases in total energy use with no or little decline in carbon intensity lead to the substantial increases in CO_2 emissions per capita (Figure 3.14) and in global totals (Figure 3.15). Emissions of CO_2 from fossil fuel use and industrial processes increase from less than 7 GtC/y in 2000 to between 22.5 and 24 GtC/y by 2100. These emissions are higher than in earlier studies such as IS92a where emissions were 20 GtC/y (Leggett et al. 1992). The model scenarios are closer in their emissions estimates to the higher scenarios in the IPCC Special Report on Emissions Scenarios (Nakicenovic and Swart 2000), particularly those included under the headings A1f and A2.

Figure 3.14 World and U.S. CO_2 Emissions per Capita across Reference Scenarios

Figure 3.15 Global and U.S. Emissions of CO_2 from Fossil Fuels and Industrial Sources across Reference Scenarios

The three scenarios display a larger share of emissions growth outside of the Annex I nations (the developed nations of the Organization for Economic Cooperation and Development [OECD], plus Eastern Europe and the former Soviet Union[1]) as shown in Figure 3.16. Annex I emissions are highest and non-Annex I emissions lowest in the IGSM reference. At least in part this is because of two factors underlying the IGSM scenarios. First, the demand for liquids is satisfied by expanding production of unconventional oil, which has relatively high carbon emissions at the point of production. The U.S., with major resources of shale oil, switches from being an oil importer to an exporter but is responsible for CO_2 emissions associated with shale oil production. Second, assumed rates of productivity growth in non-Annex I nations are lower in the IGSM scenario than in those of the other two models.

Figure 3.16. Global Emissions of Fossil Fuel and Industrial CO_2 by Annex I and Non-Annex I Countries across Reference Scenarios

In contrast, the MERGE scenario assumes that liquids come primarily from coal, a fuel that is more broadly distributed around the world than unconventional oils. MERGE also exhibits higher rates of labor productivity in the non-Annex I nations than the IGSM

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[1] Annex I is defined in the Framework Convention on Climate Change (FCCC). However, since the FCCC entered into force, the Soviet Union has broken up. As a consequence, some of the republics of the former Soviet Union are now considered developing nations and do not have the same obligations as the Russian Federation under the FCCC. Thus, strictly speaking, the aggregations employed by the three modeling teams may not precisely align with the present partition of the world's nations. However, the quantitative implications of these differences are small.

reference scenario. Finally, MERGE has a greater deployment of nuclear generation, leading to generally lower carbon-to-energy ratios overall. These three features combine to produce lower Annex I emissions and higher non-Annex I emissions than in the IGSM reference scenario. The MiniCAM reference scenario has Annex I emissions similar to those of MERGE, but higher non-Annex I fossil fuel and industrial CO_2 emissions.

The range of global fossil fuel and industrial CO_2 emissions across the three reference scenarios is relatively narrow compared with the uncertainty inherent in these developments over a century. While it is beyond the scope of this exercise to conduct a formal uncertainty or error analysis, both higher and lower emissions trajectories could be constructed.

There are at least two approaches to developing a sensible context in which view these scenarios. One is to compare them with others produced by analysts who have taken on the same or a largely similar task. The literature on emissions scenarios is populated by hundreds of scenarios of future fossil fuel and industrial CO_2 emissions. Figure 3.17 gives some sense of what earlier efforts have produced although they should be used with care. First, many were developed at earlier times and may be significantly at variance with events as they have already unfolded. Also, no effort was undertaken in the construction of the collection in the figure, to weight scenarios for the quality of underlying analysis. Scenarios for which no underlying trajectories of population or GDP are available are mixed in with efforts that incorporate the combined wisdom of a large team of interdisciplinary researchers working over the course of years. Moreover, it is not clear that the observations are independent. The clustering of year 2100 fossil fuel and industrial CO_2 emissions around 20 PgC/y (20 GtC/y) in both the pre- and post-IPCC Third Assessment Report (TAR) time-frames coincides closely with the IPCC IS92a scenario (Leggett et al. 1992). Many later scenarios were simply tuned to it, and so are not independent assessments. For these reasons and others, looking to the open literature can provide some information, but caution in interpreting literature compilations is warranted.

Figure 3.17. Global Fossil Fuel and Industrial Carbon Emissions: Historical Development and Scenarios

Another approach to provide a context is systematic uncertainty analysis. There have now been several such analyses, including efforts by Nordhaus and Yohe (1983), Reilly et al. (1987), Manne and Richels (1994), Scott et al. (2000), and Webster et al. (2002).These studies contain many valuable lessons and insights. For the purposes of this scenario exercise one useful product of these uncertainty studies is an impression of the position of any one scenario within the window of futures that might pass a test of plausibility. Also useful is the way that the distribution of outcomes is skewed upwards—an expected outcome when one considers that many model inputs, and indeed emissions themselves, are constrained to be greater than zero. Naturally, these uncertainty calculations present their own problems as well (Webster 2003).

3.5.1.3. Future Scenarios of Anthropogenic CH_4 and N_2O Emissions

The range of emissions for CH_4 and N_2O is wider than for CO_2, as can be see in Figure 3.18. The MERGE and MiniCAM base-year emissions are similar for N_2O but their estimates diverge for CH_4. In the IGSM reference scenario, methane emissions are higher in the year 2000 than in the other two, reflecting an independent assessment of historical emissions and uncertainty in the scientific literature regarding even historic emissions. Note that the IGSM has a correspondingly lower natural methane source (from wetlands, termites, etc.) that is not shown in Figure 3.18, balancing the observed concentration change, rate of oxidation, and natural and anthropogenic sources.

Figure 3.18. Global CH_4 and N_2O Emissions across Reference Scenarios

Both IGSM and MERGE exhibit steadily growing methane emissions throughout the twenty-first century as a consequence of the growth of methane-producing activities such as ruminant livestock herds, natural gas use, and landfills. Unlike CO_2, for which the combustion of fossil fuels leads inevitably to emissions without capture and storage, slight changes in activities can substantially reduce emissions of the non-CO_2 gases (Reilly et al. 2003). The MiniCAM reference scenario assumes that despite the expansion of human activities traditionally associated with methane production, emissions control technologies will be deployed in the reference scenario in response to local environmental controls. This leads the MiniCAM reference scenario to exhibit a peak and decline in CH_4 emissions in the reference scenario.

3.5.1.4. Future Scenarios of Anthropogenic F-Gas Emissions

A set of industrial products that act as GHGs are combined under the term "F-gases," which refers to a compound that is common to them, fluorine. Several are replacements for the chlorofluorcarbons that have been phased out under the Montreal Protocol. They are usefully divided into two groups: a group of hydroflurocarbons (HFCs), most of which are shorter-lived, and the long-lived perfluorocarbons (PFCs) and sulfur hexafluoride (SF_6). Figure 3.19 presents the reference scenarios for these gases. IGSM and MERGE show strong growth in the short-lived species, while MiniCAM projects about half as much growth over the century. The models show very similar projections for the long-lived gases. PFCs are used in semiconductor production and are emitted as a byproduct of aluminum smelting; they can be avoided relatively cheaply. Emissions from the main use of SF_6 in electric switchgear can easily be abated by recycling to minimize venting to the atmosphere. Many of the abatement activities have already been undertaken and the models assume they will continue to be used.

Figure 3.19 Global Emissions of Short-Lived and Long-Lived F-Gases across Reference Scenarios

3.5.2. The Carbon Cycle: Net Ocean and Terrestrial CO_2 Uptake

The stock of carbon in the atmosphere at any time is determined from an initial concentration of CO_2, to which is added anthropogenic emissions from fossil fuel and industrial sources, and from which is subtracted net CO_2 transfer from the atmosphere to the ocean and terrestrial systems. Each model represents these processes differently.

The three reference scenarios display strong increases in ocean uptake of CO_2, shown in Figure 3.20, reflecting model mechanisms that become increasingly active as CO_2 accumulates in the atmosphere. The IGSM reference scenario has the least active ocean, which results from its three-dimensional ocean representation that shows less uptake in part as a result of rising water temperatures and CO_2 levels in the surface layer and in part as a result of a slowing of mixing into the deep ocean. The MERGE model has the most active ocean, and uptake rates continue to increase over the century. As will be discussed in Chapter 4, the three ocean models produce more similar behavior in the stabilization scenarios; for example, the MERGE and MiniCAM models have almost identical ocean uptake in the Level 2 and Level 1 scenarios.

Figure 3.20. CO_2 Uptake from Oceans across Reference Scenarios

As discussed above, the net transfer of CO_2 from the atmosphere to terrestrial systems includes many processes such as deforestation (which transfers carbon from the land to the atmosphere), uptake from forest re-growth, and the net effects of atmospheric CO_2 and climate conditions on vegetation. As noted earlier, MERGE employs a neutral biosphere: by assumption its net uptake is zero with processes that store carbon, assumed to just offset those that release it. Taken together with its more active ocean system in the Reference Scenario, the behavior of the carbon cycle in total is similar to the other two models, especially MiniCAM. IGSM and MiniCAM employ active terrestrial biospheres, which on balance remove carbon from the atmosphere, as shown in Figure 3.12. Both the MiniCAM and the IGSM reference scenarios display the net effects of deforestation, which declines in the second half of the century, combined with terrestrial processes that accumulate carbon in existing terrestrial reservoirs. The IGSM reference scenario also includes feedback effects of changing climate.

3.5.3. Greenhouse Gas Concentrations

Radiative forcing is related to the concentrations of GHGs in the atmosphere. The relationship between emissions and concentrations of GHGs is discussed in Box 3.2. The concentration of gases that reside in the atmosphere for long periods of time, decades to millennia, is thus more closely related to cumulative emissions than to annual emissions. In particular, this is true for CO_2, the gas responsible for the largest contribution to radiative forcing. This relationship can be seen for CO_2 in Figure 3.21, where cumulative emissions over the period 2000 to 2100, from both the reference scenario and the four stabilization scenarios, are plotted against the CO_2 concentration in the year 2100. The results for all three models lie on essentially the same line, indicating that despite considerable differences in representation of the processes that govern CO_2 uptake, the aggregate response to increased emissions is very similar. This basic linear relationship also holds for other long-lived gases such as N_2O and SF_6 and the long-lived F-gases.

Figure 3.21. Relationship between Cumulative CO_2 Emissions from Fossil Fuel Combustion and Industrial Sources, 2000-2100, and Atmospheric Concentrations across All Scenarios

GHG concentrations rise in all three reference scenarios. As shown in Figure 3.22, CO_2 concentrations increase from 370 ppmv in year 2000 to somewhere in the range of 700 to 875 ppmv in 2100. The pre-industrial concentration of CO_2 was approximately 280 ppmv. While all three reference scenarios display the same increasing pattern, by the year 2100 there is a difference of approximately 175 ppmv among the three scenarios. This difference has implications for radiative forcing and emissions mitigation (discussed in Chapter 4).

Figure 3.22. Atmospheric Concentrations of CO_2, CH_4, N_2O, and F-gases across the Reference Scenarios

Projected increases in the concentrations of the non-CO_2 GHGs vary across the models. The MiniCAM reference concentrations of CH_4 and N_2O are on the low end of the range, reflecting assumptions discussed above about use of methane for energy. The IGSM reference scenario projects the highest concentration levels for all of the substances. The differences mainly reflect the anthropogenic emissions of the three reference scenarios, although they also are influenced by the way each model treats natural emissions and sinks for the gases. IGSM includes climate and atmospheric feedbacks to natural systems, which tend to result in an increase in natural emissions of CH_4 and N_2O. Also, increases in other pollutants generally lengthen the lifetime of CH_4 in IGSM because the other pollutants deplete the atmosphere of the hydroxyl radical (OH), which is the removal mechanism for CH_4. These feedbacks tend to amplify the difference in anthropogenic emissions exhibited by the models. The projected concentrations of the short-lived and long-lived F-gases are also presented in Figure 3.22.

3.5.4. Radiative Forcing from Greenhouse Gases

Contributions to radiative forcing are a combination of the abundance of the gas in the atmosphere and its heat-trapping potential (radiative efficiency). Of the directly released anthropogenic gases, CO_2 is the most abundant, measured in parts per million; the others are measured in parts per billion. However, the other GHGs are about 24 times (CH_4), to 200 times (N_2O), to thousands of times (SF_6, PFCs) more radiatively efficient than CO_2. Thus what they lack in abundance they make up for, in part, with radiative efficiency. However, among these substances, CO_2 is still the main contributor to increased radiative forcing from pre-industrial times and all three reference scenarios exhibit an increasing relative contribution from CO_2.

The three models display essentially the same relationship between GHG concentrations and radiative forcing, so the three reference scenarios also all exhibit higher radiative forcing, growing from roughly 2.2 W/m^2 above pre-industrial in 2000 to between 6.4 and 8.6 W/m^2 in 2100. (See Chapter 4 for a discussion of the consequences of limiting radiative forcing.) The differences in the references mean that the amount of abatement required to meet each of targets in the IGSM, in which the increase is 8.6 W/m^2, is substantially more than that required by MiniCAM, which is on the low end with 6.4 W/m^2 by the end of the century.

All three reference scenarios show that the relative contribution of CO_2 will increase in the future, as shown in Figure 3.23. From pre-industrial times to the present, the non-CO_2 gases examined here contribute slightly above 30% of the estimated forcing. In the IGSM reference scenario, the contribution of the non-CO_2 gases falls slightly to about 26% by 2100. The MiniCAM reference scenario includes little additional increase in forcing for non-CO_2 gases, largely as a result of assumptions regarding the control of methane emissions for non-climate reasons, and thus has their share falling to about 18% by 2100. The MERGE reference scenario is intermediate, with the non-CO_2 contribution falling to about 24%.

Figure 3.23. Radiative Forcing by Gas across Reference Scenarios

From the results above it can be seen that the three reference scenarios contain many large-scale similarities. All have expanding global energy systems, all remain dominated by fossil fuel use throughout the twenty-first century, all generate increasing concentrations of GHGs, and all produce substantial increases in radiative forcing. Yet the scenarios differ in many details, ranging from demographics to labor productivity growth rates to the composition of energy supply to treatment of the carbon cycle. These scenario differences shed light on important points of uncertainty that arise for the future. In Chapter 4, they will also be seen to have important implications for the technological response to limits on radiative forcing.

3.6. References

Council of Economic Advisors (CEA), 2005. Economic Report of the President, U.S. Government Printing Office, Washington, DC.

Leggett, J., W.J. Pepper, R.J. Swart, J. Edmonds, L.G. Meira Filho, I. Mintzer, M.X. Wang, and J. Wasson. 1992. "Emissions Scenarios for the IPCC: An Update." in Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment, University Press, Cambridge, UK.

Maddison, A. 2001. The World Economy: A Millennial Perspective, OECD, Paris.

Manne, A.S., and R. Richels. 1994. “The Costs of Stabilizing Global CO_2 Emissions: A Probabilistic Analysis Based on Expert Judgements,” *The Energy Journal*. **15**(1):31-56.

Morita T, Lee H-C (1998) IPCC SRES Database, Version 0.1, Emission Scenario Database prepared for IPCC Special Report on Emission Scenarios, http://www cger.nies.go.jp/cger e/db/ipcc.html.

Nakicenovic, N., P. Kolp, R. Keywan, M. Kainuma, and T. Hanaoka. 2006. "Assessment of Emissions Scenarios Revisited," forthcoming in Journal of Environmental Economics and Policy Studies

Nakicenovic N, Victor N, Morita T (1998) Emissions Scenarios Database and Review of Scenarios, Mitigation and Adaptation Strategies for Global Change, 3(2–4):95–120.

Nakicenovic, N. and R. Swart (eds.) 2000. *Special Report on Emissions Scenarios*. Cambridge University Press, Cambridge, United Kingdom.

Nordhaus, W.D. and Yohe, G.W. 1983. "Future Carbon Dioxide Emissions from Fossil Fuels," in *Changing Climate*. pp.87-153. Washington D.C.:National Academy Press.

O'Neill, B.C. 2005. "Population Scenarios Based on Probabilistic Projections: An Application for the Millennium Ecosystem Assessment," *Population and Environment*. 26(3):229-254.

Parson, E.A. et al. 2006. *Global Change Scenarios: Their Development and Use*. CCSP Product 2.1B.

Reilly, J.M., H.D. Jacoby and R.G. Prinn. 2003. Multi-Gas Contributors to Global Climate Change: Climate Impacts and Mitigation Costs of Non-CO_2 Gases, Pew Center on Global Climate Change, Washington D.C.

Reilly, J. M., J. A. Edmonds, R. H. Gardner, and A. L. Brenkert. 1987. Uncertainty Analysis of the AEA/ORAU CO_2 Emissions Model, *The Energy Journal* 8(3): 1-29.

Scott MJ, Sands RD, Edmonds JA, Liebetrau AM and Engel DW. 2000. "Uncertainty in Integrated Assessment Models: Modeling with MiniCAM 1.0". Energy Policy 27(14):855-879.

United Nations (UN), 2000: Long-Run World Population Projections: Based on the 1998 Revision. United Nations: New York.

United Nations, 2001: World Population Prospects: The 2000 Revision, Data in digital form. Population Division, Department of Economic and Social Affairs.

United Nations, 2005: World Population Prospects: The 2004 Revision, Data in digital form. Population Division, Department of Economic and Social Affairs.

Webster, M.D., M. Babiker, M. Mayer, J. M. Reilly, J. Harnisch, R. Hyman, M. C. Sarofim, and C. Wang, 2002. Uncertainty In Emissions Projections For Climate Models, Atmospheric Environment, 36(22), 3659-3670, 2002.

Webster, M. 2003. Communicating Climate Change Uncertainty to Policy-Makers and the Public, *Climatic Change* 61, 1-8.

Wigley, T. M. L. (1993) *Balancing the Carbon Budget - Implications for Projections of Future Carbon-Dioxide Concentration Changes*, Tellus Series B-Chemical and Physical Meteorology 45(5): 409-425.

Table 3.1. Population by Region across Models, 2000-2100 (millions) Regional aggregations are different in the three models; for example Minicam includes Turkey in Western Europe, IGSM and MERGE do not.

IGSM Population by Region (million)

	2000	2020	2040	2060	2080	2100
USA	283	334	379	396	395	393
Western Europe	390	388	368	331	302	289
Japan	127	126	116	113	118	119
Former Soviet Union	291	278	260	243	234	230
Eastern Europe	97	91	83	74	67	64
China	1282	1454	1500	1429	1365	1334
India	1009	1291	1503	1610	1635	1643
Africa	793	1230	1749	2163	2390	2500
Latin America	419	538	627	678	701	713
Rest of the World	1366	1848	2269	2521	2614	2652

MERGE Population by Region (millions)

Region	2000	2020	2040	2060	2080	2100
U.S.A	276	335	335	335	335	335
Western Europe	390	397	397	397	397	397
Japan	127	126	126	126	126	126
Eastern Europe Former Soviet Union	411	393	393	393	393	393
China	1275	1429	1478	1493	1498	1499
India	1017	1312	1427	1472	1489	1496
Africa Latin America Rest of World	2566	3538	4209	4677	5003	5228

MiniCAM Population by Region (millions)

Region	2000	2020	2040	2060	2080	2100
U.S.A	283	334	371	396	412	426
Western Europe	457	486	481	456	421	399
Japan	127	127	121	113	103	95
Eastern Europe	124	119	111	100	87	80
Former Soviet Union	283	284	283	275	261	253
China	1385	1578	1591	1506	1407	1293
India	1010	1312	1472	1513	1443	1300
Africa	802	1197	1521	1763	1893	1881
Latin America	525	670	786	869	929	952
Rest of World	1055	1454	1779	1976	2012	1918

Table 3.2. Reference GDP for Key Regions (trillions of 2000 U.S. $, MER), 2000-2100. This table reports GDP for all regions of the globe, but accounts for inconsistency in regional aggregations across models. Note that while regions are generally comparable, slight differences exist in regional coverage, particularly in aggregate regions. Differences for the base year, 2000, arise from these differences as well as differences in regional deflators and regional exchange rates. (Note: IGSM is in 1997$ and 1997 exchange rates, MERGE uses 1997$ and 1997 exchange rates restated to 2000$ by the ratio of US GDP for 2000 in 1997$ and 2000$, MiniCAM is in 2000$ and 2000 exchange rates.)

IGSM GDP by Region (trillions of 1997 U.S. $, MER)

	2000	2020	2040	2060	2080	2100
USA	9.1	16.9	29.3	44.4	59.8	76.4
Western Europe	9.2	15.8	27.0	41.5	57.2	74.2
Japan	4.4	7.5	13.8	21.8	30.0	38.6
Former Soviet Union	0.6	1.4	2.9	4.8	7.2	10.2
Eastern Europe	0.3	0.6	1.2	2.1	3.3	4.9
China	1.2	3.3	6.9	12.8	19.9	28.9
India	0.5	1.1	2.0	3.3	5.2	8.0
Africa	0.6	1.3	2.0	3.3	5.0	7.4
Latin America	1.6	3.0	6.3	11.5	18.0	25.9
Rest of the World	4.4	8.6	14.9	23.9	35.3	49.9

MERGE GDP by Region (trillions of 2000 U.S. $, MER)

Region	2000	2020	2040	2060	2080	2100
U.S.A	9.8	16.1	20.9	26.8	33.1	39.6
Western Europe	9.8	14.4	19.9	26.9	35.0	43.6
Japan	4.6	6.0	7.7	9.6	11.7	13.9
Eastern Europe	1.0	1.9	3.6	6.6	11.9	20.4
Former Soviet Union						
China	1.2	3.1	7.4	17.3	38.5	78.6
India	0.5	1.5	3.6	8.3	18.5	39.2
Africa	6.5	14.6	27.5	49.3	85.1	141.9
Latin America						
Rest of World						

MiniCAM GDP by Region (trillions of 2000 U.S. $, MER)

	2000	2020	2040	2060	2080	2100
USA	9.8	15.1	21.1	28.8	38.9	52.6
Western Europe	8.6	11.1	13.3	16.1	19.4	23.7
Japan	4.7	5.9	7.1	8.6	10.2	12.0
Former Soviet Union	0.4	0.8	1.4	2.3	3.6	5.7
Eastern Europe	0.4	0.7	1.4	2.4	4.0	6.6
China	1.2	4.8	11.6	20.8	34.1	49.3
India	0.5	1.6	4.8	10.7	19.5	32.0
Africa	0.6	1.2	2.1	3.9	7.7	13.8
Latin America	2.0	3.3	5.0	8.8	16.1	26.9
Rest of the World	3.2	6.3	12.5	22.6	37.4	56.6

Table 3.3. Historical Annual Average Per Capita GDP Growth Rates

	1500-1820	1820-1870	1870-1913	1913-1950	1950-1973	1973-2001
North America	0.34	1.41	1.81	1.56	2.45	1.84
Western Europe	0.14	0.98	1.33	0.76	4.05	1.88
Japan	0.09	0.19	1.48	0.88	8.06	2.14
Eastern Europe	0.10	0.63	1.39	0.60	3.81	0.68
Former U.S.SR	0.10	0.63	1.06	1.76	3.35	-0.96
Africa	0.00	0.35	0.57	0.92	2.00	0.19
Latin America	0.16	-0.03	1.82	1.43	2.58	0.91
China	0.00	-0.25	0.10	-0.62	2.86	5.32
India	-0.01	0.00	0.54	-0.22	1.40	3.01
Other Asia	0.01	0.19	0.74	0.13	3.51	2.42
World	0.05	0.54	1.30	0.88	2.92	1.41
Source: Maddison, 2001						

Figure 3.1. World and U.S. Population across Reference Scenarios. Assumed growth in global and U.S. population is similar among the three models. The global population level in 2100 spans a range from about 8.5 to 10 billion. The U.S. population level in 2100 spans a range from about 350 to 425 million.

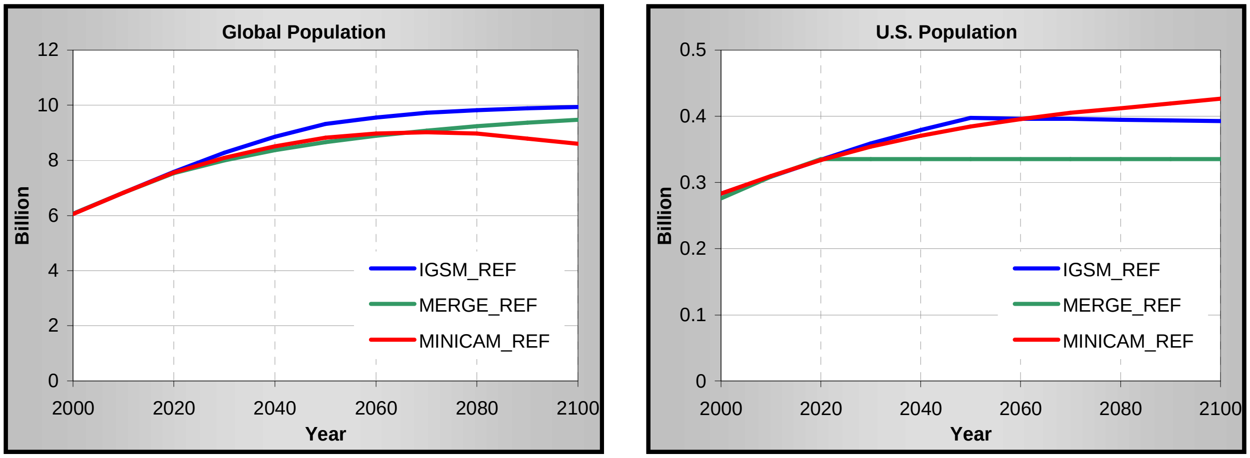


Figure 3.2. U.S. Economic Growth across Reference Scenarios. U.S. economic growth is driven in part by labor force growth, and in part by assumptions about productivity growth of labor and other factors such as by savings and investment. Projected annual average growth rates are 1.4% for MERGE, 1.7% for MiniCAM, and 2.2% for IGSM. By comparison, U.S. real GDP grew at an annual average rate of 3.4% from 1959-2004 (Economic Report of the President, CEA 2005).

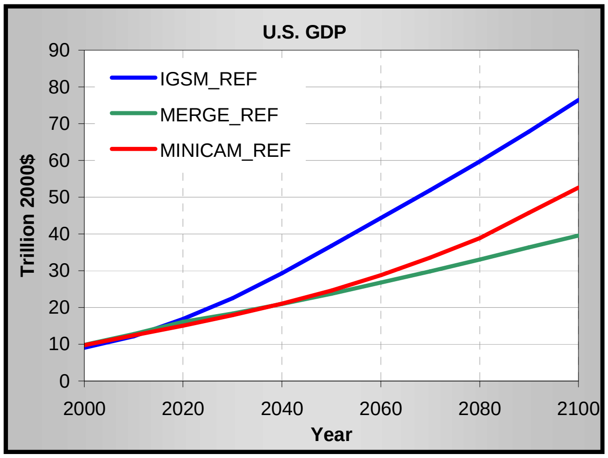


Figure 3.3. Global and U.S. Primary Energy Consumption by Fuel across Reference Scenarios (EJ/y). Global total primary energy use grows between 3 and 4 times over the century in the reference scenarios, while U.S. primary energy use grows somewhat over 1 to 2 times. Fossil fuels remain a major source, despite substantial increases in the consumption non-fossil energy sources. Note that oil includes that derived from tar sands and shale, and that coal use includes that used to produce synthetic liquid and gaseous fuels.

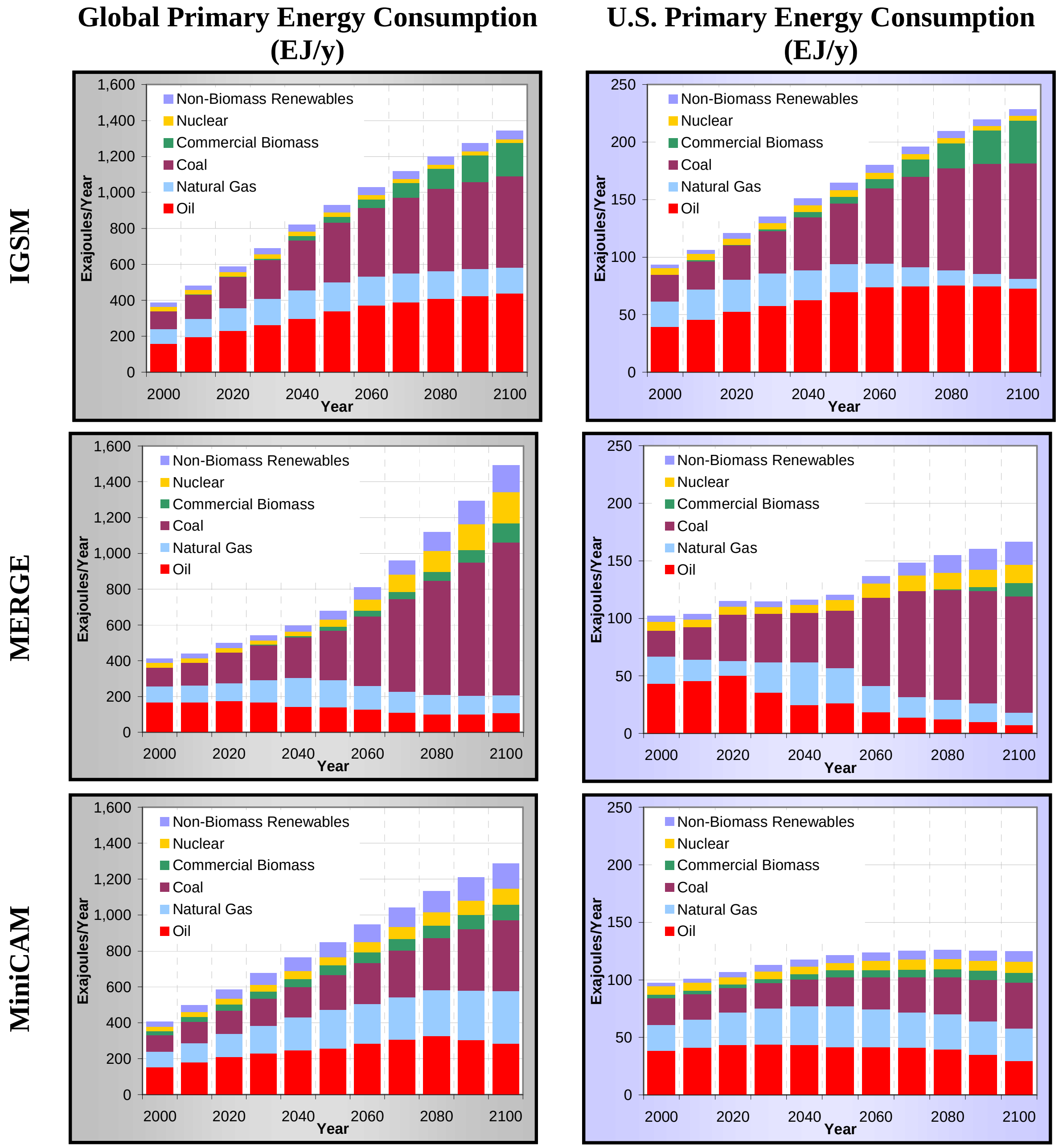


Figure 3.4. Global and U.S. Primary Energy Consumption per Capita across Reference Scenarios (gigajoules per capita). All three models project growing per capita use of energy for the world as whole. However, even after 100 years of growth, global per capita energy use is projected to be about ½ of the current U.S. level.

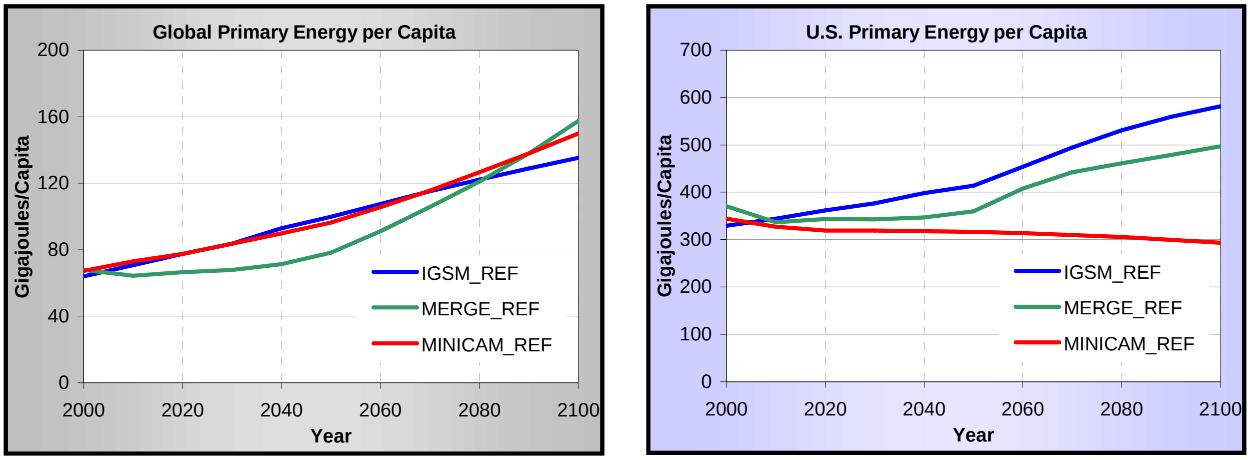


Figure 3.5. U.S. Primary Energy Intensity: Consumption per Dollar of GDP across Reference Scenarios (Index, Year 2000 Ratio = 1.0). United States total primary energy consumption per dollar of GDP is projected to continue to decline. Recent experience is a rate of decline of about 14% per decade. IGSM projects a rate of decline of about 12%, MiniCAM about 13%, and MERGE about 9% per decade.

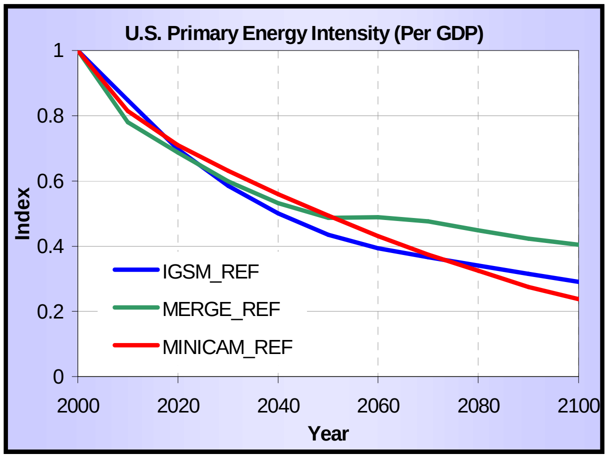


Figure 3.6. Long-term Historical Crude Oil Prices. Crude oil prices have historically been highly variable, but over the period 1947-2004 there appeared to be a slight upward trend. (Figure courtesy of James Williams, WTRG Economics)

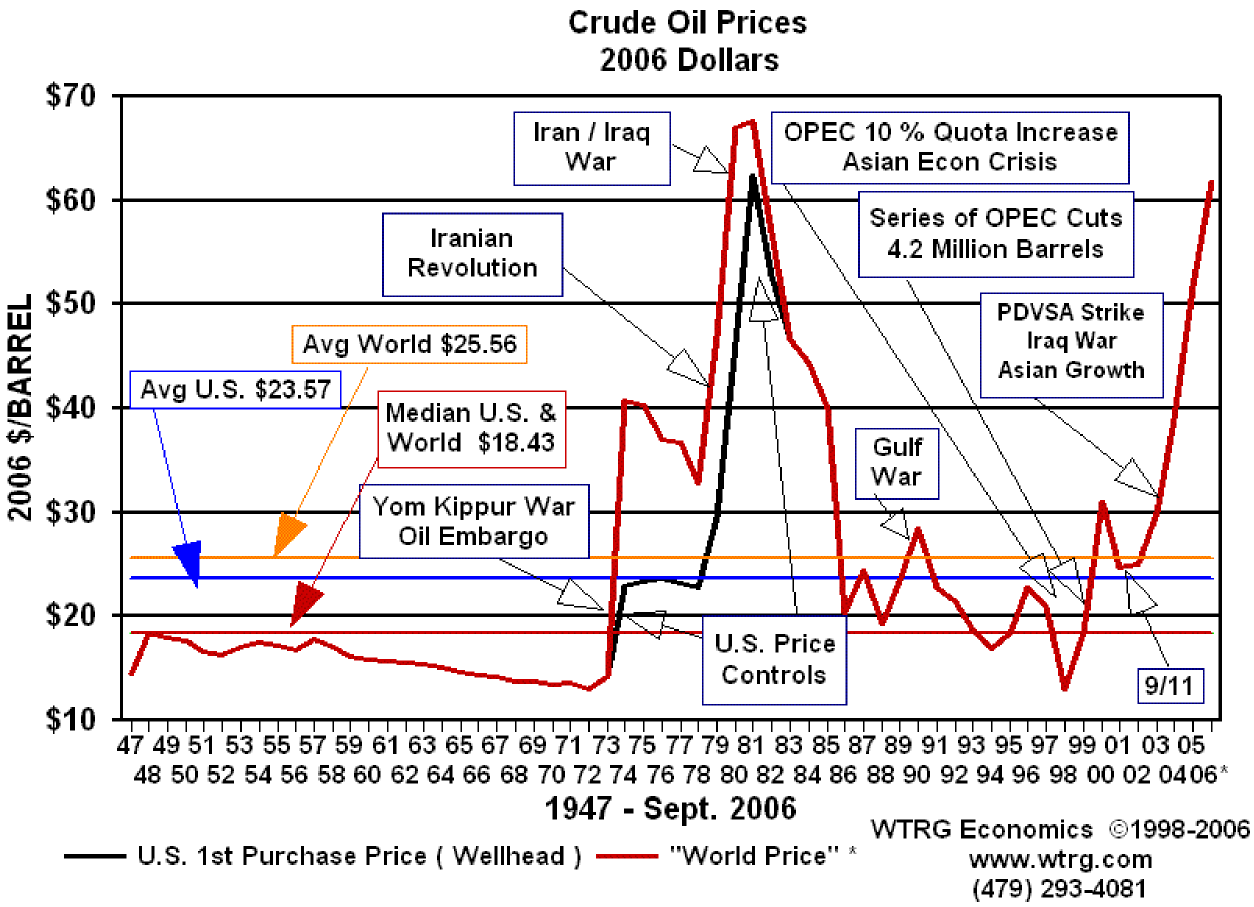
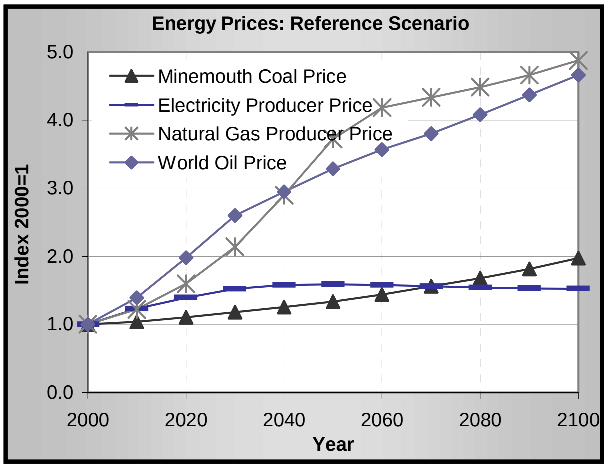
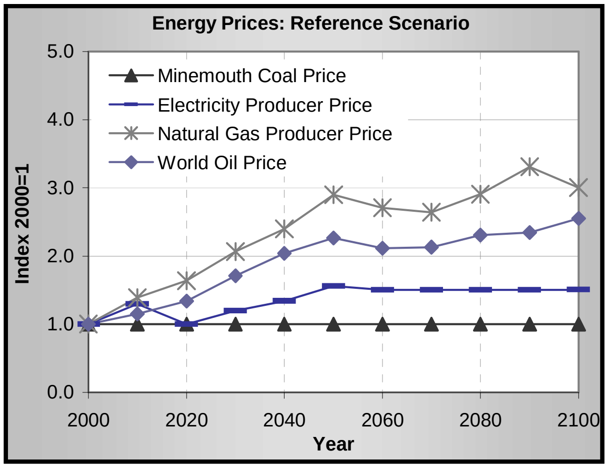


Figure 3.7. Indices of Energy Prices across Reference Scenarios (Indexed to 2000 = 1). Projected energy prices through 2100, indexed so that 2000=1.0, cover a wide range among the models but generally show a rising trend relative to recent decadal averages. MERGE price projections are intermediate—by 2100 the crude oil price is about that observed in 2005 (3 times the 2000 level). MiniCAM generally projects the lowest prices, with the projected crude oil price about twice 2000 levels in 2100, somewhat below the level reached in 2005. IGSM projects the highest prices, which for crude oil would be about 50 to 60% higher in 2100 than the price level of 2005.

IGSM



MERGE



MiniCAM

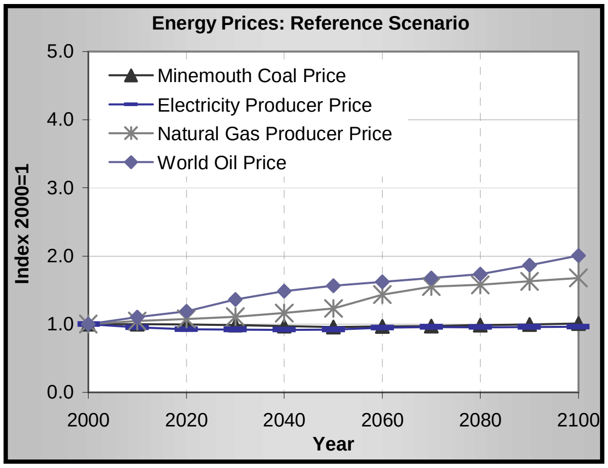


Figure 3.8. Global and U.S. Electricity Production by Source across Reference Scenarios (EJ/y of elec). Global and U.S. electricity production show continued reliance on coal, especially in the IGSM scenario, which assumes that nuclear expansion is limited by safety, waste and proliferation concerns. MERGE and MiniCAM assume that nuclear is unconstrained by non-climate concerns and so show greater expansion; they also project a greater contribution from renewable sources and somewhat greater use of electricity overall compared with IGSM. Differences in the contributions of different fuels at the global level among models are similar for the U.S. Total US electricity use is similar in MERGE and the IGSM, and somewhat lower in MiniCAM.

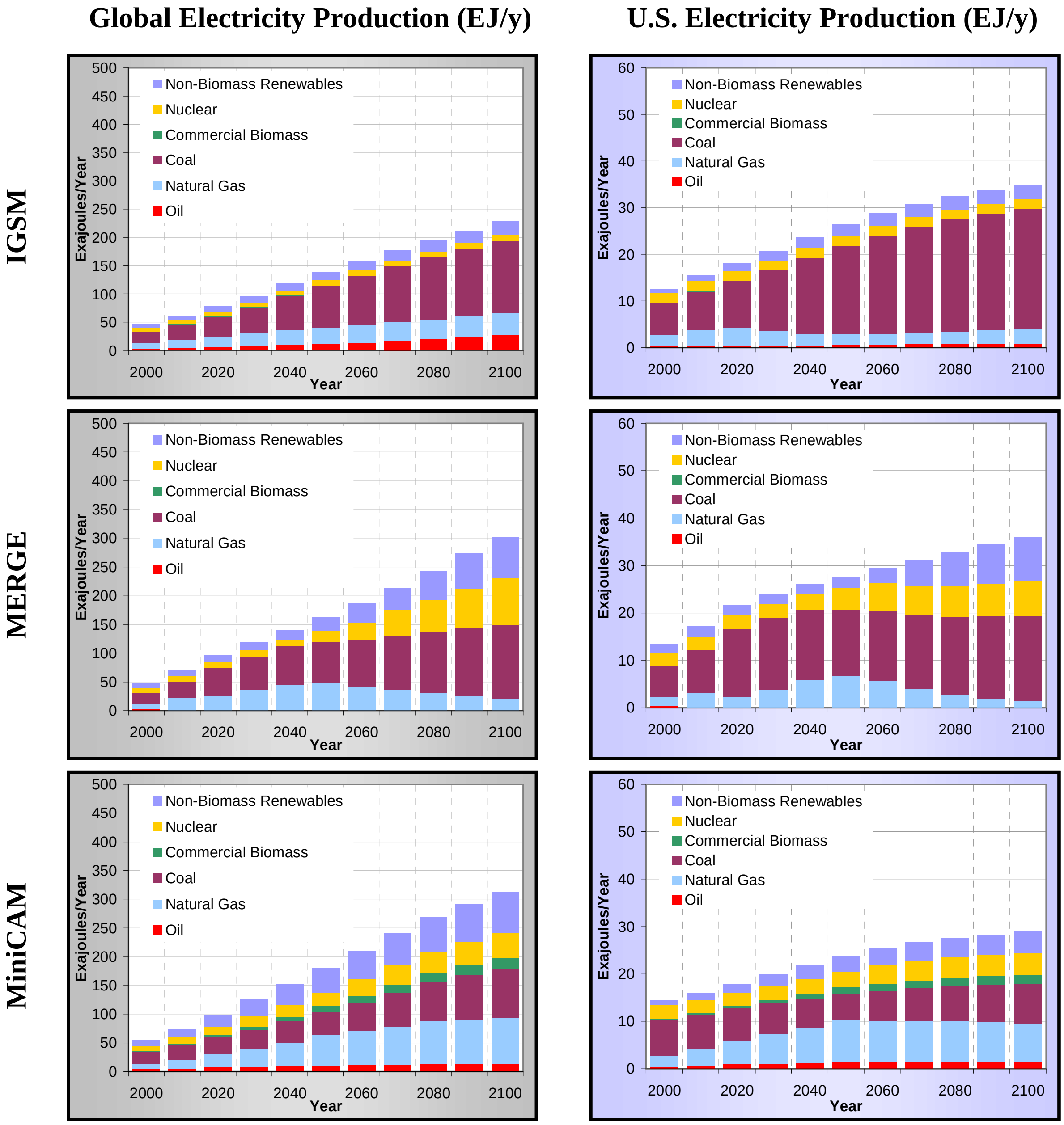
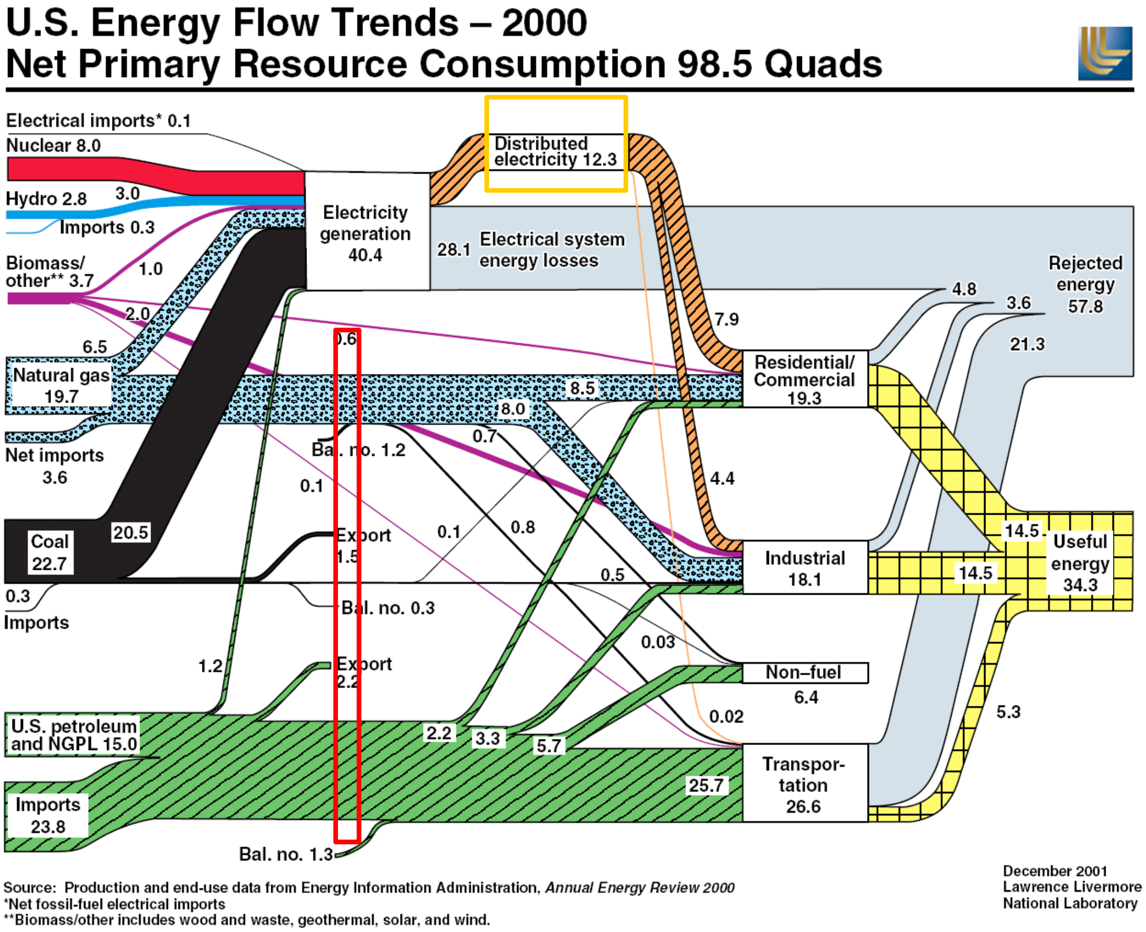


Figure 3.9. U.S. Energy Flow Diagram and Non-Electrical Energy Use for the Year 2000. Primary energy is transformed into different energy carriers that can easily be used for specific applications (e.g., space conditioning, light, and mechanical energy), but in the process losses occur. Of the 98.5 quads of primary energy used in the U.S. in the year 2000, only an estimated 34.3 quads were actually useful. Each of the models used in the study represents such conversion processes. Assumptions about efficiency improvements in conversion and end-use are one of the reasons why energy intensity per dollar of GDP is projected to fall.



Source: Production and end-use data from Energy Information Administration, *Annual Energy Review 2000*
*Net fossil-fuel electrical imports
**Biomass/other includes wood and waste, geothermal, solar, and wind.

December 2001
Lawrence Livermore
National Laboratory

Figure 3.10. Global and U.S. Primary Energy Consumed in Non-Electric Applications across Reference Scenarios (EJ/y). Non-electric energy use also remains heavily dependent on fossil fuels with some penetration of biomass energy. Primary energy is reported here, and the resurgence of coal in the projections is because of its use to produce synthetic liquids or gas.

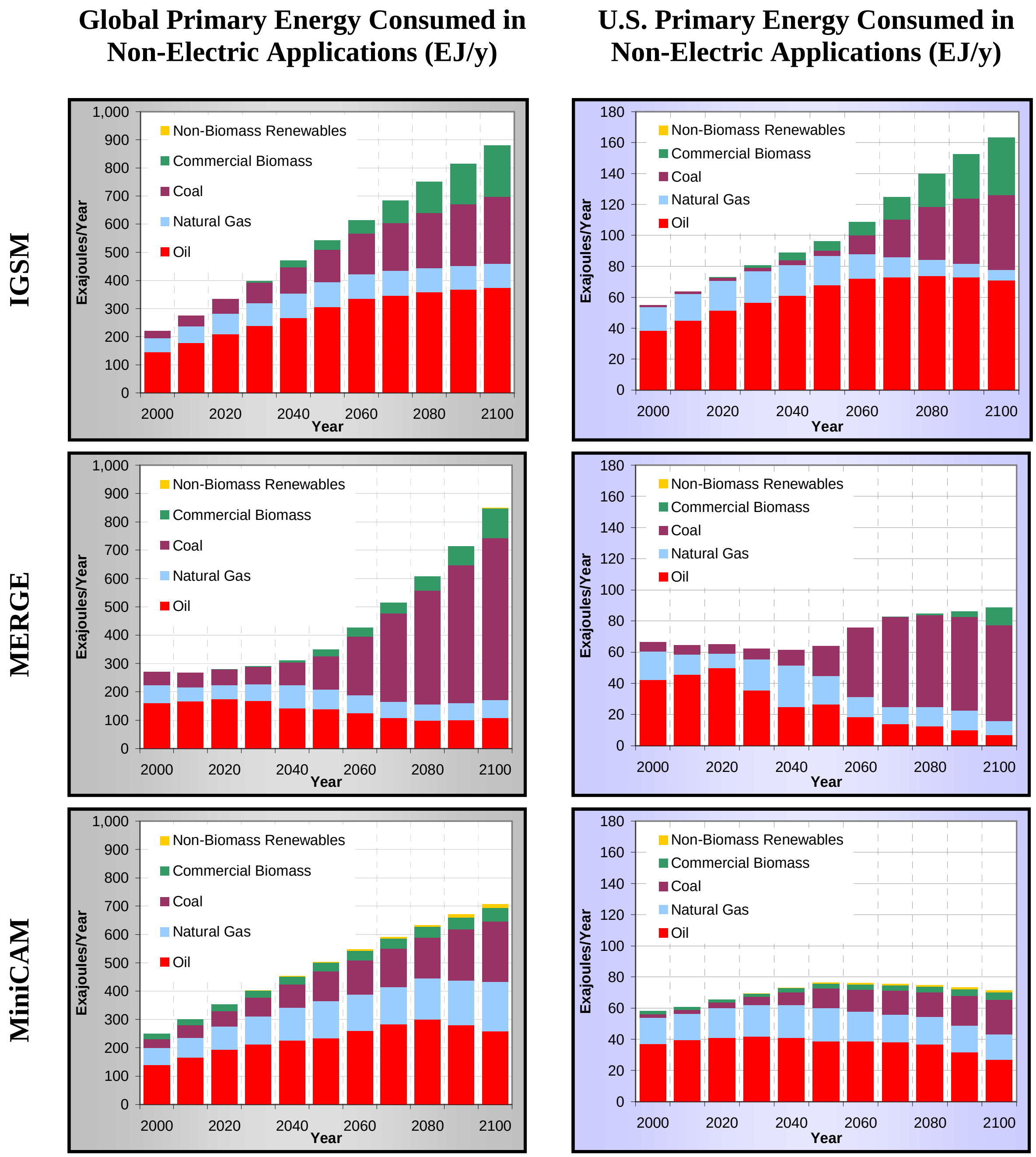
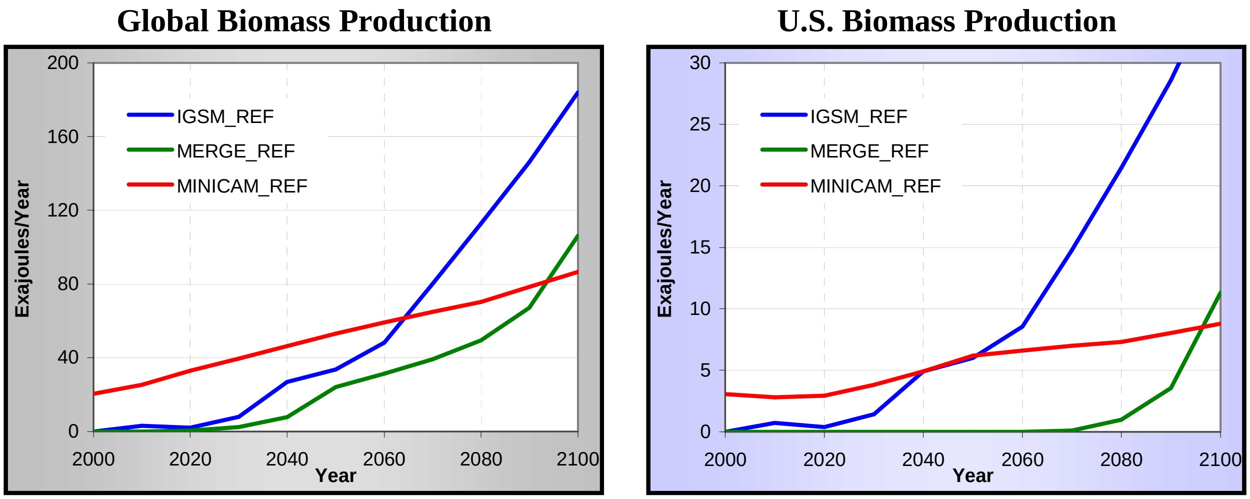


Figure 3.11. Global and U.S. Production of Biomass Energy across Reference Scenarios (EJ/y). The MiniCAM scenario includes waste derived biomass fuels as well as commercial biomass and thus shows significant use in 2000. IGSM and MERGE explicitly model only commercial biomass energy beyond that already used. Globally, both IGSM and MERGE show more biomass than does MiniCAM toward the end of the century.


Global Biomass Production

U.S. Biomass Production

Figure 3.12. Global Net Emissions of CO_2 from Terrestrial Systems Including Net Deforestation across Reference Scenarios (GtC/y). Global net emissions of CO_2 from terrestrial systems, including net deforestation, show that MiniCAM and IGSM have a slight net sink in 2000 that grows over time due mainly to reduced deforestation and CO_2 fertilization of plants. MERGE assumes a neutral terrestrial system.

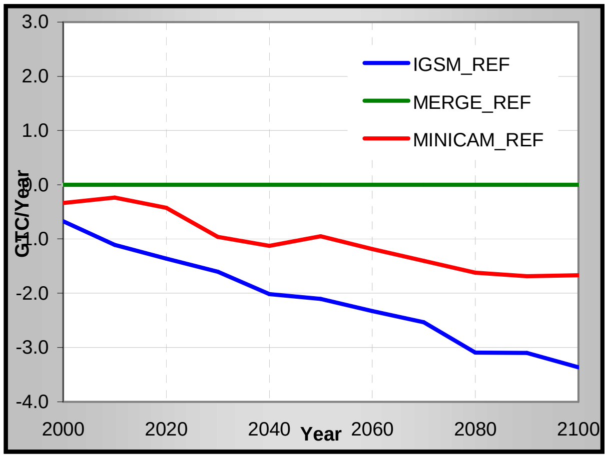
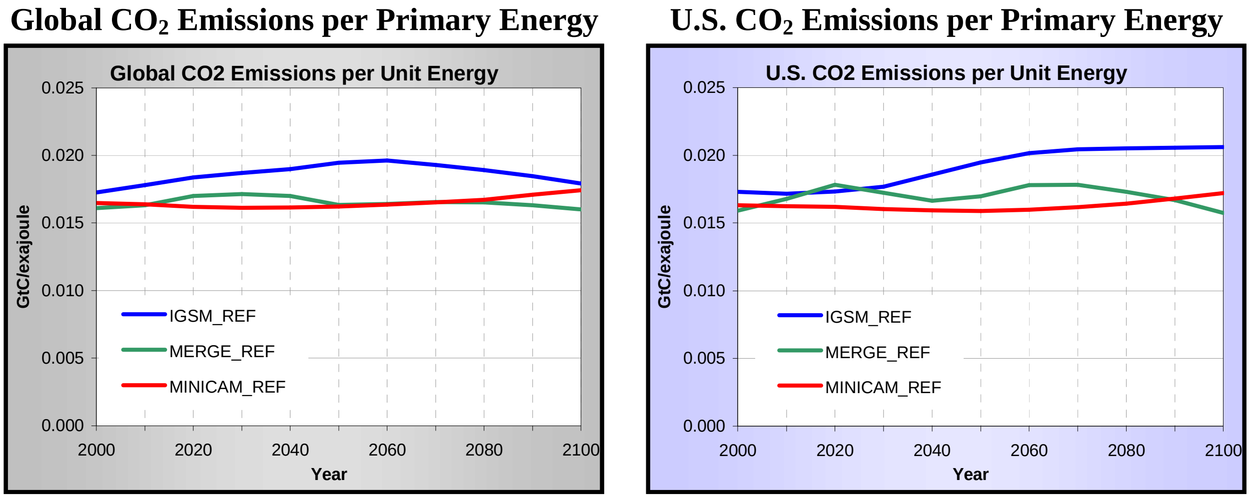
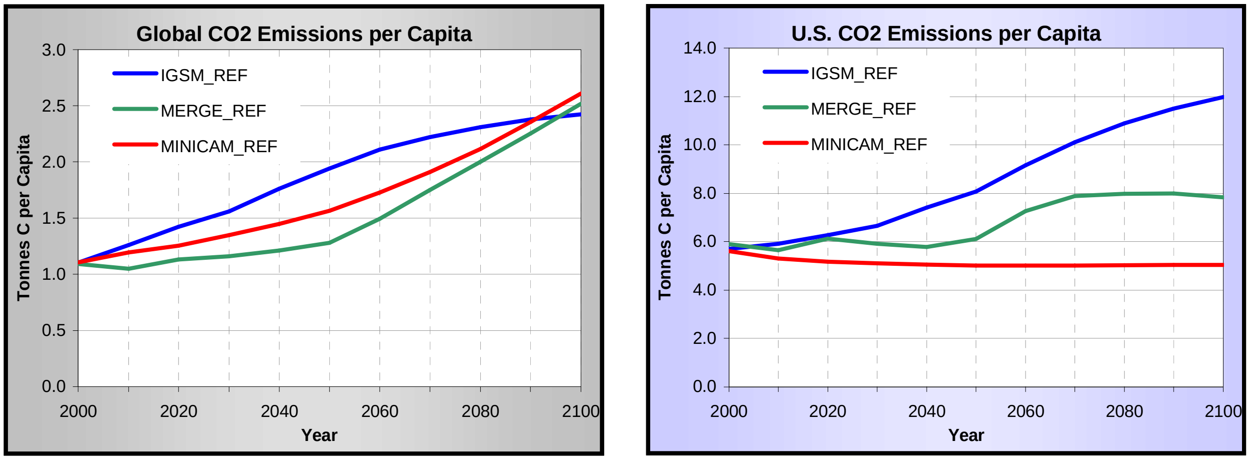


Figure 3.13. Global and U.S CO_2 Emissions from Fossil Fuel Combustion and Industrial Sources Relative to Primary Energy Consumption (GtC/exajoule). CO_2 intensity of energy use shows relatively little change in all three models, reflecting the fact that fossil fuels remain important sources of energy. Potential reductions in the CO_2 intensity of energy from more carbon-free or low-carbon energy sources is offset by a move to more carbon-intensive shale oil or synthetics from coal.


Global CO_2 Emissions per Primary Energy

U.S. CO_2 Emissions per Primary Energy

Figure 3.14. World and U.S. CO_2 Emissions per Capita across Reference Scenarios (Metric Tonnes per Capita). All three models project growing per capita fossil fuel and industrial CO_2 emissions for the world as a whole. However even after 100 years of growth, global per capita CO_2 emissions are slightly less than ½ of the 2000 U.S. level in the three scenarios.



Global CO_2 Emissions per Capita **U.S. CO_2 Emissions per Capita**

Figure 3.15. Global Emissions of CO_2 from Fossil Fuels and Industrial Sources (CO_2 from land use change excluded) across Reference Scenarios (GtC/y). In the absence of climate policy, all three models project increases in global emissions of CO_2 from fossil fuel combustion and other industrial sources, mainly cement production. By 2100, reference emissions are between 22.5 GtC/yr and 24 GtC/yr. Note that CO_2 from land-use change is excluded from this figure.

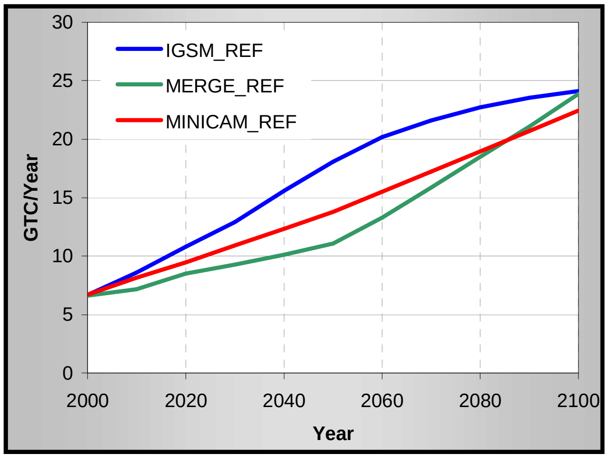


Figure 3.16. Global Emissions of Fossil Fuel and Industrial CO_2 by Annex I and Non-Annex I Countries across Reference Scenarios (GtC/y). Emissions of fossil fuel and industrial CO_2 in the reference scenarios show Non-Annex I emissions exceeding Annex I emissions for all three models by 2030 or earlier. MERGE and MiniCAM show continued relative rapid growth in emissions in Non-Annex I regions after that, so that their emissions are on the order of twice the level of Annex I by 2100. IGSM does not show continued divergence, due in part to relatively slower economic growth in Non-Annex I regions and faster growth in Annex I than the other models. IGSM also shows increased emissions in Annex I as those nations become producers and exporters of shale oil, tar sands, and synthetic fuels from coal.

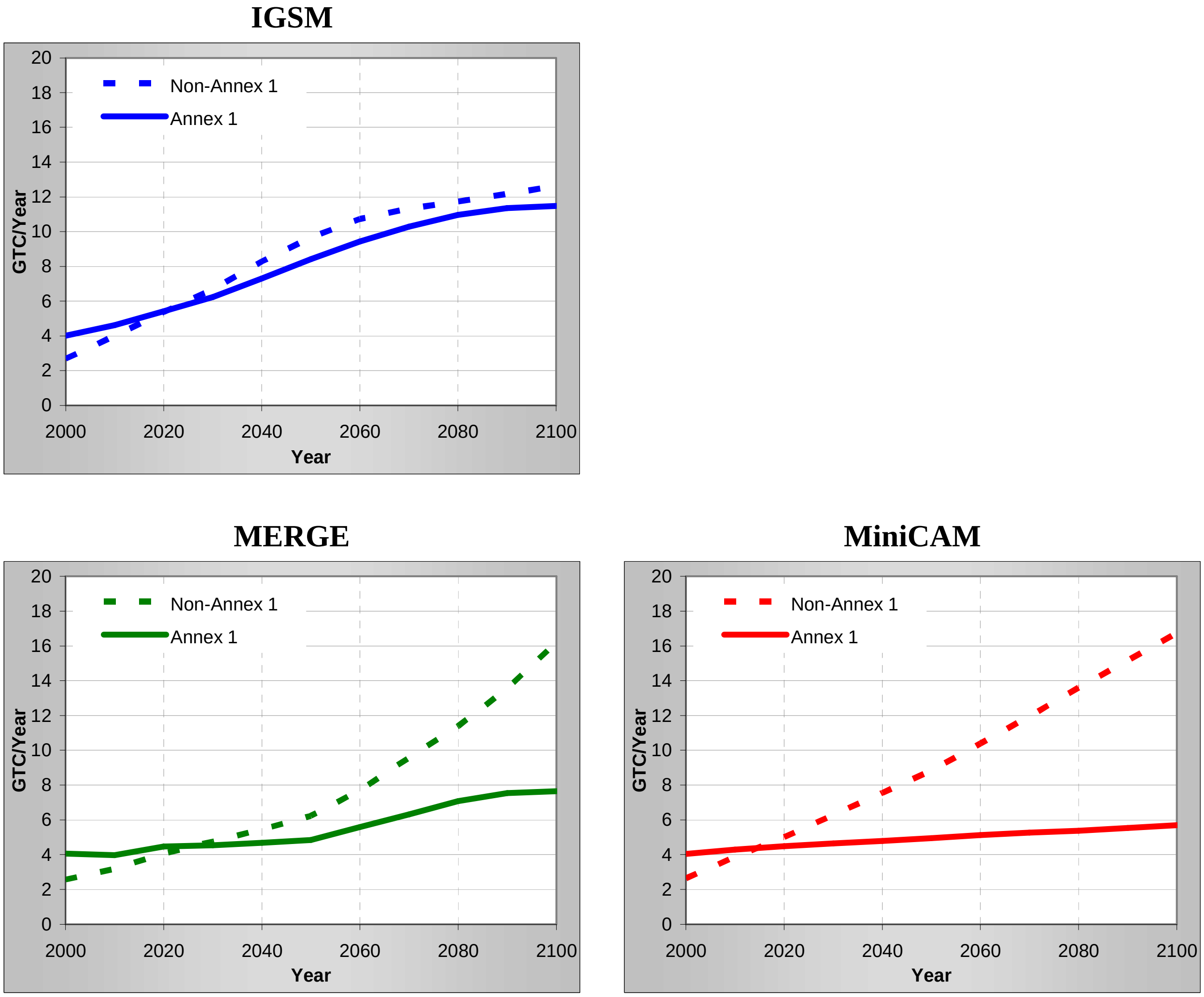
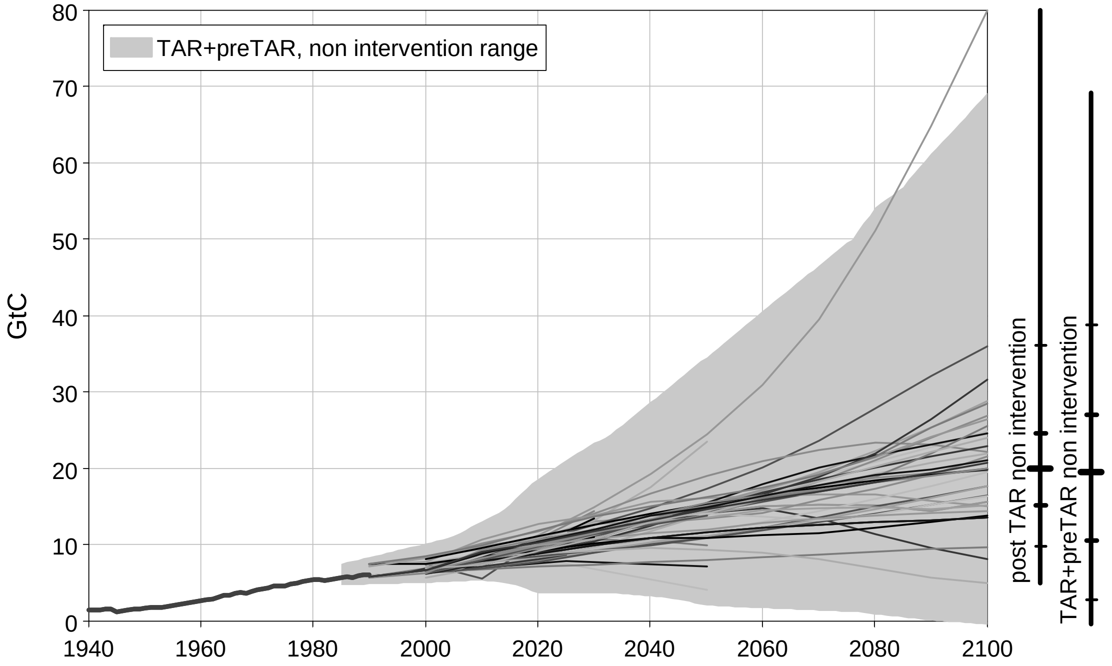


Figure 3.17. Global Fossil Fuel and Industrial Carbon Emissions: Historical Development and Scenarios (GtC/y). The 284 non-intervention scenarios published before 2001 are included in the figure as the gray-shaded range. The "spaghetti" lines are an additional 55 non-intervention scenarios published since 2001. Two vertical bars on the right-hand side indicate the ranges for scenarios since 2001 (labeled "post TAR non-intervention") and for those published up to 2001 ("TAR+preTAR non-intervention"). Sources: Nakicenovic et al. (1998), Morita and Lee (1998) and http://www-cger.nies.go.jp/cger-e/db/enterprise/scenario/scenario_index_e.html, and http://iiasa.ac.at/Research/TNT/WEB/scenario_database.html.



Source: Nakicenovic et al. (2006).

Figure 3.18. Global CH_4 and N_2O Emissions across Reference Scenarios (Mtonnes/y). Projections of global anthropogenic emissions of CH_4 and N_2O vary widely among the models. There is uncertainty in year 2000 CH_4 emissions, with IGSM ascribing more of the emissions to human activity and less to natural sources. Differences in projections reflect, to a large extent, different assumptions about whether current emissions rates will be reduced significantly for other reasons, for example, whether higher natural gas prices will stimulate capture of CH_4 for use as a fuel.

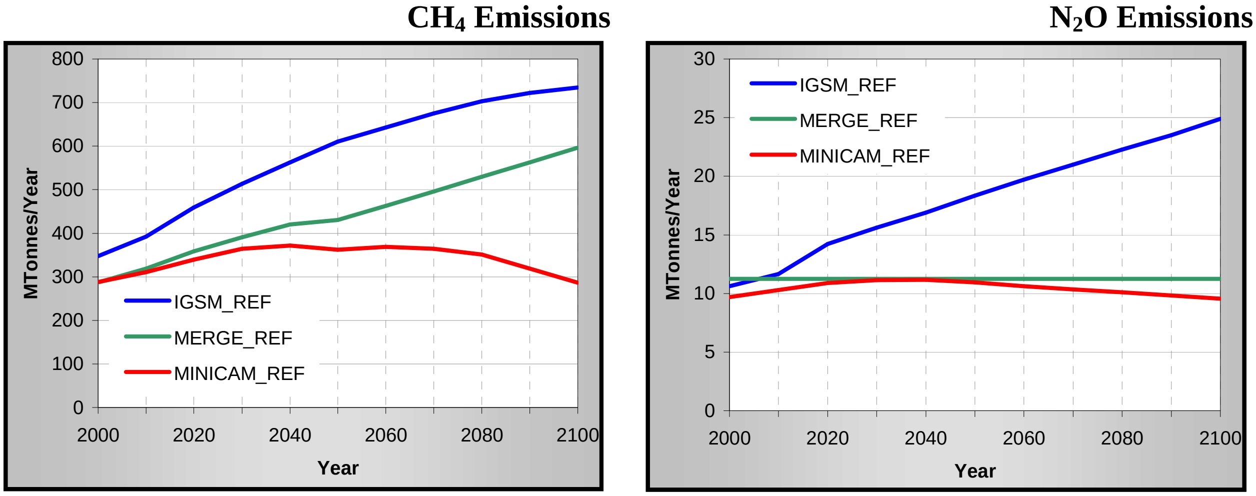


Figure 3.19. Global Emissions of Short-Lived and Long-Lived F-Gases (ktonnes/y). Global Emissions of High HFCs and others (PFCs and SF_6 aggregated)

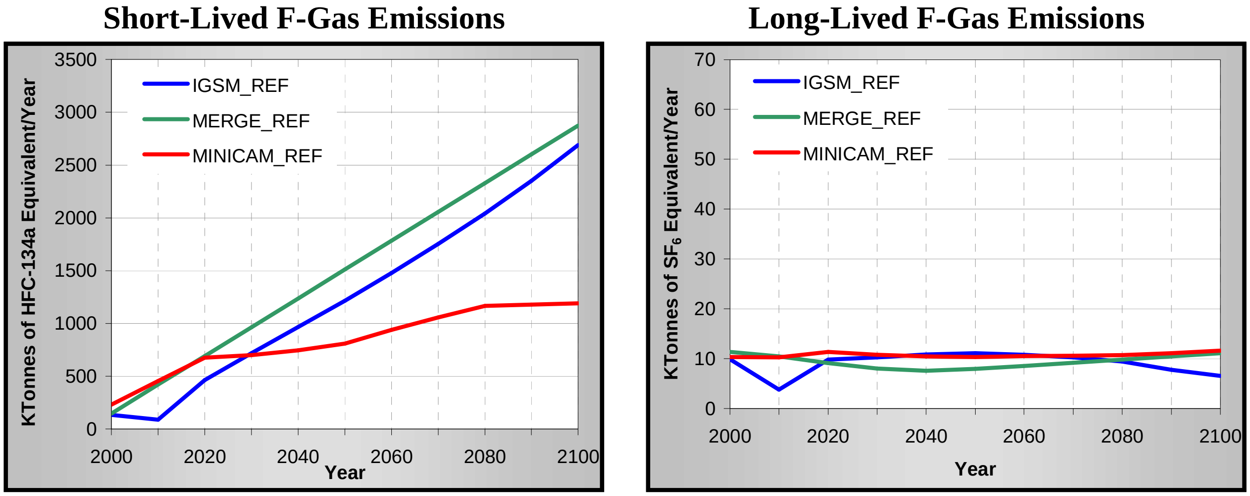


Figure 3.20. CO_2 Uptake from Oceans across Reference Scenarios (GtC/y, Expressed in Terms of Net Emissions). The ocean is a major sink for CO_2. In general, as concentrations rise, the ocean sink rises, but the IGSM results that include a three-dimensional ocean suggest less uptake and, after some point, little further increase in uptake even though concentrations are rising. The MiniCAM results show some slowing of ocean uptake although not as pronounced. MERGE shows now slowing in uptake. Although MERGE shows higher ocean uptake in the latter half of the century the effects of this increase are offset by the assumption of a neutral biosphere. Hence the behavior of its carbon cycle tends to be more similar to the other two models, especially MiniCAM (see Figure 3.22). The three ocean models produce more similar behavior in the stabilization scenarios

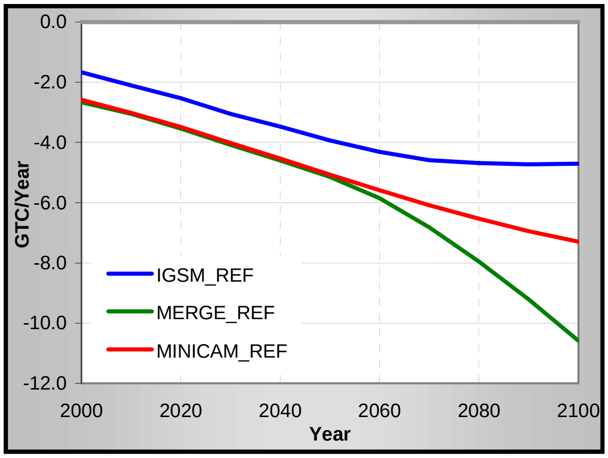


Figure 3.21. Relationship between Cumulative CO_2 Emissions from Fossil Fuel Combustion and Industrial Sources, 2000-2100, and Atmospheric Concentrations of CO_2 across All Scenarios. The relationship between cumulative carbon emissions and atmospheric concentration shows that, despite differences in how the carbon cycle is handled in each model, the models have a very similar response in terms of concentration level for a given level of cumulative emissions, as all models lie on essentially a single line. (Note that the cumulative emissions do not include emissions from land use and land-use change.)

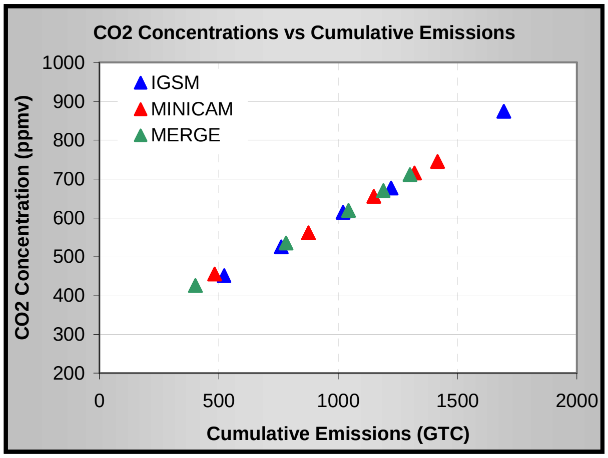
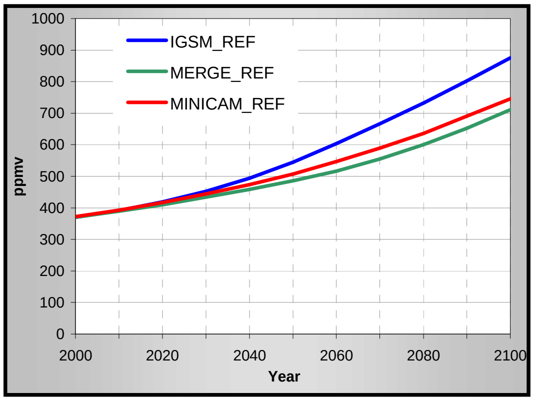
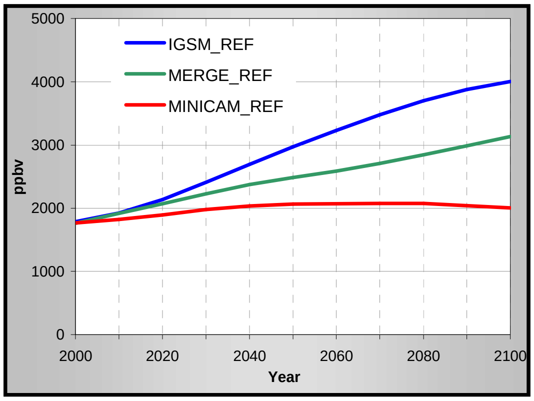


Figure 3.22. Atmospheric Concentrations of CO_2, CH_4, N_2O, and F-gases across the Reference Scenarios (Units Vary). Differences in concentrations for CO_2, CH_4, and N_2O across the three models' reference projections reflect differences in emissions and treatment of removal processes. By 2100, CO_2 concentrations range from about 700 to 900 ppmv; CH_4 concentrations range from 2000 to 4000 ppbv; N_2O concentrations range from about 380 to 500 ppbv.

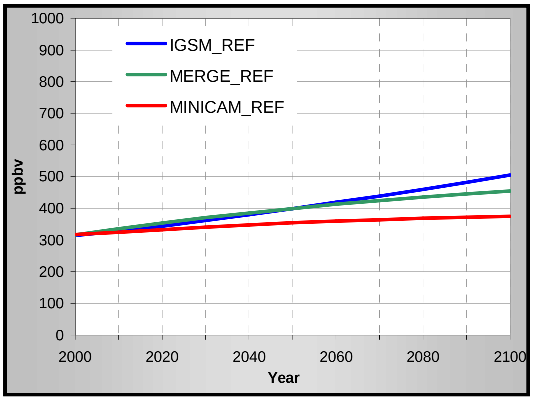
CO_2



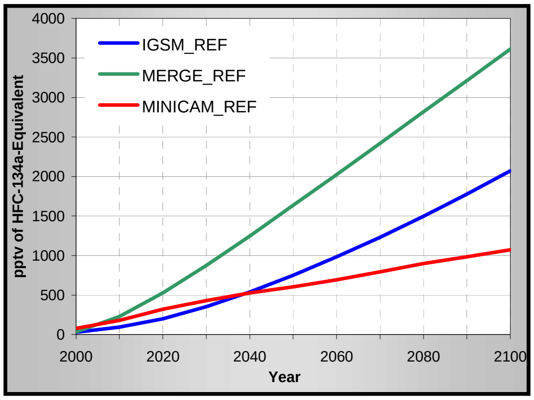
CH_4



N_2O



Short-Lived F-Gases



Long-Lived F-Gases

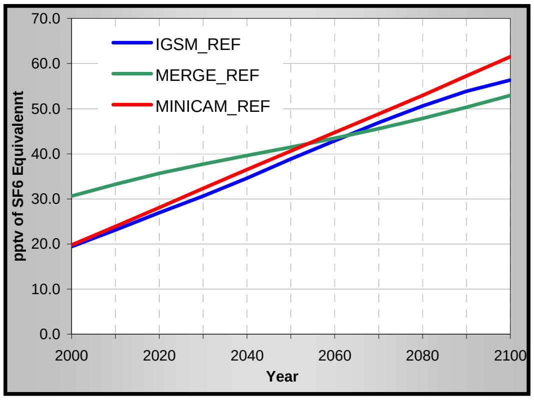
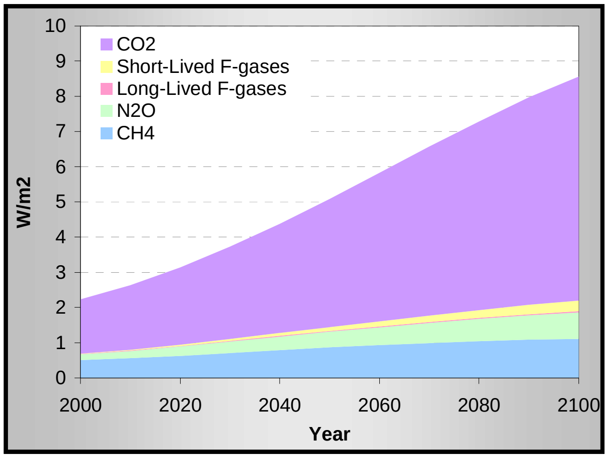
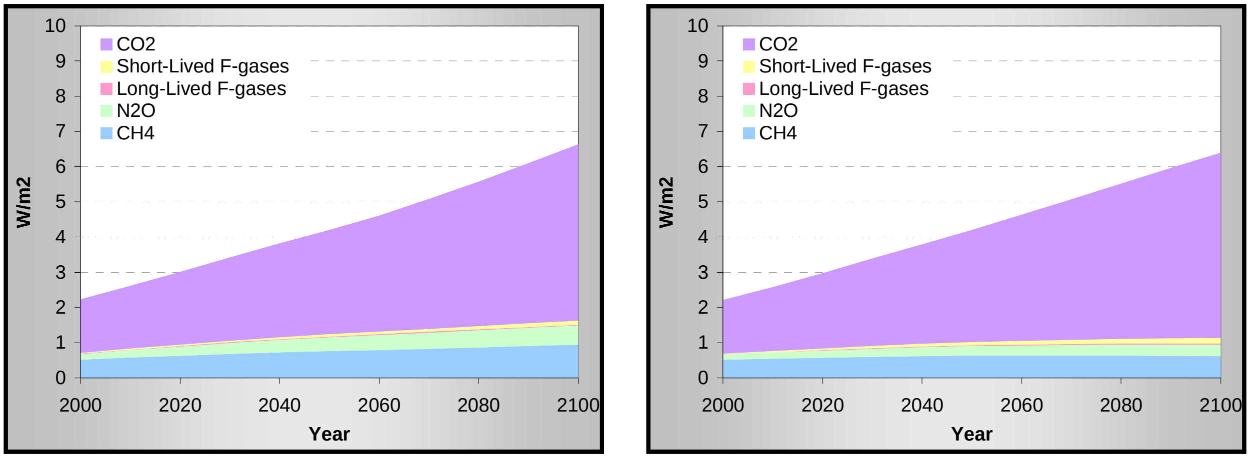


Figure 3.23. Radiative Forcing by Gas across Reference Scenarios (W/m^2). The contributions of different greenhouse gases to increased radiative forcing through 2100 show CO_2 accounting for more than 80% of the increased forcing from preindustrial for all three models. The total increase ranges from about 6.4 to 8.6 W/m^2 above pre-industrial levels.

IGSM



MERGE **MiniCAM**



4. STABILIZATION SCENARIOS

> *Stabilizing radiative forcing at levels ranging from 3.4 to 6.7 W/m^2 above pre-industrial levels (Level 1 to Level 4) implies significant changes to the world's energy, agriculture, land-use, and economic systems relative to a reference scenario that does not include long-term radiative forcing targets. Such limits would shape technology deployment throughout the century and have important economic consequences, but, as these scenarios illustrate, there are many pathways to the same end.*

4.1. Introduction

In Chapter 3, each modeling team developed scenarios of long-term greenhouse gas (GHG) emissions associated with changes in key economic characteristics, such as demographics and technology. This chapter describes how such developments might change in response to limits on radiative forcing. It illustrates that society's response to a stabilization goal can take many paths, reflecting factors shaping the reference scenario and the availability and performance of emission-reducing technologies. It should be emphasized that there has been no international agreement on a desired stabilization target; the four levels analyzed below and detailed in Table 4.1 were chosen for illustrative purposes only. They reflect neither a preference nor a recommendation. However, they correspond roughly to four of the frequently analyzed levels of CO_2 concentrations.

Table 4.1. Long-Term Radiative Forcing Limits by Stabilization Level and Corresponding Approximate CO_2 Concentration Levels

Control of GHG emissions requires changes in the global energy, economic, agriculture, and land-use systems. In all the control cases it was assumed that forcing levels would not be allowed to overshoot the targets along the path to long-term stabilization. Given this assumption, each modeling group had to make further decisions regarding the means of limitation. Section 4.2 compares the approaches of the three modeling teams. Section 4.3 shows the effect of the three strategies on GHG emissions, concentrations, and radiative forcing. The implications for global and U.S. energy and industrial systems are explored in Section 4.4 and for agriculture and land-use change in Section 4.5. Section 4.6 discusses economic consequences of measures to achieve the various stabilization levels.

4.2. Stabilizing Radiative Forcing: Model Implementations

Some features of scenario construction were coordinated among the three modeling groups and others were left to their discretion. In three areas, a common set of approaches was adopted:

- Climate policies in the reference scenario (Section 4.2.1)
- The timing of participation in stabilization scenarios (Section 4.2.2)
- Policy instrument assumptions in stabilization scenarios (Section 4.2.3).

In two areas the teams employed different approaches:

- The timing of CO_2 emissions mitigation (Section 4.2.4)
- Non-CO_2 emissions mitigation (Section 4.2.5).

4.2.1. Reference Scenario Climate Policies

Each group assumed that, as in the reference scenario, the U.S. will achieve its goal of reducing GHG emissions intensity (the ratio of GHG emissions to GDP) by 18% in the period to 2012 although implementation of this goal was left to the judgment of each group. Also, the Kyoto Protocol participants were assumed to achieve their commitments through the first commitment period, 2008 to 2012. In the reference scenario, these policies were modeled as not continuing after 2012. In the stabilization scenarios, these initial period policies were superseded by the long-term control strategies imposed by each group.

4.2.2. Timing of Participation in Stabilization Scenarios

There has been no international agreement on the desired level at which to stabilize radiative forcing or the path to such a goal, nor is there any consensus about the relative sharing of burdens other than a general call for "common but differentiated responsibilities" by the United Nations Framework Convention on Climate Change (United Nations, 1992). For the stabilization scenarios, it was assumed that policies to limit the change in radiative forcing would be applied globally, as directed by the Prospectus. Although it seems unlikely that all countries would simultaneously join such a global agreement, and the economic implications of stabilization would be greater with less-than-universal participation, the assumption that all countries participate does provide a useful benchmark.

4.2.3. Policy Instrument Assumptions in Stabilization Scenarios

Note that the issue of economic efficiency applies across both space and time. All three models assume an economically efficient allocation of reductions among nations in each time period, that is, across space. Thus, each model controls GHG emissions in all regions and across all sectors of the economy by imposing a single price for each GHG at any point in time. As will be discussed in detail in Section 4.5, the prices of emissions for the individual GHGs were different for each model. The implied ability to access emissions reduction opportunities wherever they are cheapest is sometimes referred to as "where" flexibility (Richels et al. 1996).

4.2.4. Timing of CO_2 Emissions Mitigation

The cost of limiting radiative forcing to any given level depends importantly on the timing of the associated emissions mitigation. The stabilization goal of the Framework Convention is incompletely defined. Neither the FCCC nor subsequent agreements specify the level of stabilization, how to balance reductions in the near-term against reductions later, or how to address the multiple substances that contribute to radiative forcing. There is a strong economic argument that mitigation costs will be lower if abatement efforts start slowly and then progressively ramp up, particularly for CO_2. Distributing emissions mitigation over time, such that larger efforts are undertaken later, reduces the current cost as a consequence of such effects as discounting, the preservation of energy-using capital stock over its natural lifetime, and the potential for the development of increasingly cost-effective technologies.

What constitutes such a cost-effective "slow start" depends on the concentration target and the ability of economies to make strong reductions later. While 100 years is a very long time-horizon for economic projections, it is not long enough to fully evaluate stabilization goals. In most instances, the scenarios are only approaching stabilization in 2100. Concentrations are below the targets and still rising, but the rate of increase is slowing substantially. Stabilization of atmospheric concentrations requires that any emissions be completely offset by uptake or destruction of the gas. Because ocean and terrestrial uptake of CO_2 is subject to saturation and system inertia, at least for the CO_2 concentration limits considered in this analysis, emissions need to peak and subsequently decline during the twenty-first century or soon thereafter. In the very long term (many hundreds to thousands of years), emissions must decline to virtually zero for any CO_2 concentration to be maintained. Thus, while there is some flexibility in the inter-temporal allocation of emissions, it is inherently constrained by the carbon cycle. Given that anthropogenic CO_2 emissions rise with time in all three of the unconstrained reference scenarios, the stringency of CO_2 emissions mitigation also increases steadily with time.

The models differ in the way they determine the profile of emissions reduction and how the different GHGs contribute to meeting radiative forcing targets. A major reason for the difference is the structure of the models. MERGE is an inter-temporal optimization model and is able to set a radiative forcing target and solve for the cost-minimizing allocation of abatement across gases and over time. It thus offers insights regarding the optimal path of emissions abatement. A positive discount rate will lead to a gradual phase-in of reductions, and the tradeoff among gases is endogenously calculated, based on the contribution each makes toward the long-term goal (Manne and Richels 2001). Given a stabilization target, the changing relative prices of gases over time can be interpreted as an optimal trading index for the gases that combines economic considerations with modeled physical considerations (lifetime and radiative forcing). The resulting relative weights are different from those derived using Global Warming Potential (GWP) indices, which are based purely on physical considerations (see IPCC 2001). Furthermore, economically efficient indices for the relative importance of GHG emissions mitigation will vary over time and across policy regimes.

IGSM and MiniCAM are simulation models and do not endogenously solve for optimal allocations over time and by type of gas. However, their choice of price path over time takes account of insights from economic principles that lead to a pattern similar to that computed by MERGE. The pattern was anticipated by Peck and Wan (1996) using a simple optimizing model with a carbon cycle and by Hotelling (1931) in a simpler context.

The MiniCAM team set the rate of increase in the price of carbon equal to the rate of interest plus the average rate of removal of carbon from the atmosphere by natural systems. This approach follows Peck and Wan (1996) and yields a resulting carbon price path qualitatively similar to that obtained by the MERGE team. This carbon price path ensures that the present discounted marginal cost of having one tonne of carbon less in the atmosphere during one period in the future is exactly the same regardless of whether the removal takes place today or one period later. When marginal costs are equal over time, there is no way that total costs can be reduced by making emissions mitigation either earlier or later.

As with MERGE, the exponential increase in the price of CO_2 continues until such time as radiative forcing is stabilized. Thereafter the price is set by the carbon cycle. That is, once radiative forcing has risen to its stabilization level, additional CO_2 can only enter the atmosphere to the extent that natural processes remove it, otherwise CO_2 radiative forcing would be increasing. This is relevant in the Level 1 stabilization scenario and, to a lesser extent, in the Level 2 stabilization scenario. However, it is not present in the Level 3 or

Level 4 scenarios because stabilization is not reached until after the end of the twenty-first century.

The IGSM determines a carbon price path that rises at 4% per year.. The initial carbon price is set to achieve the required concentrations and forcing. Thus, the rate of increase in the CO_2 price paths is identical for all stabilization scenarios, but the initial value of the carbon price is different. The lower the concentration of CO_2 allowed the higher the initial price. The insight behind this approach is that an entity faced with a carbon constraint and a decision to abate now or later would compare the expected return on that abatement investment with the rate of return elsewhere in the economy. The 4% rate is taken to be this economy-wide rate of return. If the carbon price were rising more rapidly than the rate of return, abatement investments would yield a higher return than investments elsewhere in the economy, so that the entity would thus invest more in abatement now (and possibly bank emissions permits to use them later). By the same logic, an increase in the carbon price lower than the rate of return would lead to a decision to postpone abatement. It would lead to a tighter carbon constraint and a higher carbon price in the future. Thus, this approach is intended to be consistent with a market solution that would allocate reductions through time.

4.2.5. Non-CO_2 Emissions Mitigation

Like CO_2, the contribution of non-CO_2 greenhouse gases to radiative forcing depends on their concentrations. However, these gases are dissociated in the atmosphere over time so that the relationship between emissions and concentrations is different from that for CO_2, as are the sources of emissions and opportunities for abatement. Each of the three modeling teams used its own approach to model their control. As noted above, the MERGE modeling team employed an inter-temporal optimization approach. The price of each GHG was determined so as to minimize the social cost of limiting radiative forcing to each level. Thus, the price of each gas was constant across regions at any point in time, but varied over time so as to minimize the social cost of achieving each level.

The MiniCAM team tied non-CO_2 GHG prices to the price of CO_2 using the GWPs of the gases. This procedure has been adopted by parties to the Kyoto Protocol and applied in the definition of the U.S. emissions intensity goal. IGSM used the same approach as MiniCAM to determine the prices for HFCs, PFCs, and SF_6, pegging the prices to that of CO_2 using GWP coefficients. For CH_4 and N_2O, however, independent emission stabilization levels were set for each gas in the IGSM because GWPs poorly represent the full effects of CH_4 and emissions trading at GWP rates leads to problems in defining what stabilization means when CH_4 and N_2O are involved (Sarofim et al. 2005). The relatively near-term stabilization for CH_4 specified in the IGSM analysis implies that near-term emissions reductions in result in economic benefit, an approach consistent with a view that there are risks associated with levels of radiative forcing below the specified atmospheric maximum. This approach is different that followed in the MERGE calculation, where any value of CH_4 abatement derives only from the extent to which it contributes to avoiding the long-term stabilization level. Under MERGE, early abatement of short-lived species like CH_4 has very little consequence for a target that will not be reached for many decades, so the optimized result places little value on abating short-lived species until the target is approached. A full analysis of the resulting climate change and its effects would be required to select between the MERGE and IGSM approaches. The different stabilization paths from these two models do provide a range of plausible scenarios for non-CO_2 GHG stabilization, however, with MiniCAM yielding an intermediate result.

4.3. Stabilization Implications for Radiative Forcing, Greenhouse Gas Concentrations, and Emissions

Despite significantly different levels of radiative forcing in their reference scenarios the modeling teams reported very similar levels of radiative forcing relative to pre-industrial levels for the year 2100 in all four stabilization scenarios. Differences across the models in year 2100 CO_2 concentrations across the four stabilization levels range between 30 and 40 GtC/yr, with much of this difference reflecting the gradual transition to stabilization that will occur sometime after 2100. Models that had relatively high CO_2 concentrations for a given stabilization level also had lower concentrations and emissions of non-CO_2 greenhouse gases, trading off reductions in these substances to make up for higher forcing from CO_2. These differences in stabilization results highlight the fact that there are many different pathways to stabilizing radiative forcing.

As a result of the economic assumptions imposed in the solutions, all of the modeling teams produced results in which the reduction in emissions below reference levels was much smaller in the period between 2000 and 2050 than between 2050 and 2100. With one exception, the stabilization scenarios were characterized by a peak and decline in global CO_2 emissions in the twenty-first century. The exception includes one Level 4 scenario in which emissions growth is near zero at the end of the century but they have not yet begun to decline. Global CO_2 emissions in the Level 1 scenarios are in decline by 2020 in all three models.

4.3.1. Implications for Radiative Forcing

Given that all the models were constrained by the same atmospheric targets, the modeling teams reported very similar levels of radiative forcing relative to pre-industrial levels for the year 2100 although the time-scale for stabilization exceeds the 2100 horizon of the analysis. Table 4.2 shows the long-term target level and the level of radiative forcing reported by each of the three modeling teams for the year 2100.[1] The differences across the models between the long-term target and the modeled radiative forcing levels are smaller for Levels 1 and 2 than for Levels 3 and 4 because the latter allow a greater accumulation of GHGs in the atmosphere than do Levels 1 and 2. For Levels 3 and 4 each modeling team required radiative forcing to be below the long-term limits in 2100 to allow for subsequent emissions to fall gradually toward levels required for stabilization.

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[1] The IGSM exceeds the Level 1 target by .1 Wm^{-2}, a negligible difference resulting from the iterative process required to achieve a radiative forcing target.

Table 4.2. Radiative Forcing in the Year 2100 across Scenarios

The radiative forcing stabilization paths for the three models are shown in Figure 4.1. Even though they reflect different criteria used to allocate abatement over time, the paths are very similar. The radiative forcing path is dominated by forcing associated with CO_2 concentrations, which in turn are driven by cumulative, not annual, emissions. Thus even fairly different time-profiles of CO_2 emissions can yield relatively little difference in concentrations and radiative forcing.

Figure 4.1. Total Radiative Forcing by Year across Scenarios

Although their totals are similar, the GHG composition of radiative forcing is different among the three modeling teams. Figure 4.2 plots the breakdown among gases in 2100 for the reference scenario along with all four stabilization levels. Forcing is dominated by CO_2 for all modeling teams at all target levels, but there are variations among models. For example, the MiniCAM control scenarios have larger contributions from CO_2 and lower contributions from the non-CO_2 gases than the other modeling teams. Conversely, the MERGE scenarios have higher contributions from the non-CO_2 gases and lower contributions from CO_2 relative to the other modeling teams.

Figure 4.2. Total Radiative Forcing by Gas in 2100 across Scenarios

4.3.2. Implications for Greenhouse Gas Concentrations

The relative GHG composition of radiative forcing across models in any scenario reflects differences in concentrations of the GHGs. The CO_2 concentration paths are presented in Figure 4.3, and the year 2100 atmospheric levels are detailed in Table 4.3. Because the actual policy targets were specified in terms of total radiative forcing from the multiple greenhouse gases, it is possible to meet those targets while varying from the CO_2 concentration levels set for them. In some of the cases that means CO_2 concentrations were in 2100 differ across models for any stabilization level. For example, the CO_2 concentrations projected by MiniCAM in the stabilization scenarios are generally higher than for the other modeling teams. Consequently, projected methane and N_2O concentrations are systematically lower as can be seen in Figure 4.4 (see also Figure 4.21).

Figure 4.3. CO_2 Concentrations across Scenarios

Table 4.3. CO_2 Concentrations in the Year 2100 across Scenarios

Differences in the gas concentrations among the three models reflect differences in the way the models make tradeoffs among gases and differences in assumed mitigation opportunities for non-CO_2 GHGs compared to CO_2.

Figure 4.4. CH_4 Concentrations across Scenarios

Approximate stabilization of CO_2 concentrations for Levels 1 and 2 occur by 2100 for all three models, but for Levels 3 and 4 concentrations are still increasing although at a slowing rate. An important implication of the less stringent stabilization levels is that substantial emissions reductions would be required after 2100. Sometime within the next century, all the stabilization paths would require emissions levels nearly as low as that for Level 1. Higher stabilization targets do not change the nature of long-term changes in emissions required in the global economy; they only delay when the abatement must be achieved.

All models show that as the rise in atmospheric concentrations slows the ocean uptake slows and even begins to decline. These natural removal processes are uncertain, and to some extent this uncertainty is reflected in differences in results from three modeling teams, as shown in Figure 4.5. The IGSM model projects the smallest amount of ocean uptake. MERGE includes the highest uptake for the least stringent levels, and MiniCAM and MERGE are almost identical for the most stringent stabilization levels.

Figure 4.5. Ocean CO_2 Uptake across Scenarios

4.3.3. Implications for Greenhouse Gas Emissions

4.3.3.1. Implications for Global CO_2 Emissions

For the Level 1 target, global CO_2 emissions begin declining after 2010 in all three modeling efforts (see Figure 4.6). The constraint is so tight that there is relatively little room for variation.

Figure 4.6. Fossil Fuel and Industrial CO_2 Emissions across Scenarios

All three modeling teams show continued emissions growth throughout the first half of the twenty-first century for Level 4, the loosest constraint, and the MiniCAM shows emissions continuing the increase throughout the century, although they are approaching a peak by 2100. Near-term variation in emissions largely reflects differences in the reference scenarios.

The scenarios of all three teams exhibit more emissions reduction in the second half of the twenty-first century than in the first half, as noted earlier, so the mitigation challenge grows with time. The precise timing and degree of departure from the reference scenario depend on many aspects of the scenarios and on each model’s representation of Earth system properties, including the radiative forcing limit, the carbon cycle, atmospheric chemistry, the character of technology options over time, the reference scenario CO_2 emissions path, the non-climate policy environment, the rate of discount, and the climate policy environment. For Level 4, 85% or more of emissions mitigation occurs in the second half of the twenty-first century in the scenarios developed here. Even for Level 1, where the limit is the tightest and near-term mitigation most urgent, 75% or more of the emissions reduction below reference occurs in the second half of the century. While this is partly a result of the “when” flexibility assumption, continuing emissions growth means that the percentage reduction is much larger as time goes.

All three of the modeling teams constructed reference scenarios in which Non-Annex 1 emissions were a larger fraction of the global total in the future than at present (see Figure 3.16). Because the stabilization scenarios are based on the assumption that all regions of the world face the same price of GHG emissions and have access to the same general set of technologies for mitigation, the resulting distribution of emissions mitigation between Annex I and Non-Annex I regions generally reflects the distribution of reference scenario emissions among them. So, when radiative forcing is restricted to Level I, all three models find that more than half of the emissions mitigation occurs in Non-Annex I regions by 2050 because more than half of reference-case emissions occur in Non-Annex I regions. Note that, with the global policy specified so that a common carbon price occurs in all regions at any one time, abatement occurs separately from, and mostly independent of, the distribution of the economic burdens of reduction.

4.3.3.2. Implications for Non-CO_2 Greenhouse Gas Emissions

The stabilization properties of the non-CO_2 greenhouse gases differ due to their lifetimes (as determined by chemical reactions in the atmosphere), abatement technologies, and natural sources. Methane has a relatively short lifetime, and anthropogenic sources are a big part of methane emissions. If anthropogenic emissions are kept constant, an approximate equilibrium between oxidation net emissions will be established relatively quickly and concentrations will stabilize. The same is true for the relatively short-lived HFCs.

Emissions under stabilization are systematically lower the more stringent the target, as can be seen in Figure 4.7. The MiniCAM modeling team, with its relatively lower reference scenario, has the lowest CH_4 emissions in stabilization scenarios. The assumed policy environment for CH_4 control is also important. Despite the fact that the IGSM modeling team has higher reference CH_4 emissions than MERGE, the MERGE scenarios have the higher emissions under stabilization in several instances. The reason is that the MERGE inter-temporal optimization leads to a low relative price for CH_4 emissions in the near-term, which grows rapidly relative to CO_2 favoring strong abatement of CH_4 only toward the end of the century, whereas IGSM controls CH_4 emissions through quantitative that lead to substantial reduction early in the century. Thus, MERGE emissions sometimes exceed those of IGSM until the relative CH_4 price rises sufficiently to induce substantial emissions reductions.

Figure 4.7. CH_4 Emissions across Scenarios

The very long-lived gases are nearly indestructible and, thus, for stabilization their emissions must be very near zero. Assessments of abatement possibilities, as represented in these models, show that it is possible, at reasonable cost, for this to be achieved as seen in the 2100 radiative forcing results in Figure 4.2. While these are useful substances, their emissions are not as difficult to abate as those from fossil energy.

N_2O is more problematic. A major anthropogenic source is from use of fertilizer for agricultural crops–an essential use. Moreover, its natural sources are important, and they are augmented by terrestrial changes associated with climate change. It is fortunate that N_2O is not a major contributor to radiative forcing because the technologies and strategies needed to achieve its stabilization are not obvious at this time. Nevertheless, differences in the control of N_2O are observed across models, as revealed in Figure 4.8, although these differences are smaller than those for CH_4.

Figure 4.8. N_2O Emissions across Scenarios

4.4. Implications for Energy Use, Industry, and Technology

Stabilization of radiative forcing at the levels examined in this study will require substantial changes in the global energy system, including some combination of improvements in energy efficiency, the substitution of low-emission or non-emitting energy supplies for fossil fuels, the capture and storage of CO_2, and reductions in end-use energy consumption.

4.4.1. Changes in Global Energy Use

The degree and timing of change in the global energy system depends on the level at which radiative forcing is stabilized. Figure 4.9 reports the reference scenario from Chapter 3 and then adds a plot of the net changes in the various primary energy sources for each stabilization level. While differences in the reference scenarios developed by each of the three modeling teams led to different patterns of response, some important similarities emerged. The lower the radiative forcing limit, the larger the change in the global energy system relative to the reference scenario; moreover, the scale of this change is larger, the further into the future the scenario looks. Also, significant fossil fuel use continues in all four stabilization scenarios. This pattern can be seen in Figure 4.10**,** which shows the same case as Figure 4.9 but in terms of total energy consumption.

Figure 4.9. Change in Global Primary Energy by Fuel across Scenarios, Stabilization Scenarios Relative to Reference Scenarios

Figure 4.10. Global Primary Energy by Fuel across Scenarios

Although atmospheric stabilization would take away much of the growth potential of coal over the century, all three models project its usage to expand above today’s levels by the end of the century in all the stabilization scenarios. In several of the Level 1 and Level 2 scenarios, the global coal industry declines in the first half of the century before recovering by 2100 to levels of production somewhat larger than today. Oil and natural gas also continue as contributors to total energy over the century although, as with coal, they are increasingly pushed from the energy mix as the stabilization level is tightened..

One reason that fossil fuels continue to be utilized despite constraints on GHG emissions is that CCS technologies are available. Figure 4.10 shows that as the carbon values rise, CCS technology takes on an increasing market share. Section 4.4.2 addresses this pattern, as well as the contribution of non-biomass renewable energy forms in greater detail.

Changes in the global energy system in response to constraints on radiative forcing reflect an interplay between technology options and the assumptions that shaped the reference scenarios. For example, the MERGE reference assumes a relatively limited ability to access unconventional oil and gas resources and the evolution of a system that increasingly employs coal as a feedstock for the production of liquids, gases, and electricity. Against this background, a constraint on radiative forcing results in reductions in coal use and end-use energy consumption. As the price of carbon rises, nuclear and non-biomass renewable energy forms and CCS augment the response.

The IGSM reference scenario assumes greater availability of unconventional oil and gas than in the MERGE scenarios. Thus, the stabilization scenarios, in general, involve less reduction in coal use by the end of the century, but a larger decline in oil and gas than in the MERGE scenarios. To produce liquid fuels for the transportation sector, the IGSM model responds to a constraint on radiative forcing by growing biomass energy crops both earlier and more extensively than in the reference scenario. Also, the IGSM model projects larger reductions in energy demand than either of the other two models.

The MiniCAM model produces the smallest reductions in energy consumption of the modeling groups. The imposition of constraints on radiative forcing leads to reductions in oil, gas, and coal, as do the other models, but also involves considerable expansion of nuclear and renewable supplies. The largest supply response is in commercial bio-derived fuels. These fuels are largely limited to bio-waste recycling in the reference scenario. As the price on CO_2 rises, commercial bio-energy becomes increasingly attractive. As will be discussed in Section 4.5, the expansion of the commercial biomass industry to produce hundreds of EJ of energy per year has implications for crop prices, land-use, land-use emissions, and unmanaged ecosystems.

The relative role of nuclear differs in each of the three analyses. The MERGE reference scenario deploys the largest amount of nuclear power, contributing 170 EJ/y of primary energy in the year 2100. In the Level 1 stabilization scenario, deployment expands to 240 EJ/y of primary energy in 2100. Nuclear power in the MiniCAM reference scenario produces 90 EJ/y in the year 2100, which in the Level 1 stabilization scenario expands to more than 180 EJ/y of primary energy in the year 2100. The IGSM scenarios show little change in nuclear power generation among the stabilization scenarios or compared with the reference, reflecting the assumption that nuclear levels are limited by policy decisions regarding nuclear siting, safety, and proliferation that are unaffected by climate policy.

Reductions in total energy demand play an important role in all of the stabilization scenarios. In the IGSM stabilization scenarios, this is the largest single change in the global energy system. While not as dramatic as the IGSM stabilization scenarios, MERGE and MiniCAM also exhibit reductions in energy demand. As will be discussed in Section 4.6, the difference in the change in energy use among the models reflects differences in the carbon prices required for stabilization which are substantially higher for the IGSM. In all three models, carbon price differences are reflected in the user prices of energy. Carbon prices, in turn, reflect technological assumptions that influence both the supply of alternative energy and the responsiveness of users to changing prices. The fuel and greenhouse gas prices discussed later in this chapter therefore can be instructive in understanding the character of technology assumptions employed in the models. As noted throughout the preceding and following discussions, the economic equilibrium nature of these three models implies that technology deployments are a reflection of prices. Technologies are deployed up to the point where marginal cost is equal to price. Thus, for example, the prices of oil and carbon determine the marginal cost of bioenergy and its deployment in the three models and that insight can be used to infer useful information about the technology assumptions that each of the models employed.

4.4.2. Changes in Global Electric Power Generation

The three models project substantial changes in electricity-generation technologies as a result of stabilization, although the MERGE and MiniCAM scenarios exhibit relatively little change in electricity demand. Indeed, across the models the relative reductions in electricity consumption under stabilization are lower than relative reductions in total primary energy. One reason for this result is that electricity price increases are smaller relative to those for direct fuel use because the fuel input, while important, is only part of the cost of electricity supply to the consumer. Also, the long-term cost of the transition to low and non-carbon-emitting sources is relatively smaller in electricity production than in the remaining sectors taken as an average.

There are substantial differences in the scale of global power generation across the three reference scenarios, as shown in Chapter 3 and repeated at the top of Figure 4.11. Power generation increases from about 50 EJ/y in the year 2000 to between 230 EJ/y (IGSM) to 310 EJ/y (MiniCAM) by 2100. In all three reference scenarios, electricity becomes an increasingly important component of the global energy system, fueled by growing quantities of fossil fuels. Despite differences in the relative contribution of different fuel sources across the three reference scenarios, total production of electricity from fossil fuel rises from about 30 EJ/y in 2000 to between 150 EJ/y and 190 EJ/y in 2100. Thus, the difference in total reference-case power generation among the models reflects differences in the deployment of non-fossil energy forms: biofuels, nuclear power, fuel cells, and other renewables such as wind, geothermal, and solar power.

Figure 4.11. Global Electricity Generation by Fuel across Scenarios

Figure 4.12. Changes in Global Electricity by Fuel across Stabilization Scenarios , Relative to Reference Scenarios

The imposition of radiative forcing limits dramatically changes the electricity sector. Common results in all 3 models is that CCS (with coal, gas, and where present with oil-generated power) is deployed at a large scale by the end of the century, and use of coal without CCS declines and eventually is not viable. The IGSM, as has been noted, restricts nuclear expansion, and other renewables are either resource limited (hydro power, electricity from biofuels) or become costlier to integrate into the grid as their share of electricity rises because they are intermittent (wind/solar). Partly as a result, natural gas use is increased in electric generation in the IGSM stabilization scenarios, especially in the nearer term before CCS becomes economically viable. In MERGE,carbon free technologies including non-biomass renewables and nuclear are viable and thus are favored over natural gas, whose use falls relative to the reference. The MiniCAM model also finds that nuclear and non-biomass renewable energy technologies capture a larger share of the market. At the less-stringent levels of stabilization, i.e., Levels 3 and 4, additional biofuels are deployed in power generation, and total power generation declines. Under the most stringent stabilization level, commercial bio-fuels used in electricity generation in MiniCAM are diverted to the transportation sector, and use actually declines relative to the reference toward the end of the century. The IGSM has biomass liquid for transportation out-competing use in electricity generation in the reference and all 4 stabilization scenarios. The difference between MiniCAM and the IGSM likely reflects the higher fuels prices in the IGSM discussed in Section 4.6.3.

All modeling groups assumed that CO_2 could be captured and stored in secure repositories, and, as noted, in all cases CCS becomes a large-scale activity. Annual capture quantities are shown in Table 4.4. It is always one of the largest single changes in the power-generation system in response to stabilization in radiative forcing, as can be seen in Figure 4.12. As with mitigation in general, CCS starts relatively modestly in all the scenarios, but grows to large levels. The total storage over the century is recorded in Table 4.5, spanning a range from 20 GtC to 92 GtC for Level 4 and 231 GtC to 278 GtC for Level 1. The modeling groups made no attempt to report either location of storage sites for CO_2 or the nature of the storage reservoirs, but these scenarios are within the range of the estimates of global geologic reservoir capacity.

Table 4.4. Global Annual CO_2 Capture and Storage in 2030, 2050, and 2100 for Four Stabilization Levels

Table 4.5. Global Cumulative CO_2 Capture and Storage in 2050 and 2100 for Four Stabilization Levels

Deployment rates in the models depend on a variety of circumstances, including capture cost, new plant construction versus retrofitting for existing plants, the scale of power generation, the price of fuel inputs, the cost of competing technologies, and the level of the CO_2 price. It is clear that the constraints on radiative forcing considered in these scenarios are sufficiently stringent that, if CCS is available at a cost and performance similar to that considered in these scenarios, it would be a crucial component of future power generation.

Yet capture technology is hardly ordinary today. Geologic storage is largely confined to experimental sites or enhanced oil and gas recovery. There are as yet no clearly defined institutions or accounting systems to reward such technology in emissions control agreements, and long-term liability for stored CO_2 has not been determined. All of these issues and more must be resolved before CCS could deploy on the scale envisioned in these stabilization scenarios. If CCS were unavailable, the effect would be to increase the cost of achieving any of these stabilization scenarios. These scenarios tend to favor CCS but that tendency could easily change with different assumptions about nuclear power that are well within the range of uncertainty about future costs and policy environment. Nuclear power carries with it issues of long term storage or disposal of nuclear materials and proliferation concerns. Thus, the viability of both CCS or nuclear depend on regulatory and public acceptance issues. Absent CCS and nuclear fission, these models would need to deploy other emissions abatement options that could potentially be more costly, or would need to envision large breakthroughs in the cost, performance, and reliability of other technologies. This study has not attempted to quantify the increase in costs or the reorganization of the energy system that would be required to achieve stabilization without CCS. This sensitivity is an important item in the agenda of future research.

The fact that no clear winner emerges from among the suite of non-fossil power-generating technologies reflects technological uncertainty that lead to differences among the modeling teams regarding expectations for future technology performance, market and non-market factors affecting deployment, and the ultimate severity of future emissions mitigation regimes.

4.4.3. Changes in Energy Patterns in the United States

Changes for the U.S. are similar to those observed for the world in general. This pattern reflects the facts that the mitigation policy is implemented globally, there are international markets in fuels, each model makes most technologies globally available over time, and the U.S. is roughly a quarter of the world total.

Energy-system changes are modest for stabilization Level 4, as shown in Figure 4.13, but even with this loose constraint, significant changes begin upon implementation of the stabilization policy (the first period shown is 2020) in the IGSM. At more stringent stabilization levels, the changes are more substantial in all three models. With Level 1 stabilization, the reduction is in U.S. primary energy consumption ranges from 8 EJ/yr to over 25 EJ/yr in 2020.

Figure 4.13. Change in U.S. Primary Energy by Fuel across Stabilization Scenarios, Relative to Reference Scenarios

Near-term changes in the U.S. energy system show more differences among models than the long term adjustments. While oil consumption always declines at higher carbon prices for all the modeling teams and all stabilization regimes, near-term changes in oil consumption do not follow a consistent pattern. There is no ambiguity regarding the effect on coal consumption, however, which declines relative to the reference scenario in all stabilization scenarios for all models in all time periods. Similarly, total energy consumption declines along all scenarios. Nuclear power, commercial biomass, and other renewable energy forms are advantaged with at least one of them always deployed to a greater extent in stabilization scenarios than in the reference scenario. The particular form and timing of expanded development varies from model to model. The same results as in Figure 4.13 are shown in Figure 4.14 in terms of absolute quantities.

The three models exhibit different responses reflecting differences in underlying reference scenarios and technology assumptions. The largest change in the U.S. energy system for the IGSM modeling team is always the reduction in total energy consumption augmented by an expansion in the use of commercial biomass fuels and deployment of CCS at higher carbon tax rates. Similarly, the largest change in the MERGE model is the reduction in total energy consumption augmented by deployment of CCS and bioenergy, augmented in some cases with increased use of nuclear power. The MiniCAM model also exhibits reductions in total energy consumption and increases in nuclear power, along with smaller additions of commercial biomass and other renewable energy forms.

Figure 4.14. U.S. Primary Energy by Fuel across Scenarios

The adjustment of the U.S. electric sector to the various stabilization levels shown in Figure 4.15 is similar to the world totals in Figure 4.12.

Figure 4.15. Change in U.S. Electricity by Fuel across Stabilization Scenarios, Relative to Reference Scenarios

It is worth re-emphasizing that reductions in energy consumption are an important component of response at all stabilization levels in all scenarios. These reductions reflect a mix of three factors:

- Substitution of technologies that produce the same energy service with lower direct-plus-indirect carbon emissions,
- Changes in the composition of final goods and services, shifting toward consumption of goods and services with lower direct-plus-indirect carbon emissions, and
- Reductions in the consumption of energy services.

This report does not attempt to quantify the relative contribution of each of these responses. Each of the models has a different set of technology options, different technology performance assumptions, and different model structures. Furthermore, no well-defined protocol exists that can provide a unique attribution among these three general processes. We simply note that all three are at work.

4.5. Stabilization Implications for Agriculture, Land-Use, and Terrestrial Carbon

The three modeling teams apply three different approaches to the production of biofuels from land. Two of the modeling teams employed explicit agriculture-land-use models to determine production of bioenergy crops. They found that stabilization scenarios lead to expanded deployment of biofuels relative to the reference scenarios.

Similarly, the three modeling teams employ different approaches to the treatment of the terrestrial carbon cycle, ranging from a simple "neutral biosphere" model to a state-of-the-art terrestrial carbon-cycle model. In two of the models, a "CO_2 *fertilization effect" plays a significant role. As stabilization levels become more stringent,* CO_2 *concentrations decline and terrestrial carbon uptake declines, with implications for emissions mitigation in the energy sector.*

Despite the differences across the modeling teams' treatments of the terrestrial carbon cycle, the aggregate behavior of their carbon cycles is similar, although this similarity likely understates many of the deeper uncertainties of how terrestrial systems will respond to environmental change and how policy incentives can be designed to create incentives for abatement strategies related to land use and land use change.

In stabilization regimes, the cost of using fossil fuels and emitting CO_2 rises, providing an increasing motivation for the production and transformation of bio-energy, as shown in Figure 4.16. In all of the scenarios, production begins earlier and produces a larger share of global energy as the stabilization limit becomes more stringent. In the presence of less-stringent stabilization limits, production of bio-crops is lower in the second half of the century in the MERGE and MiniCAM scenarios than in IGSM. Differences between the models with respect to biomass deployment are not simply due to different treatments of agriculture and land use but also result from the full suite of competing technologies and behavior assumptions.

Although total land-areas allocated to bioenergy crops are not reported in these scenarios, the extent of land area engaged in the production of energy becomes substantial. This is possible only if appropriate land is available, which hinges on future productivity increases for other crops and the potential of bioenergy crops to be grown on lands that are less suited for food, pasture, and forests. In both MiniCAM and IGSM, the two models with agriculture and land use submodels, demands on land for biofuels cause land prices to increase substantially as compared with the reference because of competition with other agricultural demands.

Figure 4.16. Global and U.S. Commercial Biomass Production across Scenarios

Stabilization scenarios limit the rise in CO_2 concentrations and reduce the CO_2 fertilization effect below that in the reference scenario, which in turn leads to smaller CO_2 uptake by the terrestrial biosphere. The effect is larger and begins earlier the more stringent the stabilization level. For example, Figure 4.17 shows that in the IGSM Level 4 scenario, the effect becomes substantial after 2070 and amounts to about 0.8 GtC/y in

2100. The IGSM Level 1 scenario begins to depart markedly from the reference before 2050, and the departure from reference grows to approximately 2.0 GtC/y by 2100. The effect of the diminished CO_2 fertilization effect is to require emissions mitigation in the energy-economy system to be larger by the amount of the difference between the reference aggregate net terrestrial CO_2 uptake and the uptake in the stabilization scenario.

Figure 4.17. Net Terrestrial Carbon Flux to the Atmosphere across Scenarios

The MiniCAM model includes a second effect that results from the interaction between the energy system and land use. MiniCAM uses the terrestrial carbon-cycle model of MAGICC as one component to determine the aggregate net carbon flux to the atmosphere. MiniCAM also determines land-use change emissions (e.g., deforestation) from an interaction between the choice of land use and associated carbon stocks and flows. Thus, economic competition among alternative human activities, crops, pasture, managed forests, bioenergy crops, and unmanaged ecosystems determine land use, which in turn (along with its associated changes) determines land-use change emissions. Thus, terrestrial uptake in MiniCAM is reduced because of the lower CO_2 fertilization effects as in the IGSM, and there are interactions between the agriculture sector and the unmanaged terrestrial carbon stocks in both the reference and stabilization scenarios. MERGE maintains its neutral biosphere in the stabilization scenarios.

One implication of the MiniCAM approach is that stabilization scenarios lead to increased pressure to deforest in order to clear space for biomass crops. This effect is best exhibited in the Level 1 scenarios, in which the terrestrial biosphere becomes a net source of carbon rather than a sink from 2050 to past 2080. The effect subsides after 2080 because commercial biomass production ceases to expand beyond 2080, reducing any further pressure to deforest for biomass crops.

MiniCAM results reported in Figure 4.17 assume that both fossil fuel and terrestrial carbon are priced. Thus, there is an economic incentive to maintain and/or expand stocks of terrestrial carbon as well as an incentive to bring more land under cultivation to grow bioenergy crops. Carbon value exerts an important counter-pressure to deforestation and other land-use changes that generate increased emissions. To illustrate the importance of valuing terrestrial carbon, especially in more stringent stabilization scenarios, sensitivity cases were run using MiniCAM in which no price was applied to terrestrial carbon emissions. These sensitivity results showed increased levels of land-use change emissions when terrestrial carbon was not valued. The reason was that the value of carbon in the energy system created an incentive to expand bioenergy production without a counter incentive to maintain carbon in terrestrial stocks. But the resultant deforestation increased terrestrial CO_2 emissions, requiring even greater reductions in fossil fuel CO_2 emissions and even higher prices on fossil fuel carbon. This increased the demand for bioenergy and led to even more deforestation. Thus, without a value on terrestrial carbon, a vicious cycle can emerge in which accelerated deforestation (which occurs when terrestrial carbon is not valued) leads to a higher emissions mitigation requirement in the energy sector, which in turn leads to higher carbon prices, and then to an increased demand for biomass fuels and, thus, is a positive feedback to land-use change emissions. The MiniCAM results reported here, which involve a policy architecture that places a value on terrestrial carbon, avoids the vicious cycle described above. Most proposed policy architectures have not envisioned such complete incentives for land use and land use change (Reilly and Asadoorian, 2006). This sensitivity study illustrates the potential importance of this aspect of effective policy design related to land use.

Despite the significant differences in the treatment of terrestrial systems in the three models, it is interesting to recall from Figure 3.20 that the overall behavior of the three carbon-cycle models is similar.

4.6. Economic Consequences of Stabilization

> *The price paths for CO_2 and the other GHGs that are needed to achieve the stabilization targets show similar patterns across the three models. However there are substantial differences in the estimate of the magnitude of the effort needed. Many factors contribute to the differences, but the largest factors are differences among reference scenarios (which determine the size of the needed reductions) and variation in assumptions about technology developments that may be achieved by the latter half of the century. For the most stringent Level 1, for example, carbon prices in 2050 range from $450 to $850 per ton, and in 2100 range from $600 to several thousand dollars, with the IGSM results producing the higher-end costs in all scenarios.*
>
> *The penalties on CO_2 emissions have an influence on the producer prices of fossil fuels. For oil and coal the main effect is a fall in the producer price, with the oil price most affected in the EPPA stabilization scenarios. Effects on natural gas prices are influenced as well, particularly in the EPPA scenarios, where with less stringent targets gas prices increase due to substitution toward gas. Electricity prices generally increase because they reflect the carbon allowance price but the increase is moderated because of the possibility of substituting non-carbon, and lower carbon emitting fuels, and the fact that fuel cost (inclusive of carbon price) is only one component of cost. These effects are, of course, on the producer price; the consumer user cost for all fuels (fuel price plus the carbon price for emitted carbon, plus any added cost of capturing and storing carbon) are higher under the stabilization scenarios.*
>
> *The macroeconomic costs of stabilization, measured as change in Global World Product, mirror the results for carbon prices, rising over time and with the stringency of the constraint. Substantial differences appear among the models with the ISGM producing considerably higher costs than the other two. For example, the estimated reduction in Gross World Product for stabilization at Level 1 at mid-century is about 2% for MiniCAM and MERGE to approximately 5% for EPPA. In 2100 on the other hand the range is from 16% for EPPA to between 1% and 2% for the other two models. This difference stems from differences in Reference Scenario emissions and differenet assumptions about technology development, particularly in the second half*

of the century. The range is an indication of the limits to knowledge of technology advance a half-century and more into the future.

4.6.1. Variation in Carbon Prices across Models

All three modeling teams show that Level 1 requires much higher carbon prices than the other three stabilization levels, as can be seen in Figure 4.18. All implemented prices or constraints that provided economic incentives to abate emissions, and the instruments used can be interpreted as the carbon value that would be consistent with either a universal cap-and-trade system or a harmonized carbon tax.

Figure 4.18. Carbon Prices across Stabilization Scenarios

The similarity of the general pattern of the price paths, rising over time, reflects the similarity of an economic approach employed by the three modeling teams, discussed in Section 4.2. The carbon cycle requires all stabilization paths eventually to reach an emissions peak and thereafter to reduce emissions to ever lower levels – a pattern that tends to generate a rising carbon price over time. Stabilization Levels 2, 3, and 4 would eventually require emissions levels in the post- 2100 period to fall to levels as low or lower than Level 1 stabilization scenario emissions in 2100. Thus, stabilization of concentrations at these higher levels delays the ultimate emissions limitation task in time.

The IGSM shows the highest marginal costs in all four stabilization scenarios. Yet the marginal abatement curves of the IGSM, MERGE, and MiniCAM models are very similar for the 2050 period when plotted in terms of percentage reduction from reference, seen in Figure 4.19. The model behaviors diverge in the post-2050 period, reflecting differences in long-term technology expectations, and this variation has repercussions for earlier periods. The IGSM results anticipate less significant technological breakthroughs so overall price incentives for abatement must be higher late in the century to achieve particular percentage reductions. With relatively low cost abatement options appearing after 2050, the MiniCAM carbon prices are lower for the same percentage reductions in 2100, as shown in the figure. The MERGE results are based on technology assumptions similar to MiniCAM and also show a marginal abatement curve lower than that of the IGSM.

Figure 4.19. Relationship between Carbon Price and Percentage Abatement in 2050 and 2100

The reference scenario also plays an important role, with the IGSM producing higher CO_2 emissions in the middle of the century than the other models, contributing to cumulative CO_2 emissions that must be abated at some point to achieve stabilization targets. The results also depend on other scenario components, such as interactions with land-use emissions and non-CO_2 GHGs. Recall that the MiniCAM model has higher CO_2 emissions and higher CO_2 concentrations in the stabilization scenarios than the other models as a direct consequence of its estimate for more substantial opportunities for emissions mitigation opportunities in the non-CO_2 GHGs, in particular for CH_4, thus leaving room under the forcing caps for a large contribution from CO_2.

With a somewhat larger mitigation burden in the middle of the century, the IGSM scenarios require larger percentage cuts in CO_2 emissions in 2050, thus moving IGSM further up the mitigation supply schedule than the other two models. By 2100, the marginal abatement curves show the IGSM abating a somewhat lower percentage but generating much higher carbon prices. Thus, by this point the different technological assumptions of the models dominate.

Prior to 2050, absolute differences in carbon prices across the scenarios are smaller than in 2100 (see Table 4.6**)**, while relative differences are far larger. Of note, the carbon price rises and then falls in the MERGE Level 1 scenario. This result derives, among other things, from the forward-looking structure of MERGE along with limits on the pace at which energy-sector capital can be put retired and replaced. A substantial transition takes place in the middle of the century that tends to push against these limits; the transition effects are less substantial later in the century.

Table 4.6. Carbon Prices in 2020, 2030, 2050, and 2100, Stabilization Scenarios

4.6.2. Stabilization and Non-CO_2 Greenhouse Gases

Each of the three models employs a different approach to the non-CO_2 GHGs. After CO_2, CH_4 is the next largest component of reference scenario radiative forcing. The three models project different reference scenario emissions (Figure 3.18). The IGSM reference scenario starts in the year 2000 at about 350 MtC/y and rises to more than 700 MtC/y (Figure 4.7), while the MERGE and MiniCAM models begin in the year 2000 with 300 MtC/y in the year 2000. These are anthropogenic methane emissions and the differences reflect existing uncertainties in how much of total methane emissions are from anthropogenic and natural sources. MERGE CH_4 emissions grow to almost 600 MtC/y in the reference scenario. The MiniCAM reference scenario is characterized by a peak in CH_4 emission at less than 400 MtC/y, followed by a decline to about 300 MtC/y.

Each of the groups took a different approach to setting a stabilization constraint on CH_4. The MiniCAM scenarios employ GWP coefficients, so the price of CH_4 is simply the price of CO_2 multiplied by the GWP – a constant as seen in Figure 4.20.

Figure 4.20. Relative Prices of CH_4 and N_2O to Carbon across Stabilization Scenarios

In contrast, the MERGE model determines the relative price of CH_4 to carbon in the inter-temporal optimization. The ratio of CH_4 to carbon prices begins very low although it is higher the more stringent the stabilization goal. The relative price then rises at a constant exponential rate of 9% per year in the Level 2, 3, and 4 stabilization scenarios. The Level 1 stabilization regime begins from a higher initial price of CH_4 and grows at

8% per year until is approaches a ratio of between 9 and 10 to 1, where it remains relatively constant. These results are the product of an inter-temporal optimization for which a constraint in the terminal value of radiative forcing is the only goal. Manne and Richels (2001) have shown that different patterns are possible if other formulations of the policy goal, such as limiting the rate of change of radiative forcing, are taken into account.

IGSM employs a third approach. Methane emissions are limited to a maximum value in each stabilization scenario: Level 4 at 425 MtC/y; Level 3 at 385 MtC/y; Level 2 at 350 MtC/y; and Level 1 at 305 MtC/y. As a consequence, the ratio of the price of CH_4 to carbon initially grows from one-tenth to a maximum of between 3 and 14 between the years 2050 and 2080 and then declines thereafter. As previously discussed, this reflects an implicit assumption that a long run requirement of stabilization means that eventually each substance must be (approximately) independently stabilized, and absent an explicit evaluation of damages of climate change, any relative time path of relative GHG prices can not be determined.

As with CH_4, reference emissions of N_2O vary across the three modeling groups (see Figure 3.17). The IGSM reference trajectory roughly doubles from approximately 11 MtC/y to approximately 25 MtC/y. In contrast, the MERGE and MiniCAM reference scenarios are roughly constant over time.

The MERGE model also sets the price of N_2O as part of the inter-temporal optimization process, as shown in Figure 4.20. Note that the relative price trajectory has a value that begins at roughly the level of the GWP-based relative price used in the MiniCAM scenarios and then rises, roughly linearly with time. The relative price approximately doubles in the Level 4 stabilization scenario, but is almost constant in the Level 1 stabilization scenario. Thus, in the Level 1 scenario the relative price path of the MERGE scenario and the MiniCAM scenarios are virtually the same.

In contrast, IGSM stabilization sets a path to a pre-determined N_2O concentration for each stabilization level, and the complexity of the price paths in Figure 4.20 shows the difficulty of stabilizing the atmospheric level of this gas. Natural emissions of N_2O are calculated, which vary with the climate consequences of stabilization. The main anthropogenic source, agriculture, has a complicated relationship with the rest of the economy through the competition for land use.

The approaches employed here do not necessarily lead to the stabilization of the concentrations of these gases before the end of the twenty-first century, as concentrations are still rising slowly in some cases but below the target (see Figure 4.3 and Figure 4.21). How the longer term stabilization target was approached was independently developed by each modeling team.

Figure 4.21. N_2O Concentrations across Scenarios

4.6.3. Stabilization and Energy Markets

The carbon price drives a wedge between the producer price of fuels and the cost to the user. Table 4.7 provides an approximation of that of the relationship. A given carbon price has the largest impact on user cost of coal in percentage terms because the fuel price per unit of energy is low and carbon emissions are relatively high per unit of energy. In comparison, natural gas prices were at historic highs in recent years and CO_2 emissions per unit of energy are low and so especially as a percentage of the fuel price a given carbon price has a relatively smaller effect.

Table 4.7. Relationship Between a $100/ton Carbon Tax and Energy Prices

Stabilization scenarios tend to result in a lower world price of oil (Figure 4.22). Level 4 stabilization scenarios have a relatively modest effect on the oil price, particularly prior to 2040 but this effect is stronger the more stringent the level of stabilization. The three models give different degrees of oil price reduction, ranging from the IGSM model which shows the most pronounced effects, to the MERGE model which shows a substantial effect only in the level 1 scenario. The effect on world oil prices in turn depends on many factors, including how the supply of oil is characterized, the carbon price, and the availability of substitute technologies for providing transportation liquids, such as biofuels or hydrogen.

Figure 4.22. World Oil Price, Reference and Stabilization Scenarios

Figure 4.23. United States Mine-mouth Coal Price, Reference and Stabilization Scenarios

Figure 4.24. United States Natural Gas Producers' Price, Reference and Stabilization Scenarios

Figure 4.25. United States Electricity Price, Reference and Stabilization Scenarios

Coal prices are similarly depressed in stabilization scenarios (see Figure 4.23). The effect is mitigated by two features: the assumed availability of CCS technology, which allows the continued large-scale use of coal in power generation in the presence of a positive price of carbon, and a coal supply schedule that is highly elastic. That is, demand for coal can exhibit large increases or decreases without much change in price. The high elasticity of supply in the MERGE model results leave coal prices largely unchanged across the scenarios, while MiniCAM and IGSM show lower supply price elasticities and hence greater price responses.

The impact on the natural gas producer price is more complex (see Figure 4.24). Natural gas has roughly one-half the carbon-to-energy ratio of coal. Thus, emissions can be reduced without loss of available energy simply by substituting natural gas for coal or oil. As a consequence, two effects on the natural gas producer price work in opposite directions. First, as the price of carbon rises, natural gas tends to be substituted for other fuels, increasing its demand. But natural gas substitutes, such as electricity, bioenergy, or energy-efficiency technologies, will tend to displace it from markets, as happens for the more carbon-intensive fuels. Thus, depending on the strength of these two effects, the producer price of gas can either rise or fall.

The natural gas price is most affected in the IGSM stabilization scenarios, reflecting the greater substitution of natural gas for coal in IGSM stabilization Levels 2, 3, and 4. At Level 1 stabilization, natural gas use is reduced over the entire period. On balance, the natural gas price is less affected by stabilization in the MERGE and MiniCAM models when the substitution and conservation effects are roughly offsetting.

While the price the sellers receive for oil and coal tends to be either stable or depressed, that is not the full cost of using the fuel. Buyers pay the market price, plus the value of the carbon emissions associated with the fuel, which is the price of carbon times the fuel’s carbon-to-energy ratio. If they employ CCS, the carbon emissions are lower but they face the added cost of CCS. Any additional carbon cost will be reflected in the fuel buyer’s fuel price if the carbon taxes, or required permits in a cap-and-trade system, are placed upstream with fuel producers. On the other hand, the actual fuel price impact they see may be similar to the producer price impact if carbon is regulated downstream where the fuel is used. In this case, fuel users would be able to buy fuel relatively inexpensively but would pay a separate large price for necessary carbon charges associated with emissions.

The effect on the price of electricity is another unambiguous result (see Figure 4.25). Because power generators are fossil fuel consumers, the price of electricity contains the implicit price of carbon in the fuels used for generation. All of the scenarios exhibit upward pressure on electricity prices, and the more stringent the stabilization level, the greater the upward pressure. The pressure is limited by the fact that there are many options available to electricity producers to lower emissions. These options include, for example, the substitution of natural gas for coal, the use of CCS, the expanded use of nuclear power, the use of bioenergy, and the expanded use of wind, hydro, and other renewable energy sources.

4.6.4. Total Cost of Stabilization

Estimating the macroeconomic cost of stabilization is not a simple task either conceptually or computationally. From an economic perspective, cost is the value of the loss in welfare associated with undertaking the prescribed policy measures – or equivalently, the value of activities that society will not be able to undertake as a consequence of pursuing stabilization? While the concept is easy enough to articulate, defining an unambiguous measure is problematic. We cannot directly observe consumers’ preference functions, only the consumption decisions they face for a given set of prices. One aspect of the difficulty this limit presents is demonstrated by Arrow’s Impossibility Theorem (Arrow 1950) which holds that a social welfare function only exists if preferences among individuals are identical. Since we do not directly observe preferences it is not clear that a well-defined social welfare function exists, and in its absence any measure of "cost" is a more or less satisfactory compromise.

Stabilization is further complicated by the need to aggregate the welfare of individuals who have not yet been born and who may or may not share present preferences. Even if these problems were not difficult enough, economies can hardly be thought to currently be at a maximum of potential welfare. Pre-existing market distortions impose costs on the economy, and climate measures may interact with them so as to reduce or exacerbate their effects. Any measure of global cost also runs into the further problem of international purchasing power comparisons discussed in Chapter 3. Finally, climate change is only one of many public goods, and measures to address other public goods (like urban air quality) can either increase or decrease cost. In order to create a metric to report that is consistent and comparable across the three modeling platforms, all of these issues would have to be addressed in some way.

Beyond conceptual measurement issues, any measure including GDP, depends importantly on features of the scenario such as the assumed participation by countries of the world, the terms of the emissions limitation regime, assumed efficiencies of markets, and technology availability – the latter including energy technologies, non-CO_2 gas technologies, and related activities in non-energy sectors, e.g., crop productivity that strongly influences the availability and cost of producing commercial biomass energy. In almost every instance, scenarios of the type explored here employ more or less idealized representations of economic structure, political decision and policy implementation, i.e., conditions that likely do not well reflect the real world, and these simplifications tend to lead to lower mitigation costs.

Finally, making an estimate of global economic cost that reflects welfare would require explicit consideration of how the burden of reduction was shared among countries, and the welfare consequences of income effects on poorer versus wealthier societies. Of course, if the world were to discover and deploy lower cost technology options than those assumed here, these costs could be lower. On the other hand, if society does not deliver the cost and performance for the technologies assumed in these scenarios, costs could be higher.

While all of the above considerations have not been extensively investigated in the literature, the implications of less than ideal implementation has been investigated and these analyses show that it could increase the costs substantially. Richels et al. (1996) showed that for a simple policy regime, eliminating international "where" and "when" flexibility, while assuming perfect "where" flexibility within countries, could potentially raise costs by an order of magnitude compared to a policy that employed "where" and "when" flexibility in all mitigation activities. Richels and Edmonds (1995) showed that stabilizing CO_2 emissions could be twice as expensive as stabilizing CO_2 concentrations and leave society with higher CO_2 concentrations. Babiker et al. (2000) similarly showed that limits on "where" flexibility within countries can substantially increase costs – although employing "where" flexibility also can increase costs in the context of tax distortions (Babiker et al., 2003a,b; Babiker et al., 2004; Paltsev, et al., 2005)

With that prologue, Figure 4.26 reports the change of Gross World Product during the twenty-first century in the year in which they occur measured at market exchange rates. This information is also displayed in Table 4.8. The use of market exchange rates is a convenient choice given the formulations of the models employed here, but as discussed above and in Chapter 3 the approach has limits (see the Box 3.1 in Chapter 3). While change in Gross World Product is not the intellectually most satisfying measure it serves as a common reference point.

Figure 4.26. Global GWP Impacts of Stabilization across Stabilization Levels

Table 4.8. Percentage Change in Gross World Product in Stabilization Scenarios

Overall, the models yield similar patterns in the cost results. For example, as the degree of stringency in the radiative forcing target tightens costs go up: costs of Level 1 GWP reductions always exceed Level 2 and so forth. Furthermore, GWP reductions rise non-linearly as the degree of stringency increases. However, for any degree of stringency significant variation is observed across the models. These differences in turn can be traced to differences in model assumptions. While it was not possible to undertake the intensive model inter-comparisons that would be necessary to fully unravel the sources of these differences, some insights are possible.

As shown in Figure 4.19, the price of carbon for a given percentage reduction in emissions are similar among the models through mid-century. Differences in cost through 2050 are thus mainly the result of differences in the required abatement. The reference projections contribute to this difference. The IGSM reference scenario reaches 18 GtC/y in 2050 compared with 12 GtC/y for MERGE and 14 GtC/y for MiniCAM (Figure 4.6). Thus, for a given stabilization emissions trajectory, the IGSM would tend to have the highest global GDP cost because it must abate more emissions and, as does so is forced up the abatement schedule to higher carbon prices.

In the post-2050 period, the relationship between emissions mitigation and the price of carbon, shown in Figure 4.19, is less similar across the three models. For the year 2100 the relationship between carbon prices and percentage emissions mitigation in MiniCAM and MERGE has shifted to the right relative to its 2050 positions while the IGSM mapping has shifted to the left. These differences reflect differences in assumptions about the availability of technological options for reducing carbon emissions.

An important aspect of how the carbon price paths were set in these scenarios—rising at or near the discount rate—means that abatement requirements and costs will be smoothed over the whole period. The lack of low-cost technological options in the IGSM toward the end of the century tends to shift abatement (and abatement cost) back to the first half of the century, relative to the result for MiniCAM and MERGE. Thus, carbon prices and global GDP costs are higher throughout the century for the IGSM model, and costs through 2050 are high because of the relatively higher reference through 2050 but also because abatement in the first of half of the century is favored because fewer opportunities exist to abatement in the second half of the century.

Much of the difference in technological opportunities in the second half of the century result from differences in end-use sectors, buildings, industry and transport, rather than in power generation. In power generation all three models have essentially decarbonized by the year 2100 (Figure 4.11), but not in the end-use sectors where fossil fuels remain important. One aspect of this, is that end use sectors in the MERGE and MiniCAM scenarios make greater use of electricity than in the IGSM stabilization scenarios. Thus, the relative ease that all three models display in removing carbon from power generation is especially helpful to the MERGE and MiniCAM stabilization scenarios as end-use applications substitute more easily to electricity to deliver energy services in these models. The variation in estimated cost serves to underscore the importance of the rate and character of technological change over long periods of time, and the fundamental uncertainty regarding technology developments more than half a century into the future.

4.7. References

Arrow, K. 1950. "A Difficulty in the Concept of Social Welfare," The Journal of Political Economy, Volume 58, Issue 4 (August), pages 328-346.

Babiker, M., Bautista, M.E., Jacoby, H.D., Reilly, J.M. 2000. Effects of Differentiating Climate Policy by Sector: A U.S. Example. MIT Joint Program on the Science and Policy of Global Change, Report No. 73, (May).

Babiker, M., G. Metcalf, and J. Reilly, 2003a. “Tax Distortions and Global Climate Policy”, Journal of Economic and Environmental Management, 46: 269-287, 2003.

Babiker, M., L. Viguier, J. Reilly, A.D. Ellerman & P. Criqui, 2003b. “The Welfare Costs of Hybrid Carbon Policies in the European Union”, Environmental Modeling and Assessment, 8: 187-197.

Babiker, M., J. Reilly, and L. Viguier. 2004. ‘Is Emissions Trading Always Beneficial,’ Energy Journal, 25(2): 33-56.

IPCC (Intergovernmental Panel on Climate Change). 2001. Climate Change 2001: The Scientific Basis. The Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. J. T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P. J. van der Linden and D. Xiaosu (Eds.). Cambridge University Press, Cambridge, UK. pp 944.

Hotelling, Harold. (1931). "The Economics of Exhaustible Resources." Journal of Political Economy, 39, 137-175.

Manne, A.S. and R. Richels. 2001. “An alternative approach to establishing tradeoffs among gases,” Nature, 419:675-676.

Paltsev, S., H, Jacoby, J. Reilly, L. Viguier and M. Babiker. 2005. “Modeling the Transport Sector: The Role of Existing Fuel Taxes, In: Energy and Environment [R. Loulou, J-P Waaub, and G. Zaccour, eds.], Springer, New York: 211-238

Peck, S.C. and Y.H. Wan. 1996. “Analytic Solutions of Simple Greenhouse Gas Emission Models,” Chapter 6 of *Economics of Atmospheric Pollution*, E.C. Van Ierland and K. Gorka (eds.), Springer Verlag.

Reilly, J. and M. Asadoorian, “Mitigation of Greenhouse Gas Emissions From Land Use: Creating Incentives Within Greenhouse Gas Emissions Trading Systems,” Climatic Change, (in press) 2006.

Richels, R. and J. Edmonds. 1995. "The Economics of Stabilizing Atmospheric CO_2 Concentrations," *Energy Policy*, 23(4/5):373-78 (6 pages).

Richels, R., J. Edmonds, H. Gruenspecht, and T. Wigley. 1996. “The Berlin Mandate: The Design of Cost-Effective Mitigation Strategies.” Climate Change: Integrating Science, Economics and Policy, CP-96-1:29-48. N. Nakicenovic, W.D. Nordhaus, R. Richels, and F.L. Toth (eds.), International Institute for Applied Systems Analysis, Laxenburg, Austria (20pp).

Sarofim, M.C., C.E. Forest, D.M. Reiner & J.M. Reilly. 2005. "Stabilization and Global Climate Policy", Global and Planetary Change, 47 (2005) 266-272. Also as MIT Joint Program on the Science and Policy of Global Change Reprint No. 2005-5, available at http://mit.edu/globalchange/www/.

Wigley, T.M.L., R. Richels & J. A. Edmonds. 1996. "Economic and Environmental Choices in the Stabilization of Atmospheric CO_2 Concentrations," Nature. 379(6562):240-243.

United Nations. 1992. Framework Convention on Climate Change. United Nations, New York.

Table 4.1. Long-Term Radiative Forcing Limits by Stabilization Level and Corresponding Approximate CO_2 Concentration Levels

Stabilization Level	Long-Term Radiative Forcing Limit (Wm^{-2} relative to pre-industrial)	Approximate 2100 CO_2 Limit (ppmv)
Level 4	6.7	750
Level 3	5.8	650
Level 2	4.7	550
Level 1	3.4	450

Table 4.2. Radiative Forcing in the Year 2100 across Scenarios

		Radiative Forcing in 2100 (Wm^{-2} relative to pre-industrial)		
Stabilization Level	Long-Term Radiative Forcing Limit (Wm^{-2} relative to pre-industrial)	IGSM	MERGE	MiniCAM
Ref	No Constraint	8.6	6.6	6.4
Level 4	6.7	6.1	6.2	6.1
Level 3	5.8	5.4	5.7	5.5
Level 2	4.7	4.4	4.7	4.5
Level 1	3.4	3.5	3.4	3.4

Table 4.3. CO_2 Concentrations in the Year 2100 across Scenarios (ppmv)

		CO_2 Concentration in 2100 (ppmv)		
Level	Approximate Long-term CO_2 Concentration Limit (ppmv)	IGSM	MERGE	MiniCAM
Ref	--	875	711	746
Level 4	750	677	670	716
Level 3	650	614	619	656
Level 2	550	526	535	562
Level 1	450	451	426	456

Table 4.4. Global Annual CO_2 Capture and Storage in 2030, 2050, and 2100 for Four Stabilization Levels

		Annual Global Carbon Capture and Storage (PgC/y)		
Stabilization Level	Year	IGSM	MERGE	MiniCAM
Level 4	2030	0.01	0.00	0.09
	2050	0.44	0.00	0.15
	2100	4.12	2.31	0.72
Level 3	2030	0.05	0.00	0.10
	2050	0.83	0.00	0.19
	2100	4.52	4.79	2.75
Level 2	2030	0.12	0.00	0.13
	2050	1.96	0.44	0.38
	2100	4.97	6.63	5.56
Level 1	2030	0.37	0.66	0.82
	2050	2.76	2.24	2.95
	2100	4.44	7.17	6.23

Table 4.5. Global Cumulative CO_2 Capture and Storage in 2050 and 2100 for Four Stabilization Levels

		Cumulative Global Carbon Capture and Storage (PgC)		
Stabilization Level	Year	IGSM	MERGE	MiniCAM
Level 4	2050	4	0	3
	2100	92	20	21
Level 3	2050	8	0	4
	2100	153	64	52
Level 2	2050	19	3	6
	2100	208	188	144
Level 1	2050	37	32	43
	2100	231	274	278

Table 4.6. Carbon Prices in 2020, 2030, 2050, and 2100, Stabilization Scenarios

	2020 ($/tonne C)			2030 ($/tonne C)		
Stabilization Level	IGSM	MERGE	MiniCAM	IGSM	MERGE	MiniCAM
Level 4	$18	$1	$1	$26	$2	$2
Level 3	$30	$2	$4	$44	$4	$7
Level 2	$75	$8	$15	$112	$13	$26
Level 1	$259	$110	$93	$384	$191	$170

	2050 ($/tonne C)			2100 ($/tonne C)		
Stabilization Level	IGSM	MERGE	MiniCAM	IGSM	MERGE	MiniCAM
Level 4	$58	$6	$5	$415	$67	$54
Level 3	$97	$11	$19	$686	$127	$221
Level 2	$245	$36	$69	$1,743	$466	$420
Level 1	$842	$574	$466	$6,053	$609	$635

Table 4.7. Relationship Between a $100/ton Carbon Tax and Energy Prices

Fuel	Base Cost ($2005)	**Added Cost ($)**	Added Cost (%)
Crude Oil ($/bbl)	$60.0	$12.2	20%
Regular Gasoline ($/gal)	$2.39	$0.26	11%
Heating Oil ($/gal)	$2.34	$0.29	12%
Wellhead Natural Gas ($/tcf)	$10.17	$1.49	15%
Residential Natural Gas ($/tcf)	$15.30	$1.50	10%
Utility Coal ($/short ton)	$32.6	$55.3	170%
Electricity (c/kWh)	9.6	1.76	18%

Source: Bradley et al. (1991), updated with US average prices for the 4th quarter of 2005 as reported by US DOE, EIA, Short-Term Energy and Winter Fuels Outlook October 10th, 2006 Release

Table 4.8. Percentage Change in Gross World Product in Stabilization Scenarios

Level 1

	2020	2040	2060	2080	2100
IGSM	2.1%	4.1%	6.7%	10.1%	16.1%
MERGE	0.7%	1.4%	1.9%	1.8%	1.5%
MiniCAM	0.2%	0.7%	1.3%	1.3%	1.2%

Level 2

	2020	2040	2060	2080	2100
IGSM	0.5%	1.2%	2.3%	3.9%	6.8%
MERGE	0.0%	0.1%	0.4%	0.6%	0.8%
MiniCAM	0.0%	0.1%	0.3%	0.5%	0.6%

Level 3

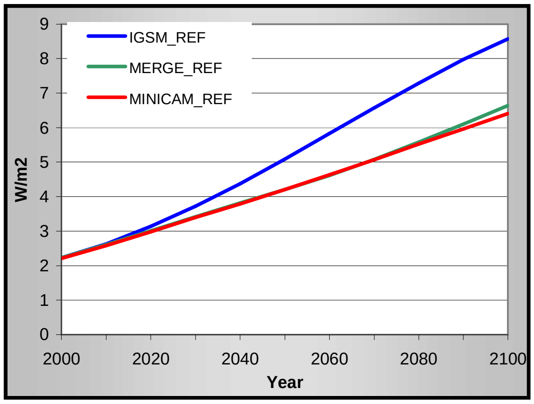
	2020	2040	2060	2080	2100
IGSM	0.2%	0.4%	0.9%	1.8%	3.1%
MERGE	0.0%	0.0%	0.1%	0.2%	0.3%
MiniCAM	0.0%	0.0%	0.0%	0.1%	0.3%

Level 4

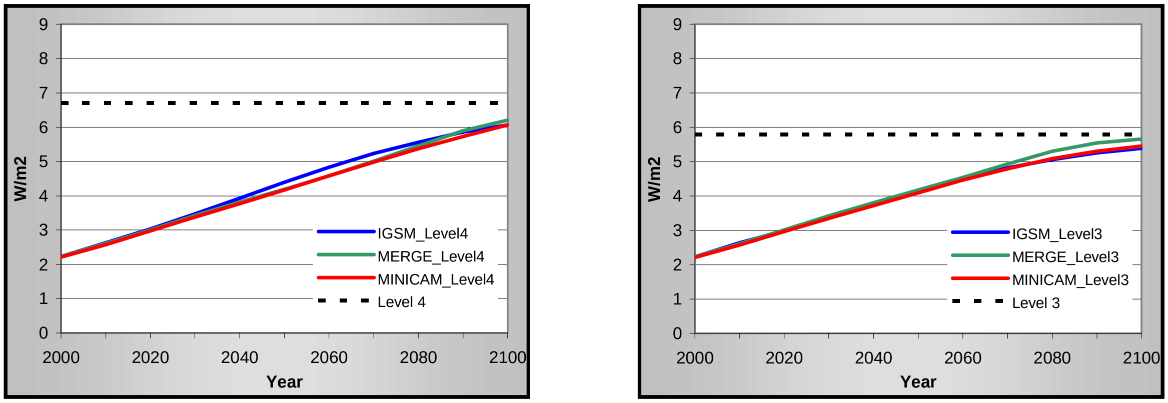
	2020	2040	2060	2080	2100
IGSM	0.1%	0.2%	0.4%	0.9%	1.7%
MERGE	0.0%	0.0%	0.0%	0.1%	0.2%
MiniCAM	0.0%	0.0%	0.0%	0.0%	0.0%

Figure 4.1. Total Radiative Forcing by Year across Scenarios (W/m^2). Radiative forcing trajectories (W/m^2; increase from preindustrial) for the reference and four stabilization levels show differences among the models for the reference case but similar results in each of the stabilization scenarios. This result is a reflection of the design of the scenarios. Radiative forcing is stabilized or close to stabilized in the Level 1 and Level 2 scenarios. Radiative forcing remains below the Levels 3 and 4 targets in 2100, allowing for a gradual approach to the target levels in the following century.

Reference Scenarios



Level 4 Scenarios **Level 3 Scenarios**



Level 2 Scenarios **Level 1 Scenarios**

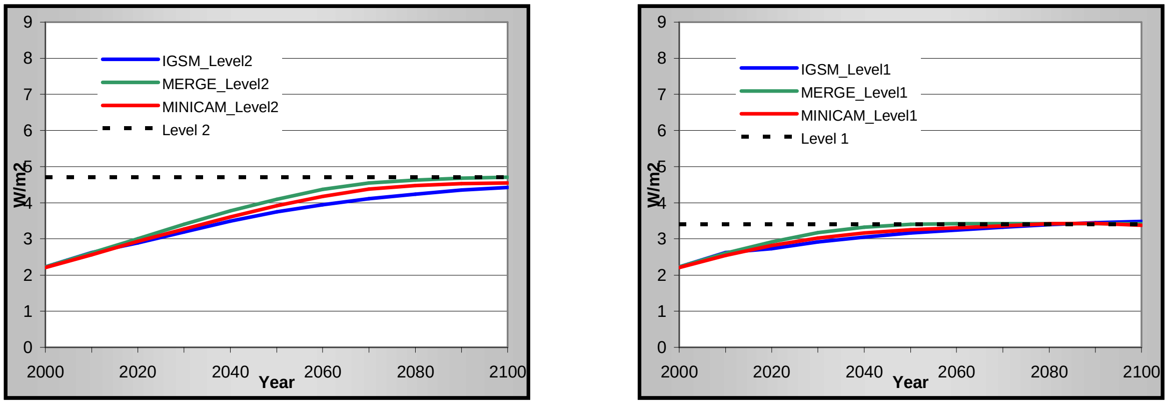
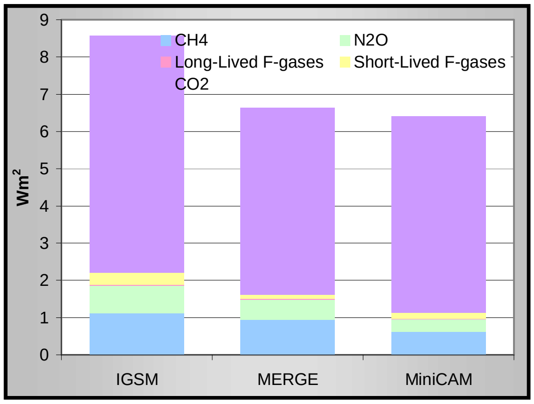
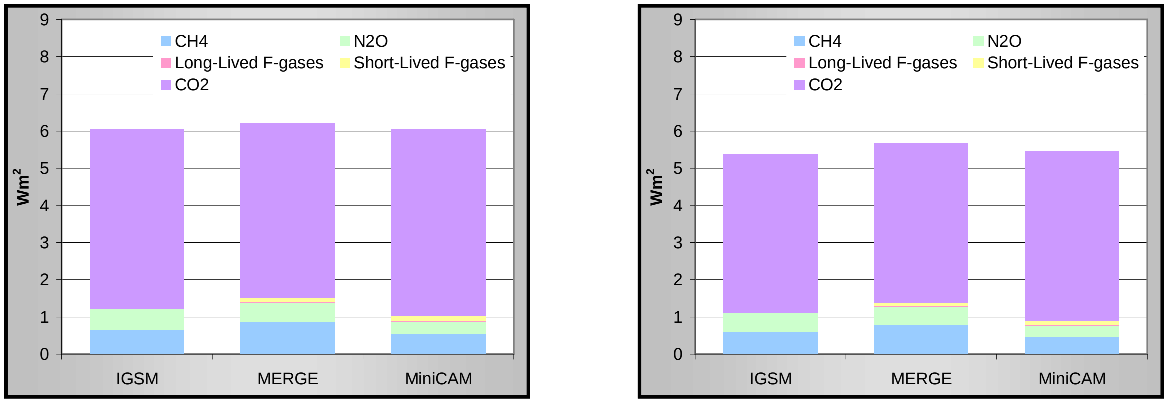


Figure 4.2. Total Radiative Forcing by Gas in 2100 across Scenarios (W/m^2 relative to preindustrial). CO_2 is the main contributor to radiative forcing by the end of the century. IGSM has the highest contribution from non-CO_2 GHGs in the reference, but MERGE has the highest contribution from non-CO_2 GHGs in the stabilization cases, implying greater non-CO_2 control efforts in the IGSM simulations. MiniCAM contributions are the lowest in all scenarios, reflecting assumptions control of these substances for non-climate reasons.

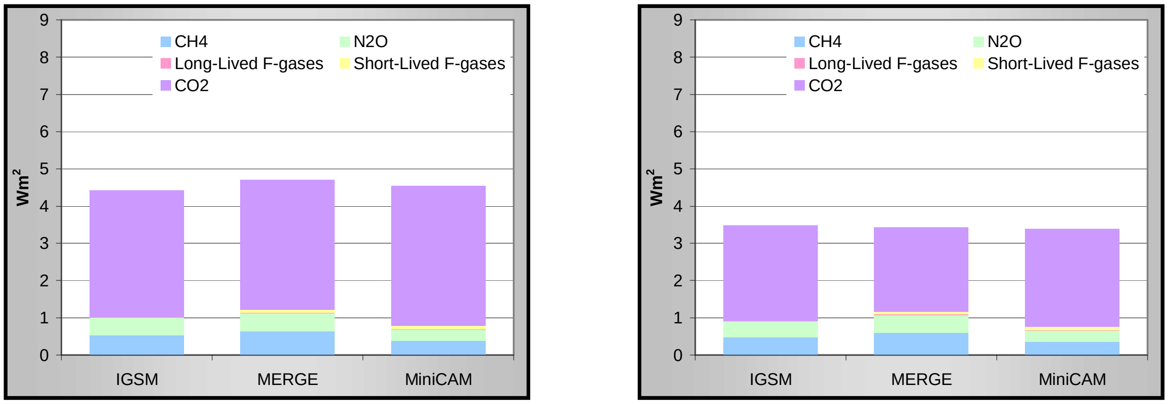


Reference Scenarios



Level 4 Scenarios

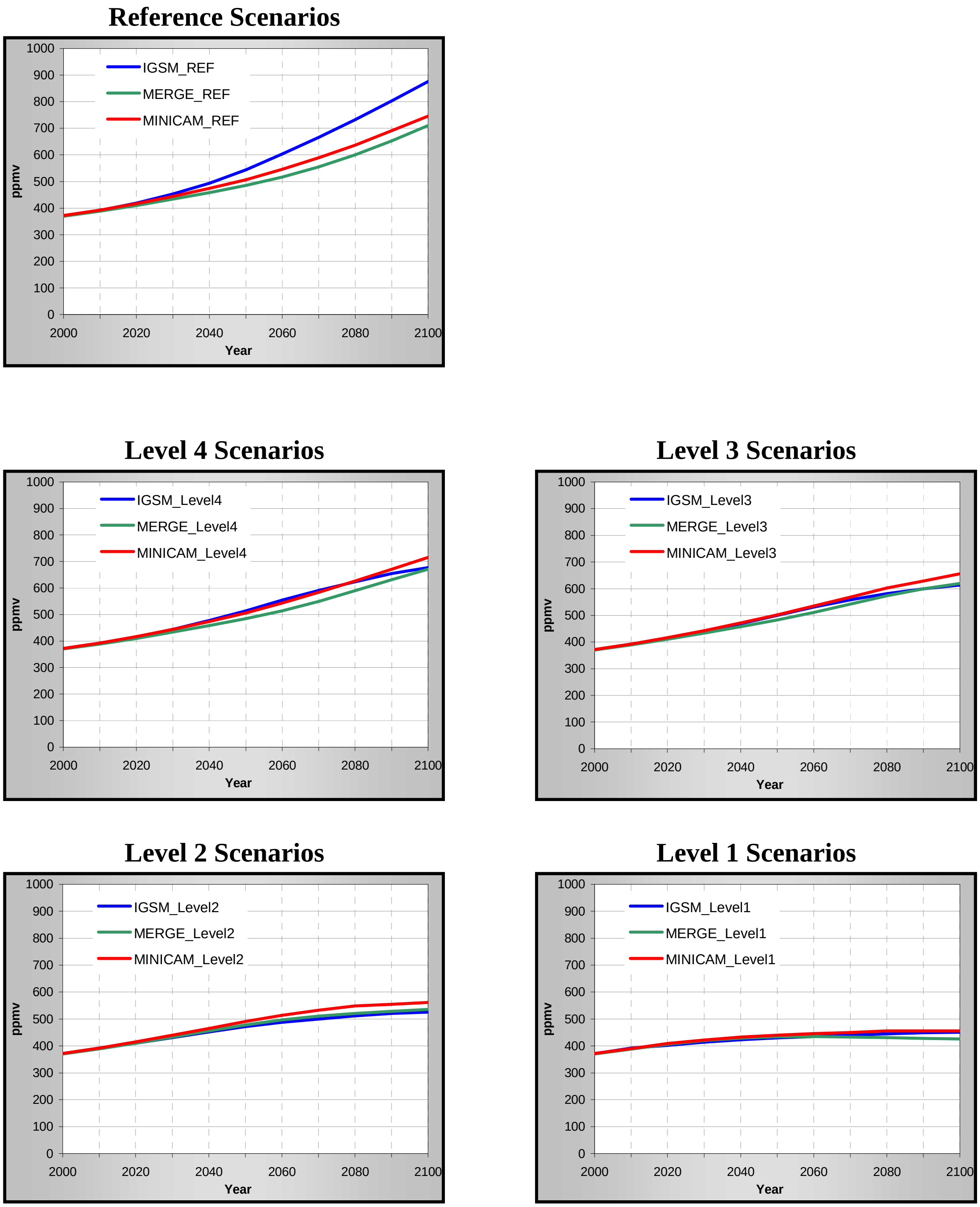
Level 3 Scenarios



Level 2 Scenarios

Level 1 Scenarios

Figure 4.3. CO_2 Concentrations across Scenarios (ppmv). In the reference scenarios atmospheric concentrations of CO_2 range from about 700 ppmv to 875 ppmv in 2100 across the models, with no sign of slowing. Radiative forcing targets were chosen so that CO_2 concentration levels would be approximately 450, 550, 650, and 750 ppmv at stabilization for Levels 1, 2, 3, and 4, respectively. None of the models reach these targets precisely. Differences among models occur because of the relative contribution of other GHGs to meeting the radiative forcing targets, and because for Levels 3 and 4 the models simulated a gradual approach to the stabilization level that will not be reached until the following century.


Reference Scenarios

Level 4 Scenarios

Level 3 Scenarios

Level 2 Scenarios

Level 1 Scenarios

Figure 4.4. CH_4 Concentrations across Scenarios (ppbv). There are larger differences among the models for CH_4 concentrations than for CO_2. These differences stem from different reference scenarios, abatement potentials, and methods of inter-gas comparisons that determined abatement levels. MiniCAM used 100-year GWPs. MERGE endogenously values abatement as it contributes to the stabilization target, leading to relatively little value for controlling CH_4 until the target was approached due to the gas's relatively short lifetime. IGSM stabilizes CH_4 concentrations independently, requiring constant emissions.

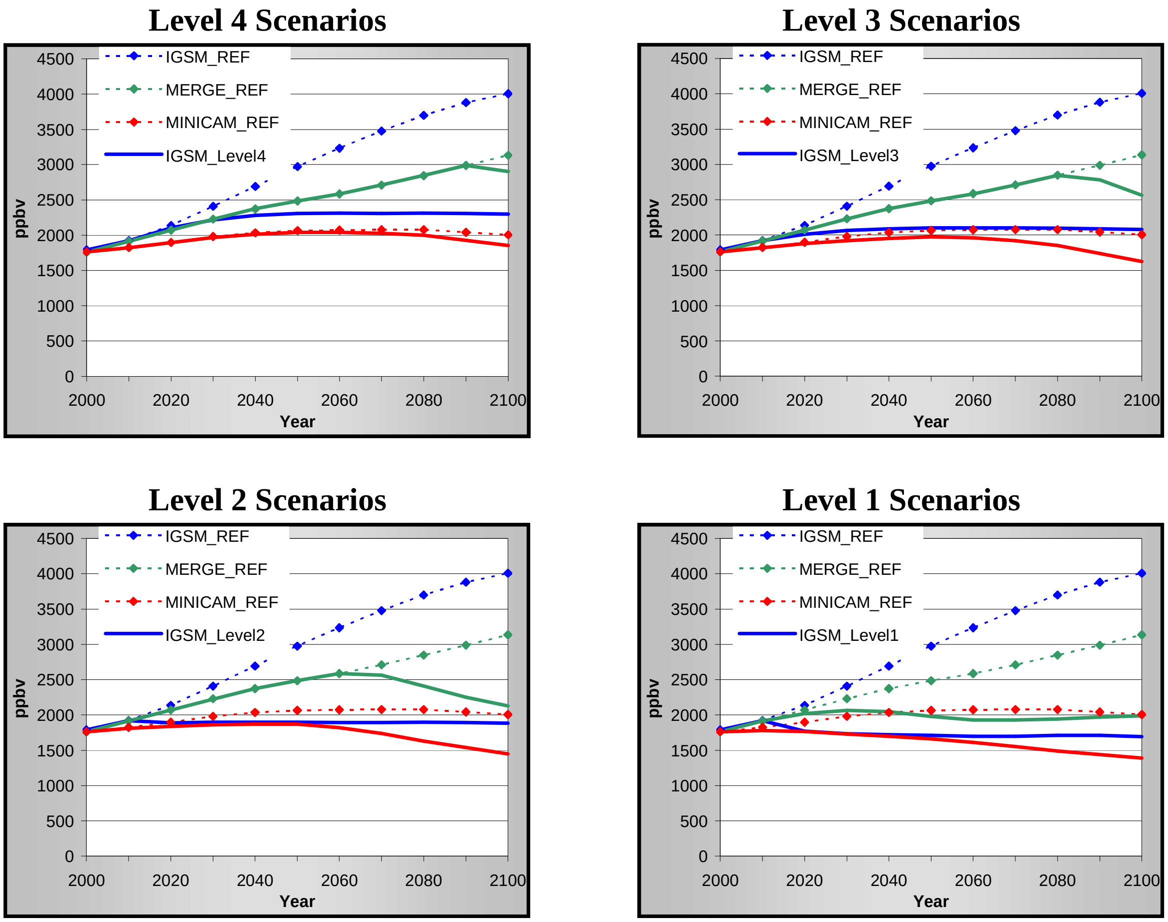
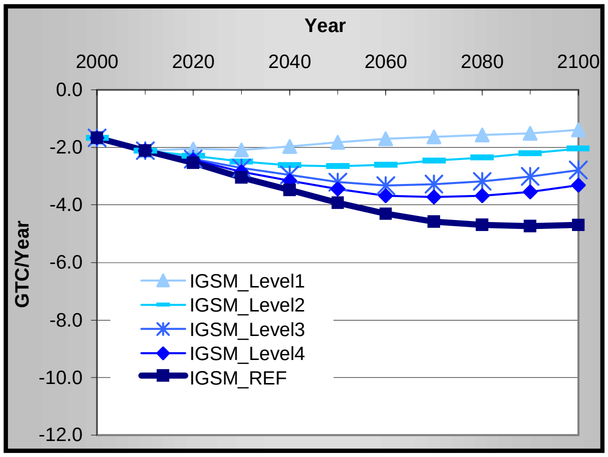


Figure 4.5. Ocean CO_2 Uptake across Scenarios (GtC/y). Oceans have taken up approximately one-half of anthropogenic emissions of CO_2 since pre-industrial times, and future ocean behavior is an important determinant of atmospheric concentrations. The three-dimensional ocean used for the IGSM simulations shows the least ocean carbon uptake and considerable slowing of carbon uptake even in the reference when carbon concentrations are continuing to rise. MERGE shows the largest uptake in the reference, and greatest reduction from reference in the stabilization scenarios. MiniCAM is intermediate at most stabilization levels. At the more stringent stabilization levels, the MERGE and MiniCAM results are similar.

IGSM Scenarios



MERGE Scenarios **MiniCAM Scenarios**

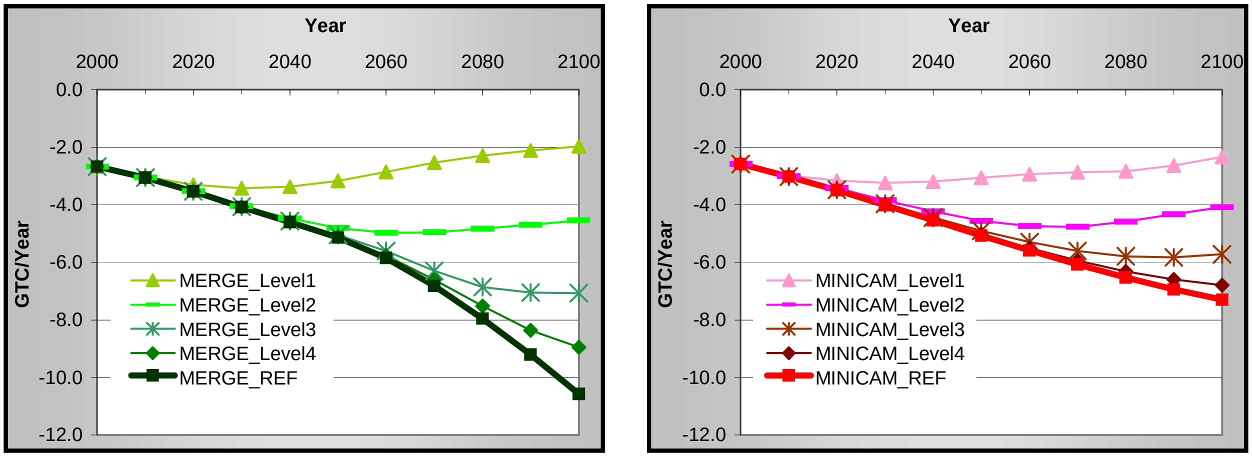
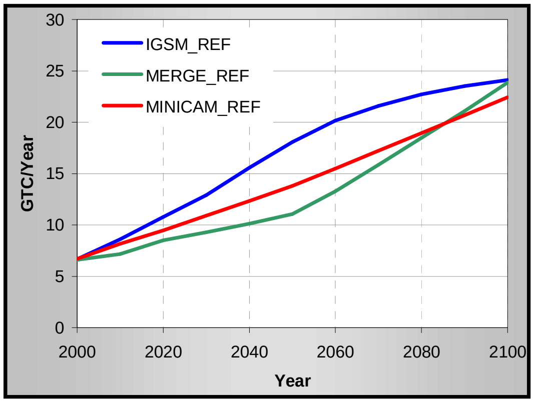
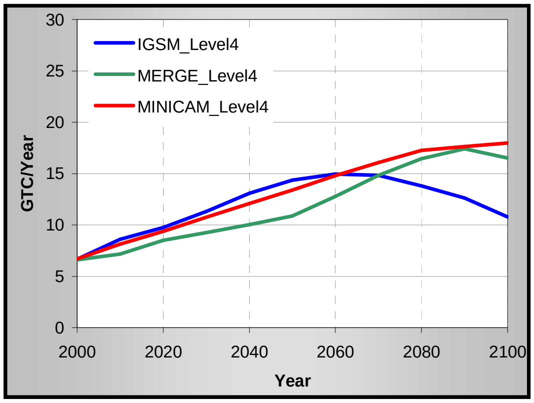


Figure 4.6. Fossil Fuel and Industrial CO_2 Emissions across Scenarios (GtC/y). Fossil fuel CO_2 emissions vary among the models in the reference, but all three simulate 2100 emissions in the range of 22.5 to 24 GtC. Level 1 stabilization would require large global emissions reductions as soon as the stabilization policy was put in place (as the scenarios were designed, after 2012). Across the models, emissions are below current levels by 2100 in the Level 1 and Level 2 scenarios. Emissions peak sometime around the mid-century to early in the next century in the Level 3 and Level 4 scenarios and then begin a decline that would continue beyond the simulation horizon.

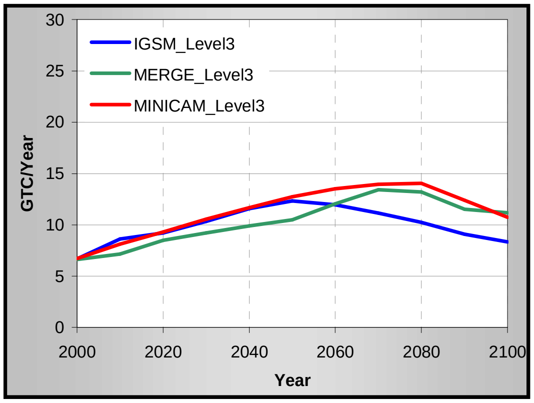
Reference Scenarios



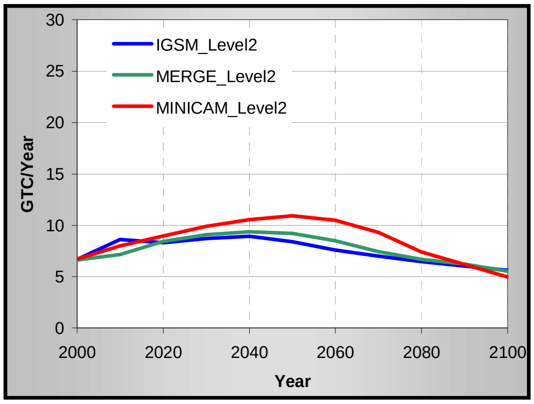
Level 4 Scenarios



Level 3 Scenarios



Level 2 Scenarios



Level 1 Scenarios

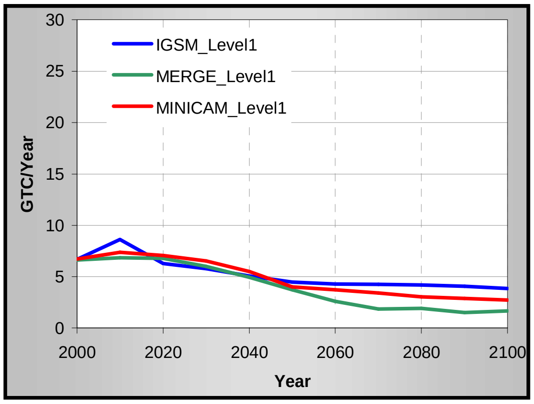


Figure 4.7. CH_4 Emissions across Scenarios (MT CH_4/y). Emissions of anthropogenic CH_4 vary widely among the models, reflective of uncertainty even in the current anthropogenic emissions. With current concentrations and destruction rates relatively well-known, the difference in current levels means that IGSM ascribes relatively more to anthropogenic sources and relatively less to natural sources than do MERGE and MiniCAM. Wide differences in scenarios for the future reflect differing modeling approaches, outlooks for activity levels that lead to abatement, and assessments of whether emissions will be abated in the absence of climate policy.

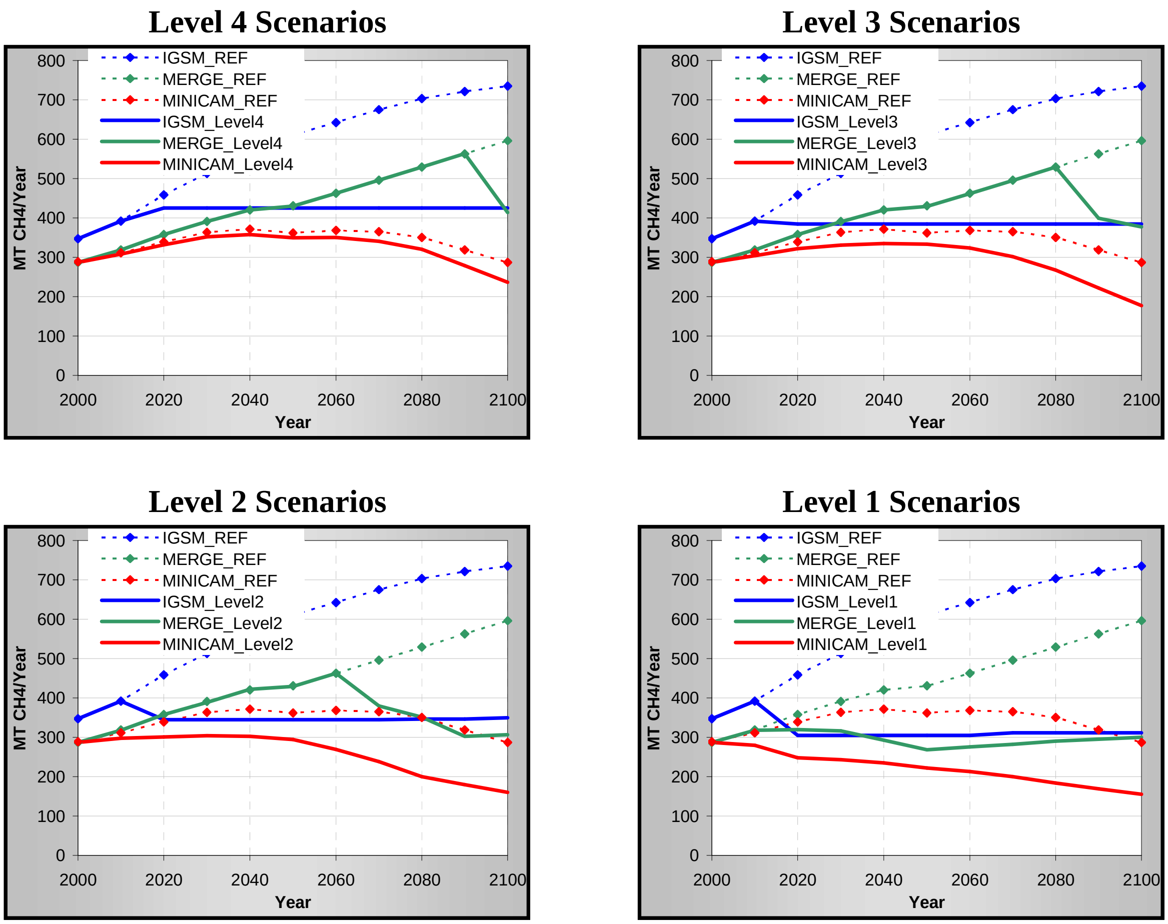
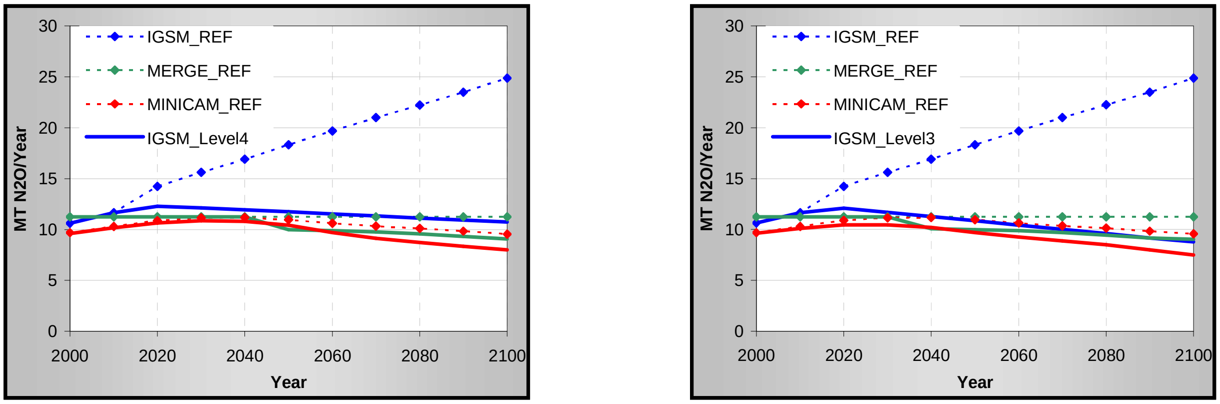


Figure 4.8. N_2O Emissions across Scenarios (MT N_2O/y). Anthropogenic emissions of N_2O in stabilization scenarios show similarity among the models despite a large difference in reference emissions scenarios.

Level 4 Scenarios **Level 3 Scenarios**



Level 2 Scenarios **Level 1 Scenarios**

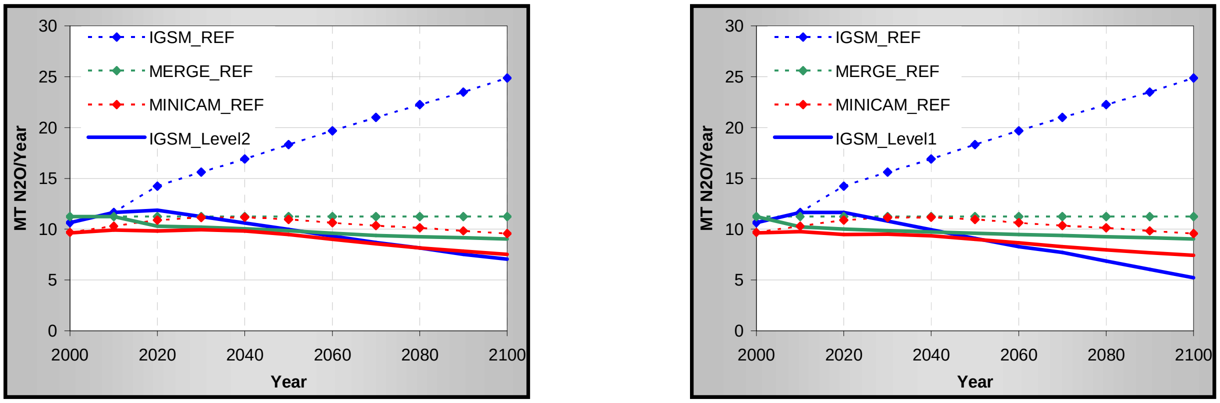


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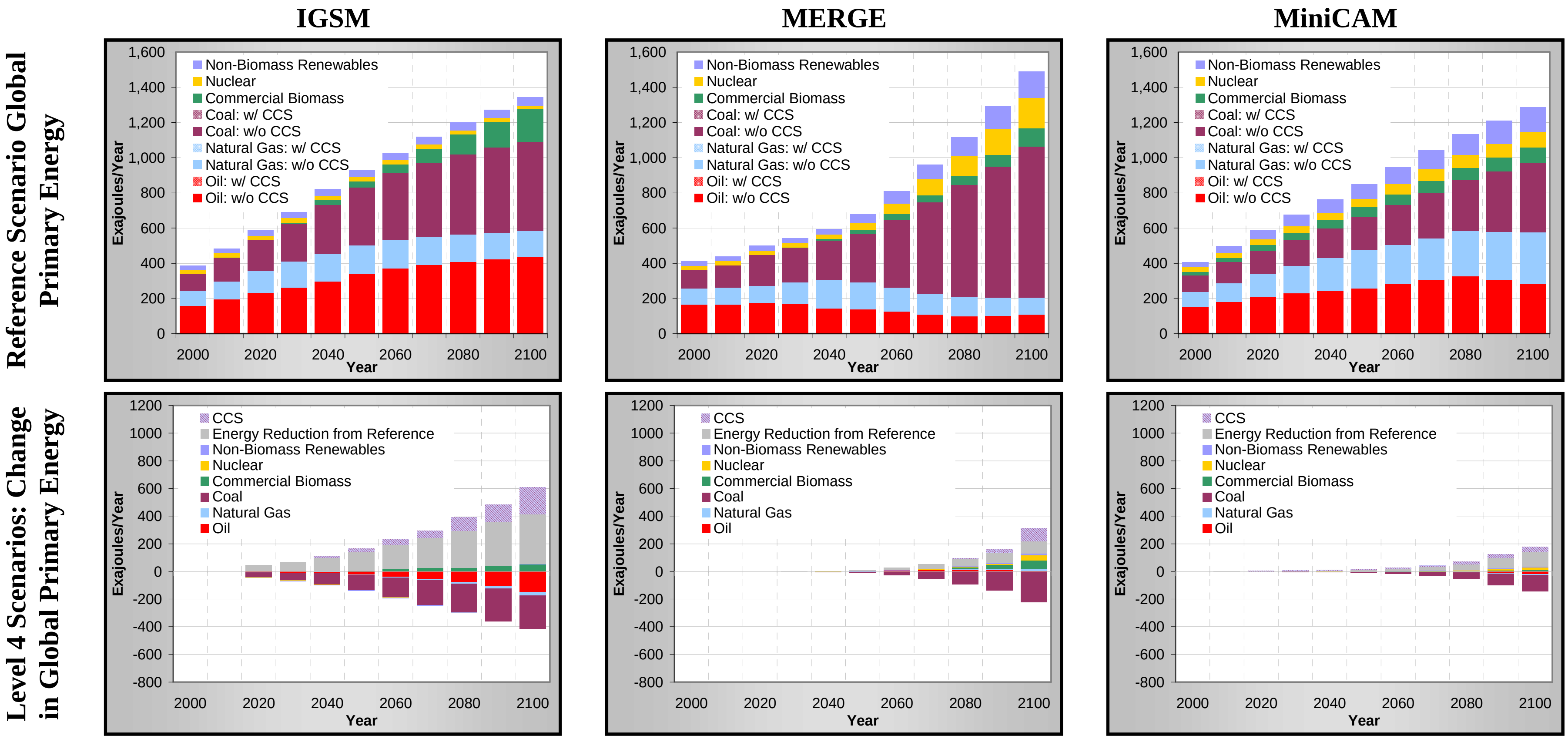
Figure 4.9. Change in Global Primary Energy by Fuel across Stabilization Scenarios, Relative to Reference Scenarios (EJ/y): Fuel-source changes from the reference to the stabilization scenarios show significant transformation of the energy system for all three models. The transformation can begin later under the Levels 3 and 4 targets, but would need to continue into the following century. The transformation includes reductions in energy consumption, increased use of carbon-free sources of energy (biomass, other renewables, nuclear), and addition of carbon capture and sequestration. The contribution of each varies among the models, reflecting different assessments of the economic viability, policy assumptions, and resource limits.



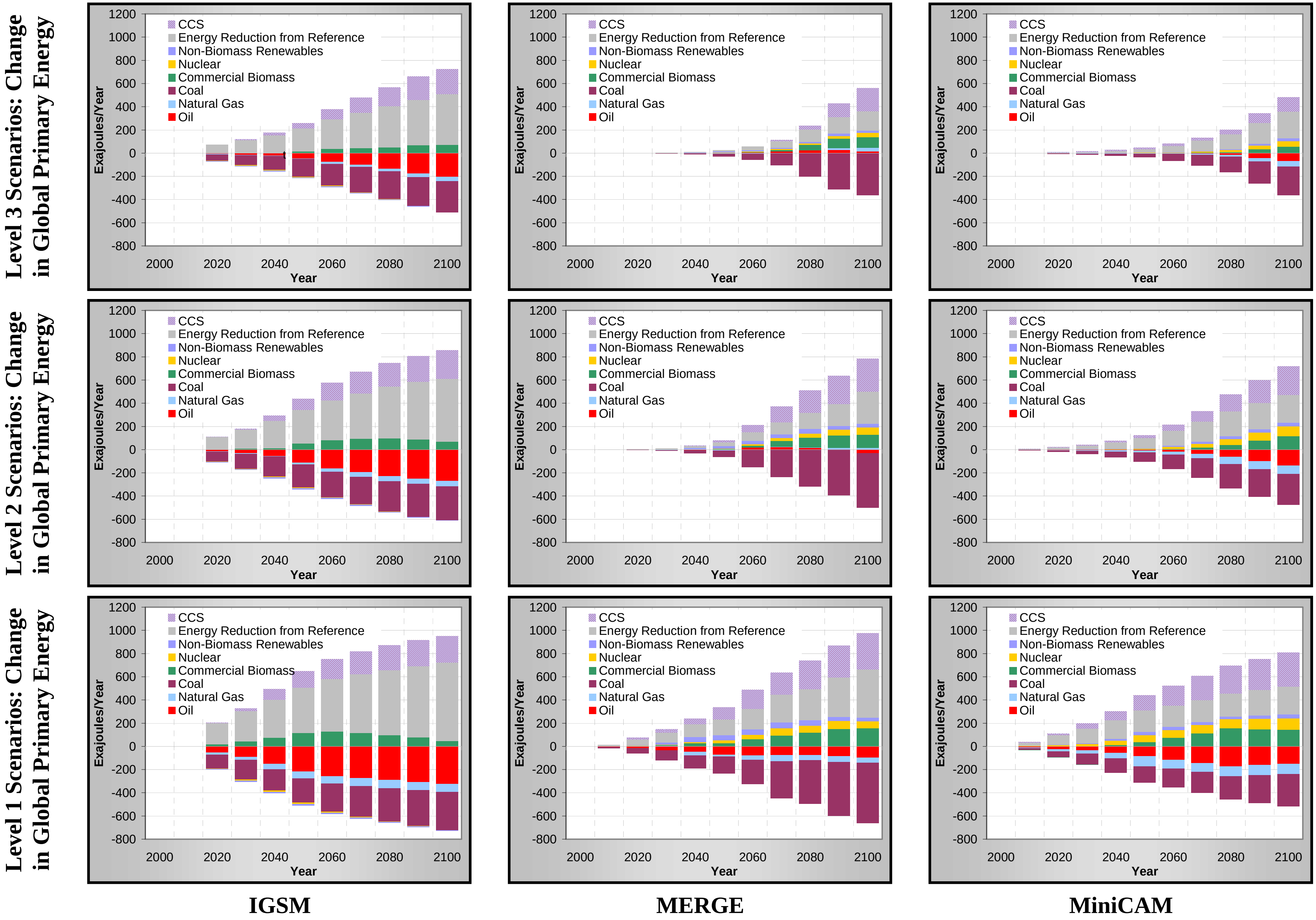
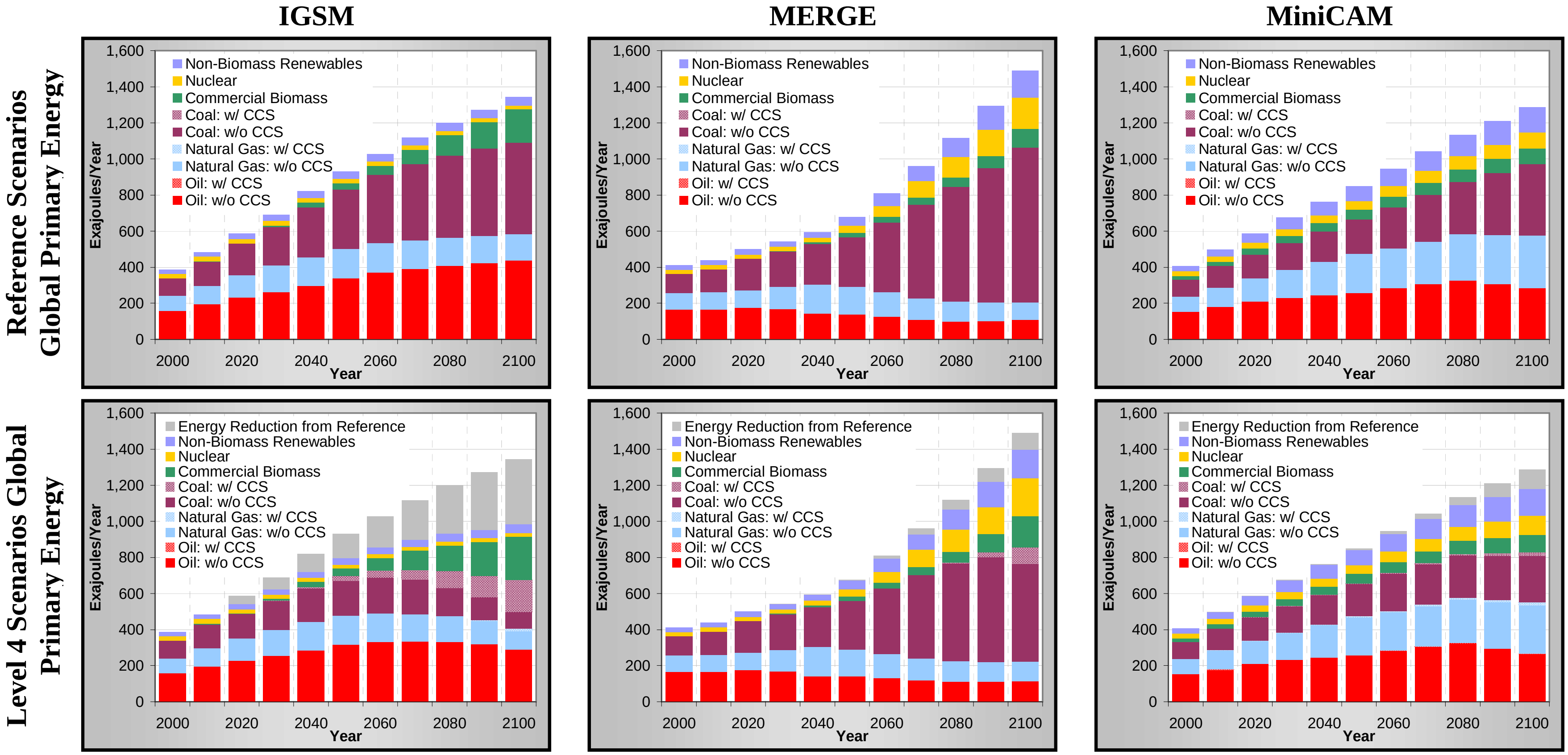

Level 3 Scenarios: Change in Global Primary Energy
Level 2 Scenarios: Change in Global Primary Energy
Level 1 Scenarios: Change in Global Primary Energy
CCS
Energy Reduction from Reference
Non-Biomass Renewables
Nuclear
Commercial Biomass
Coal
Natural Gas
Oil
Exajoules/Year
1200
1000
800
600
400
200
0
-200
-400
-600
-800
2000
2020
2040
2060
2080
2100
Year
IGSM
MERGE
MiniCAM

Figure 4.10. Global Primary Energy by Fuel across Scenarios (EJ/y). The transition to stabilization, reflected most fully in the Level 1 scenario, means nearly complete phase-out of fossil fuel use unless carbon capture and sequestration is employed. Under the most stringent stabilization constraint the simulations include a 7- to 14-fold increase in non-fossil energy sources from present levels. IGSM simulations indicate more of the carbon reduction is met through demand reductions than the other two models, with 2100 energy use cut by up to one-half relative to the reference scenario in 2100. MiniCAM, in contrast reduces total energy by less than 20 percent. Levels 2, 3, and 4 require progressively less transformation compared with the reference scenario in the coming century, delaying these changes until the following century (beyond the simulation horizon).



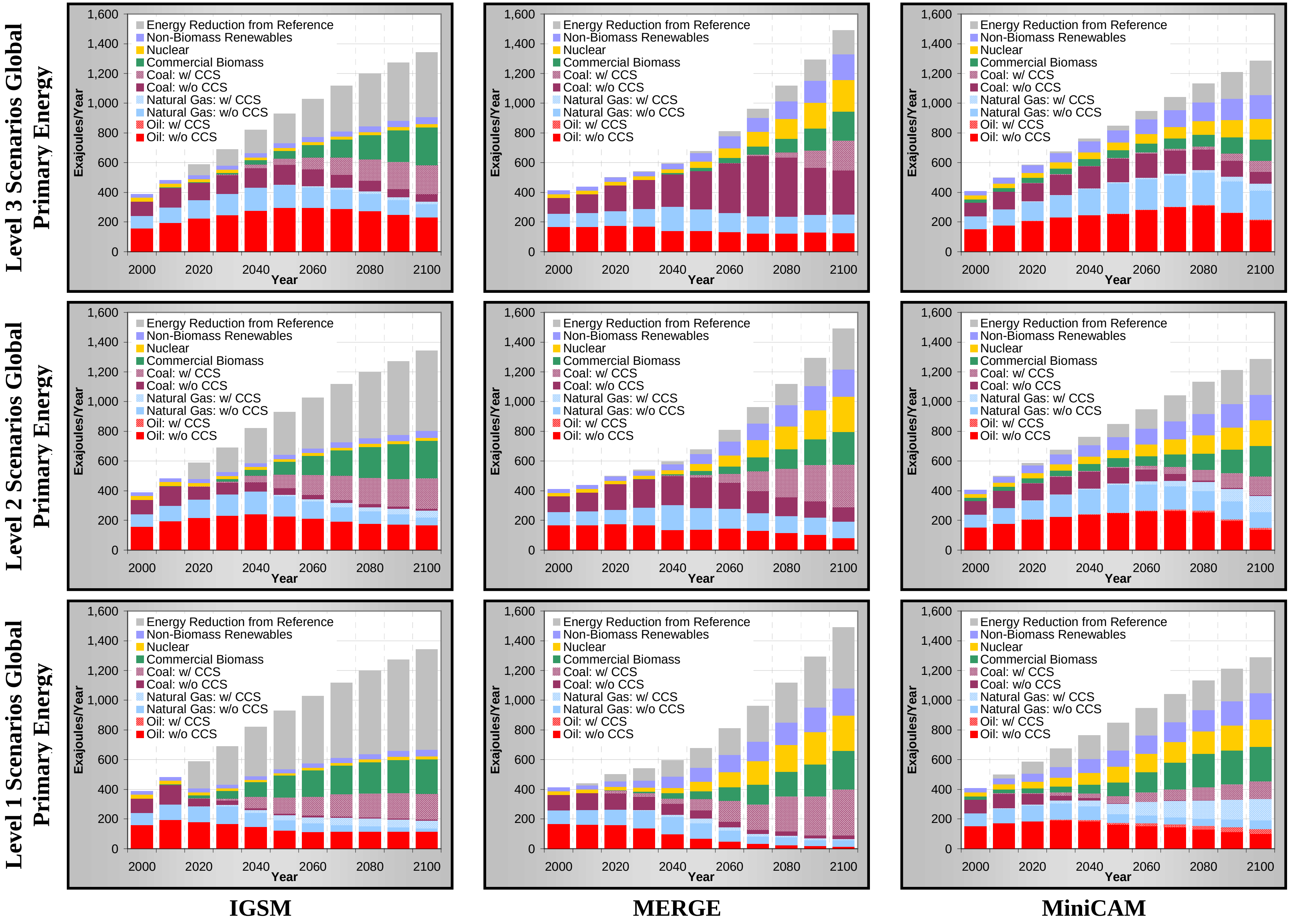
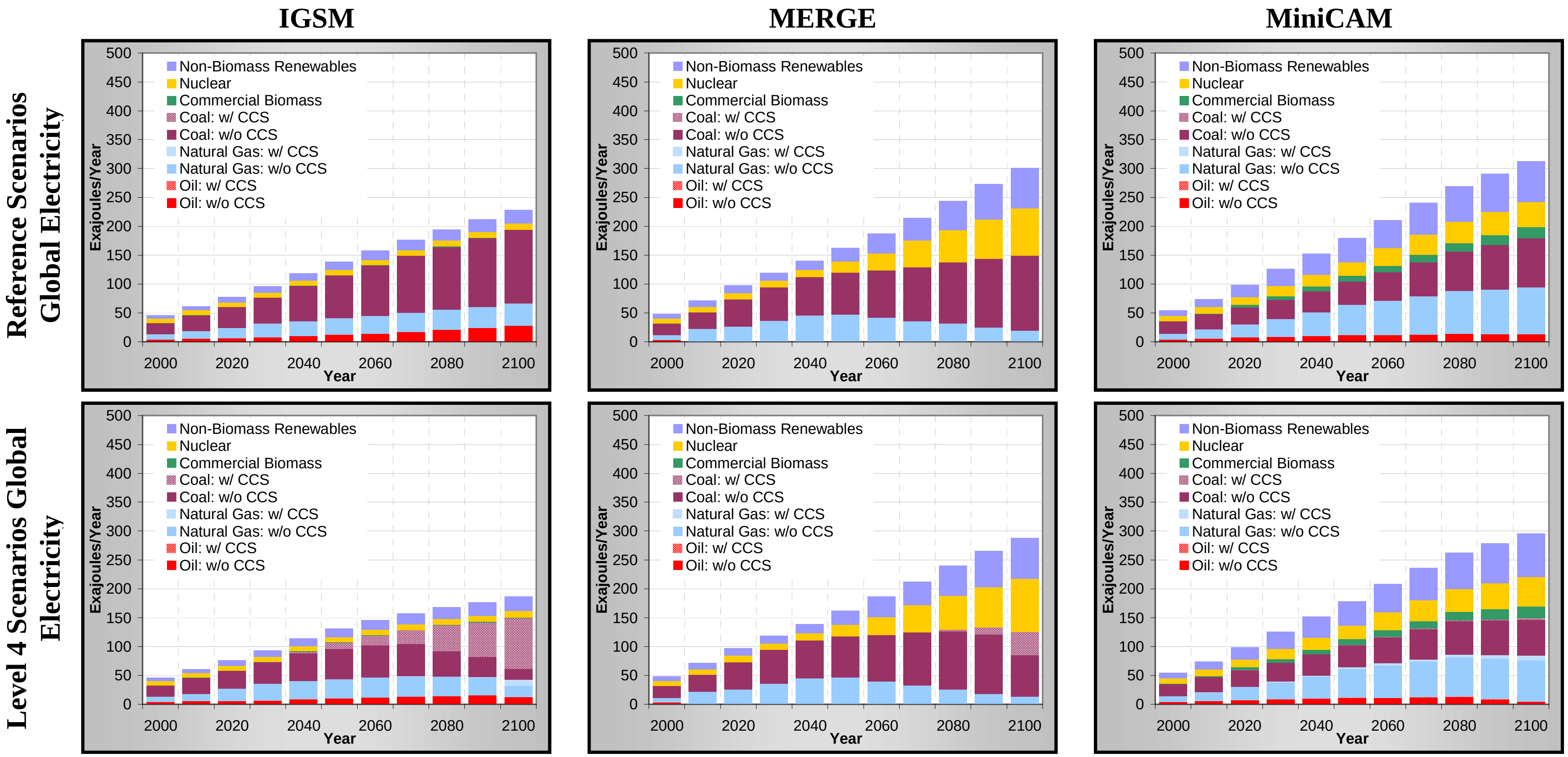

Level 3 Scenarios Global Primary Energy
Level 2 Scenarios Global Primary Energy
Level 1 Scenarios Global Primary Energy
IGSM
MERGE
MiniCAM
Exajoules/Year
Year
0
200
400
600
800
1,000
1,200
1,400
1,600
2000
2020
2040
2060
2080
2100
Energy Reduction from Reference
Non-Biomass Renewables
Nuclear
Commercial Biomass
Coal: w/ CCS
Coal: w/o CCS
Natural Gas: w/ CCS
Natural Gas: w/o CCS
Oil: w/ CCS
Oil: w/o CCS

Figure 4.11. Global Electricity by Fuel across Scenarios (EJ/y). Global electricity sources would need to be transformed to meet stabilization goals. Carbon capture and sequestration are important in all three models; thus, while coal use is reduced, it remains an important electricity fuel. Use of CCS is the main supply response in IGSM, in part because nuclear power is limited by assumption to reflect non-climate policy concerns. Nuclear and renewable electricity sources play a larger role in MERGE and MiniCAM simulations.



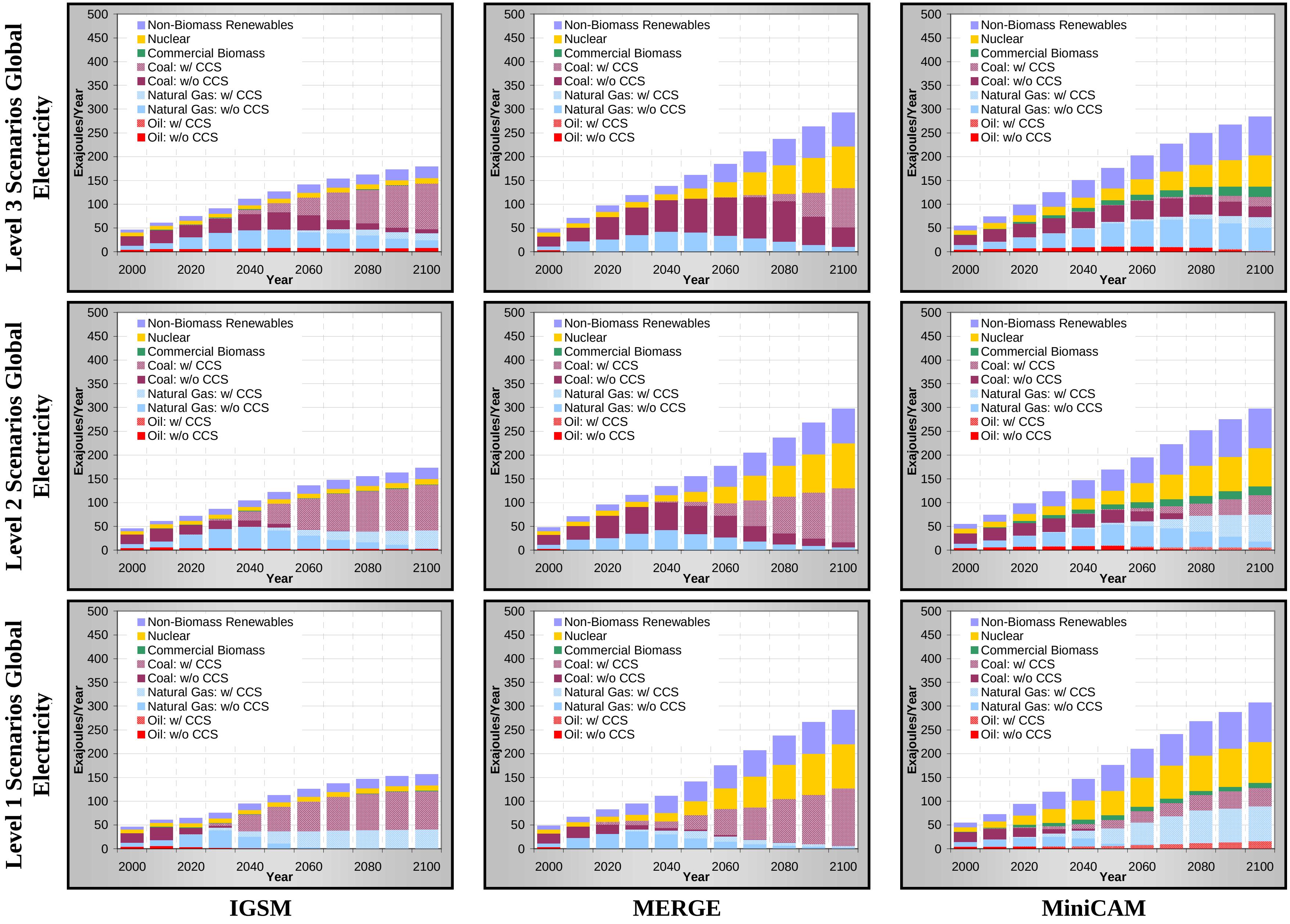
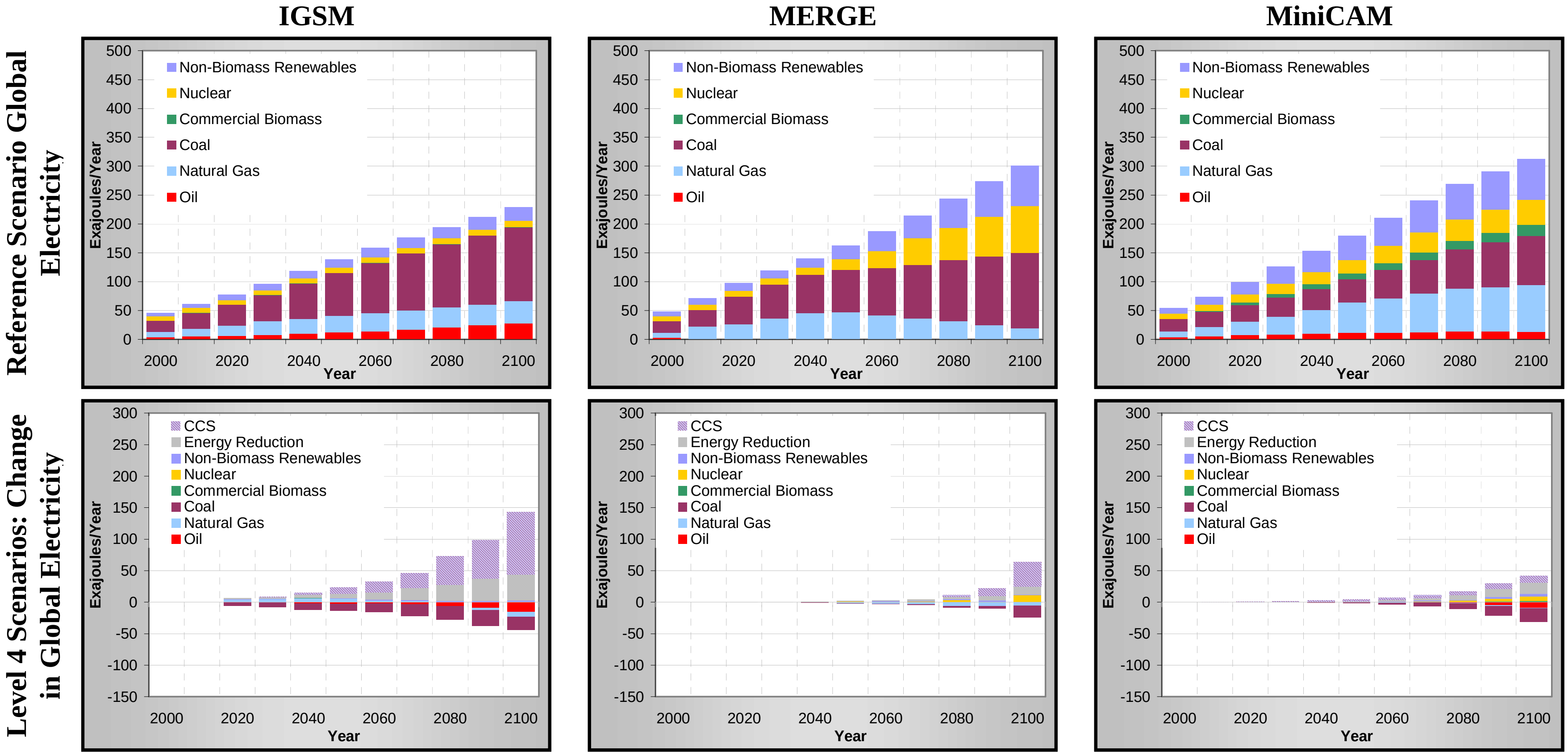

Level 3 Scenarios Global Electricity
Level 2 Scenarios Global Electricity
Level 1 Scenarios Global Electricity
IGSM
MERGE
MiniCAM
Non-Biomass Renewables
Nuclear
Commercial Biomass
Coal: w/ CCS
Coal: w/o CCS
Natural Gas: w/ CCS
Natural Gas: w/o CCS
Oil: w/ CCS
Oil: w/o CCS
Exajoules/Year
0
50
100
150
200
250
300
350
400
450
500
Year
2000
2020
2040
2060
2080
2100

Figure 4.12. Changes in Global Electricity by Fuel across Stabilization Scenarios, Relative to Reference Scenarios (EJ/y). There are various electricity technology options that could be competitive in the future, and different assessments of their relative economic viability, reliability, and resource availability lead to different scenarios for the global electricity sector in reference and stabilization scenarios across the models. IGSM simulations project relatively little change in the electricity sector in the reference, with continued reliance on coal. MERGE and MiniCAM project large transformations from current in the reference. All three models anticipate that large changes relative to the reference scenario would be required to meet the stabilization targets. In the less stringent scenarios, many of these changes would be pushed into the next century.



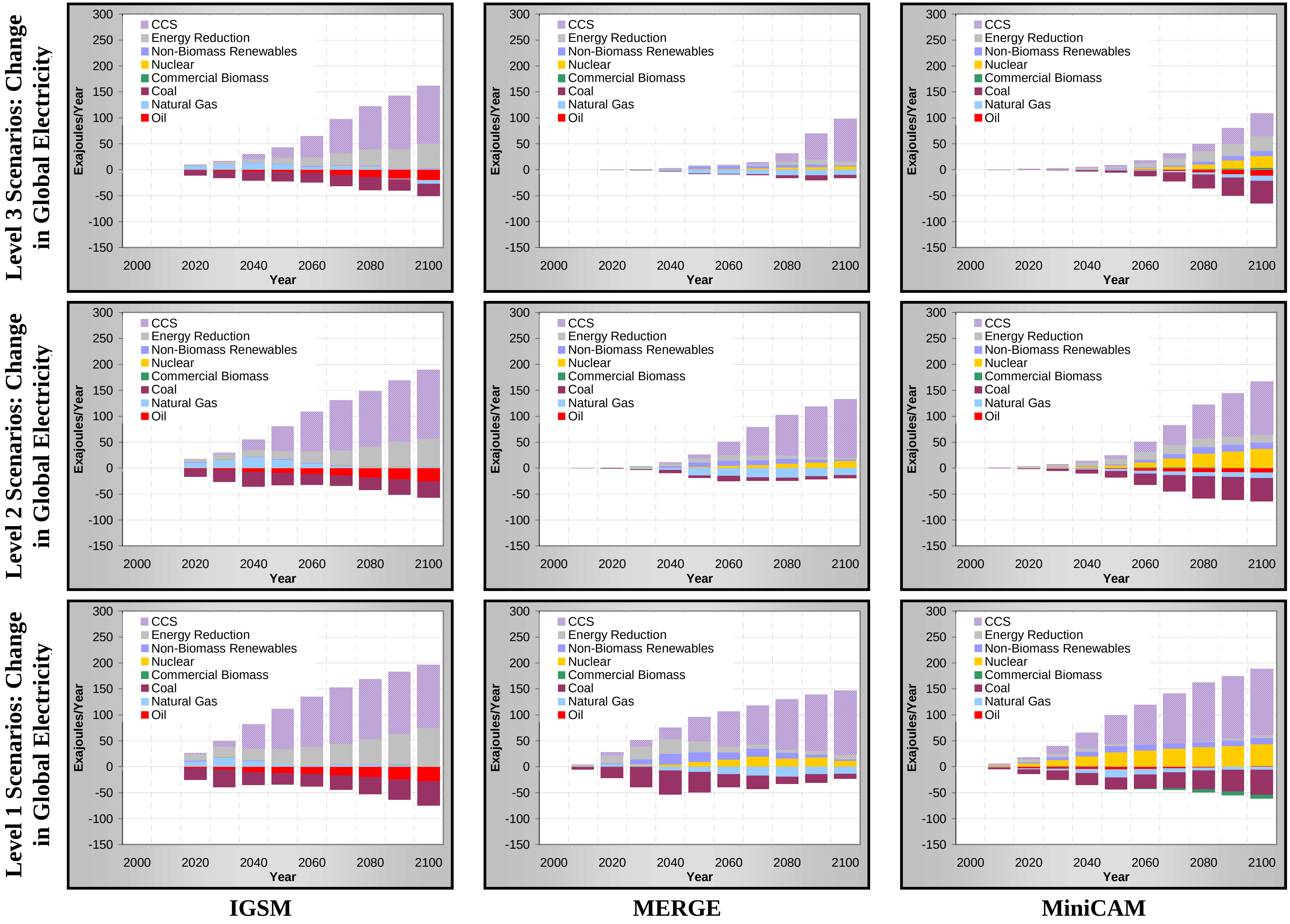
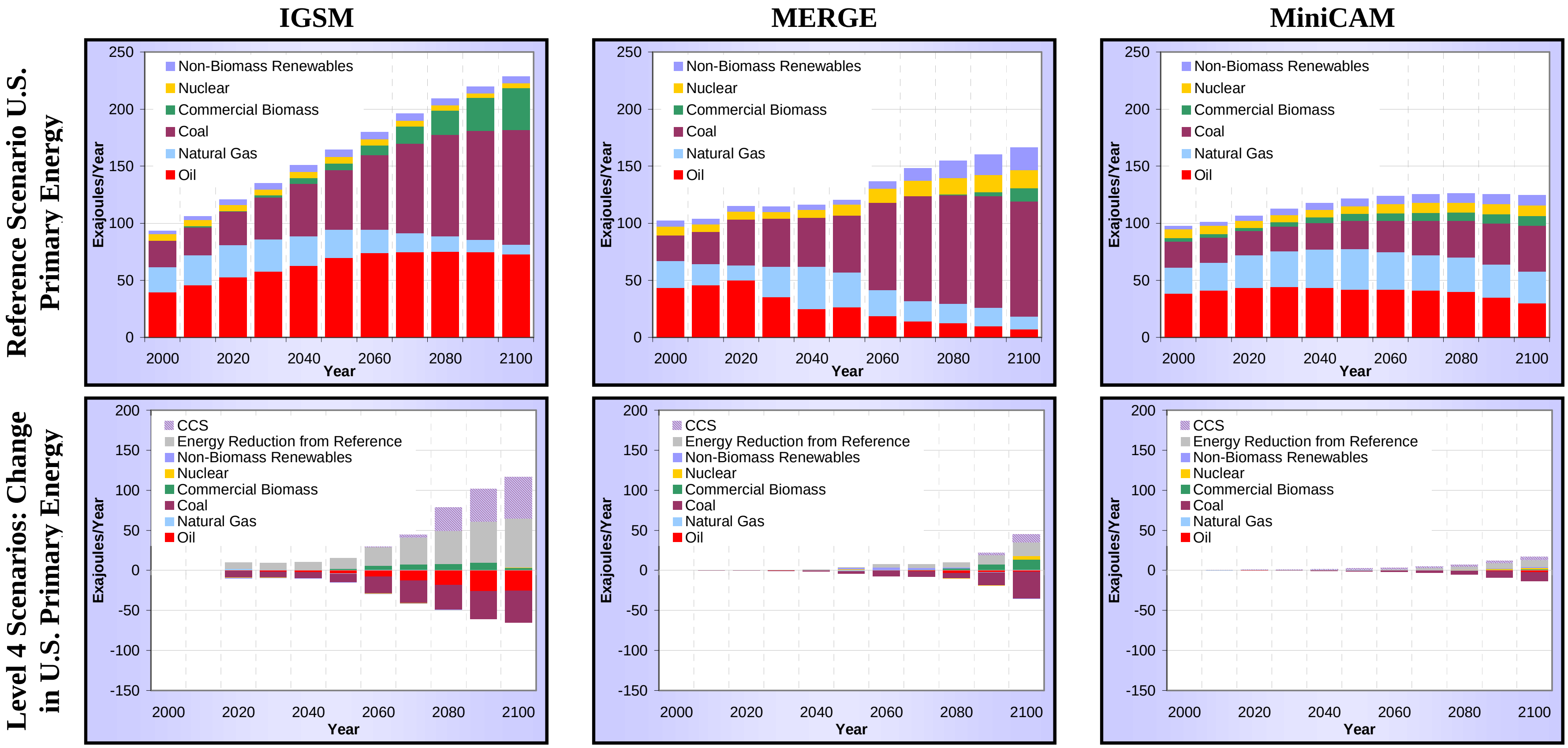

Level 3 Scenarios: Change in Global Electricity
Level 2 Scenarios: Change in Global Electricity
Level 1 Scenarios: Change in Global Electricity
IGSM
MERGE
MiniCAM
CCS
Energy Reduction
Non-Biomass Renewables
Nuclear
Commercial Biomass
Coal
Natural Gas
Oil
Exajoules/Year
300
250
200
150
100
50
0
-50
-100
-150
Year
2000
2020
2040
2060
2080
2100

Figure 4.13. Changes in U.S. Primary Energy by Fuel across Stabilization Scenarios, Relative to Reference Scenarios (EJ/y). Scenarios for the United States energy system under reference and the changes needed under the stabilization scenarios involve transformations similar to those reported for the global system. Although it is not illustrated in this figure, one difference is the transformation from conventional oil and gas to synthetic fuel production derived from shale oil or coal. IGSM projects heavy use of shale oil in the reference with some coal gasification, whereas MERGE simulates synthetic liquid and gaseous fuels derived from coal. MiniCAM utilizes moderate levels of both.



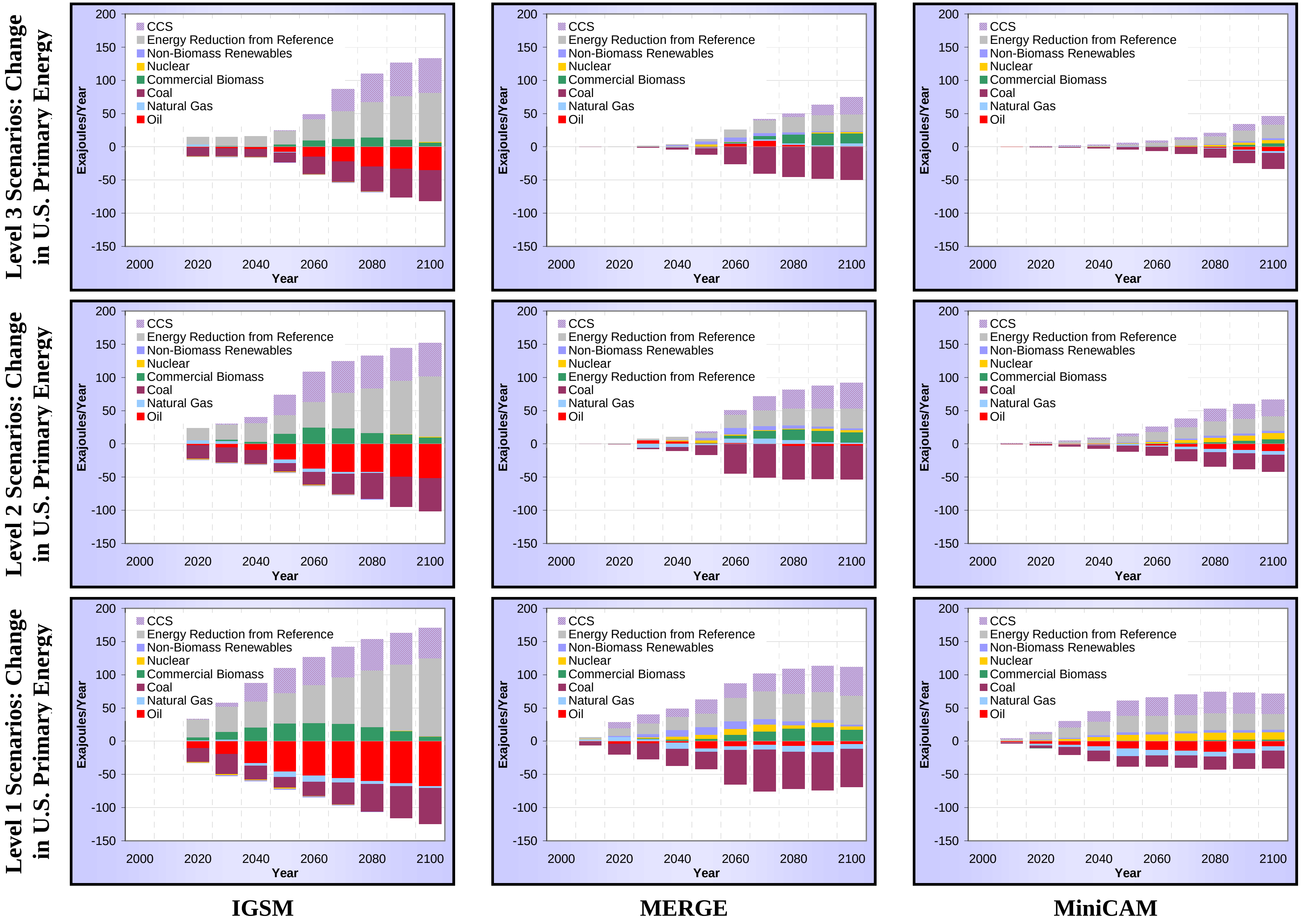
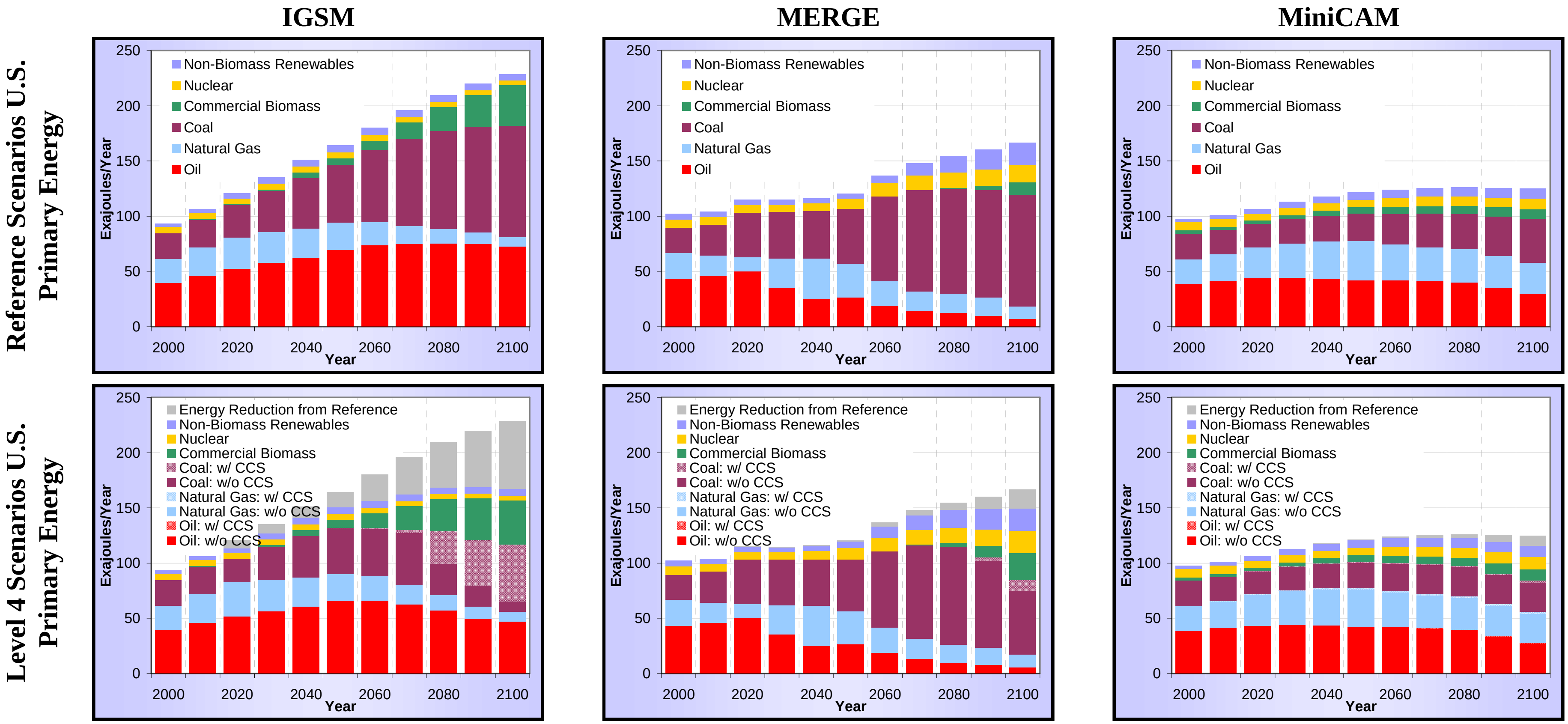

Level 3 Scenarios: Change in U.S. Primary Energy
Level 2 Scenarios: Change in U.S. Primary Energy
Level 1 Scenarios: Change in U.S. Primary Energy
IGSM
MERGE
MiniCAM
Exajoules/Year
Year
200
150
100
50
0
-50
-100
-150
2000
2020
2040
2060
2080
2100
CCS
Energy Reduction from Reference
Non-Biomass Renewables
Nuclear
Commercial Biomass
Energy Reduction from Reference
Coal
Natural Gas
Oil

Figure 4.14. U.S. Primary Energy by Fuel across Scenarios (EJ/y). Simulated United States primary energy use under the four stabilization levels shows considerable difference among the three models. All three models exhibit a diverse energy mix throughout the century, although the IGSM scenarios include relatively less nuclear power and non-biomass renewables than the other models. The relative contributions of different technologies over the course of the century depend on the specific cost and performance characteristics of the competing technologies represented in the models—assumptions that are highly uncertain.



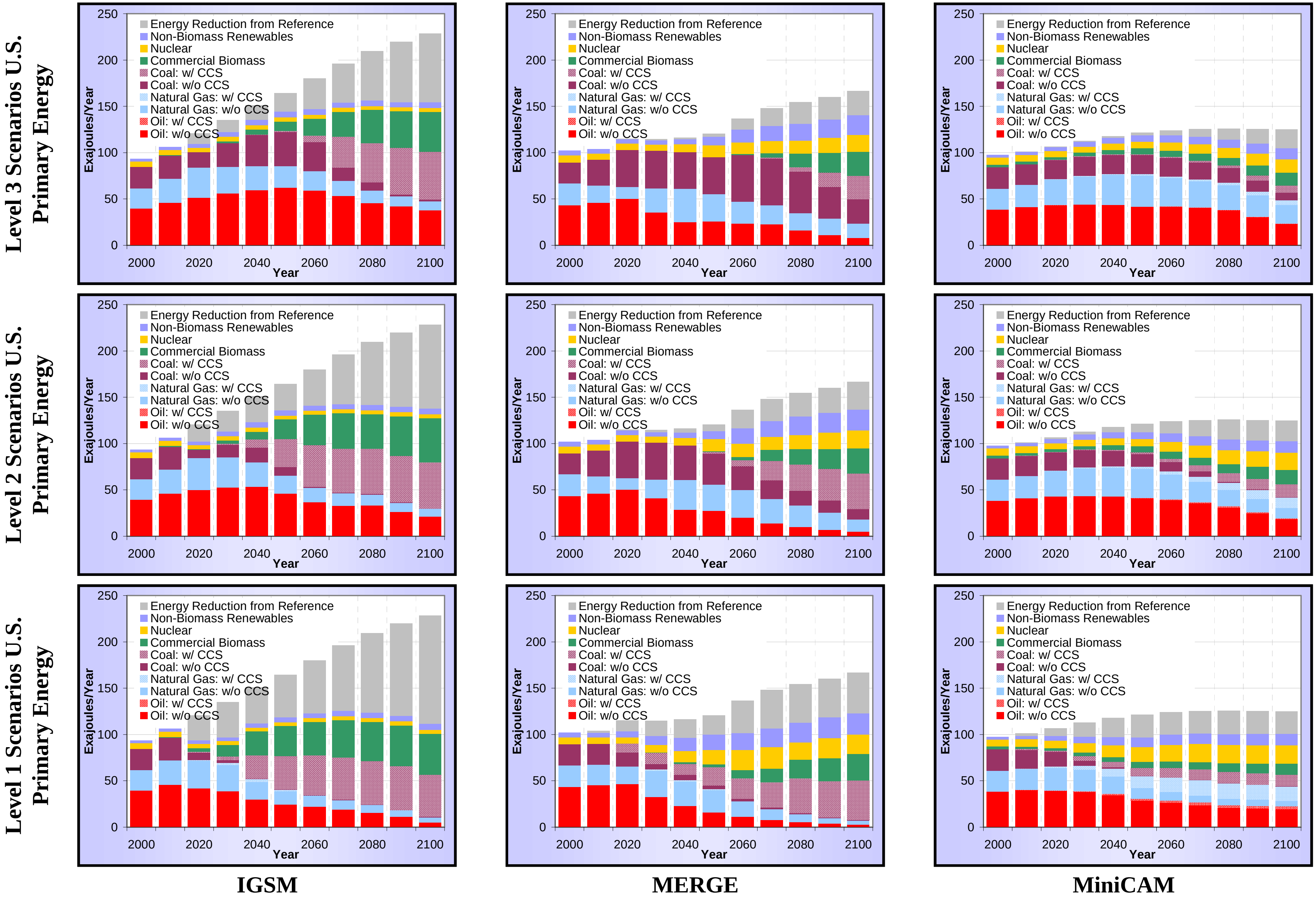
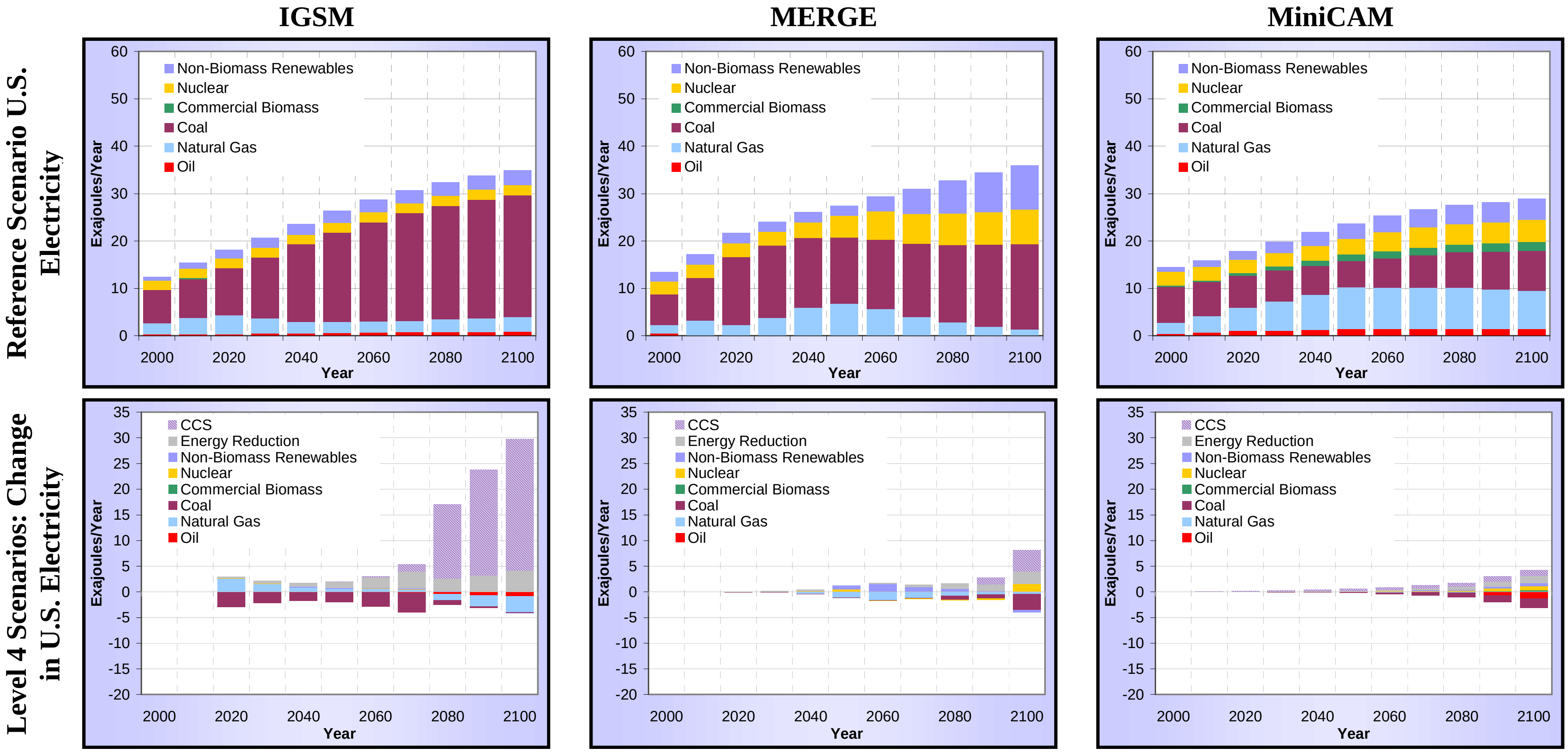

Level 3 Scenarios U.S. Primary Energy
Level 2 Scenarios U.S. Primary Energy
Level 1 Scenarios U.S. Primary Energy
Energy Reduction from Reference
Non-Biomass Renewables
Nuclear
Commercial Biomass
Coal: w/ CCS
Coal: w/o CCS
Natural Gas: w/ CCS
Natural Gas: w/o CCS
Oil: w/ CCS
Oil: w/o CCS
Exajoules/Year
0
50
100
150
200
250
2000
2020
2040
2060
2080
2100
Year
IGSM
MERGE
MiniCAM

Figure 4.15. Change in U.S. Electricity by Fuel across Stabilization Scenarios, Relative to Reference Scenarios (EJ/y). United States electricity generation sources and technologies will need to be substantially transformed to meet stabilization targets. Carbon capture and sequestration figure in all three models under stabilization scenarios, but the contribution of other sources and technologies and the total amount of electricity used differ substantially.



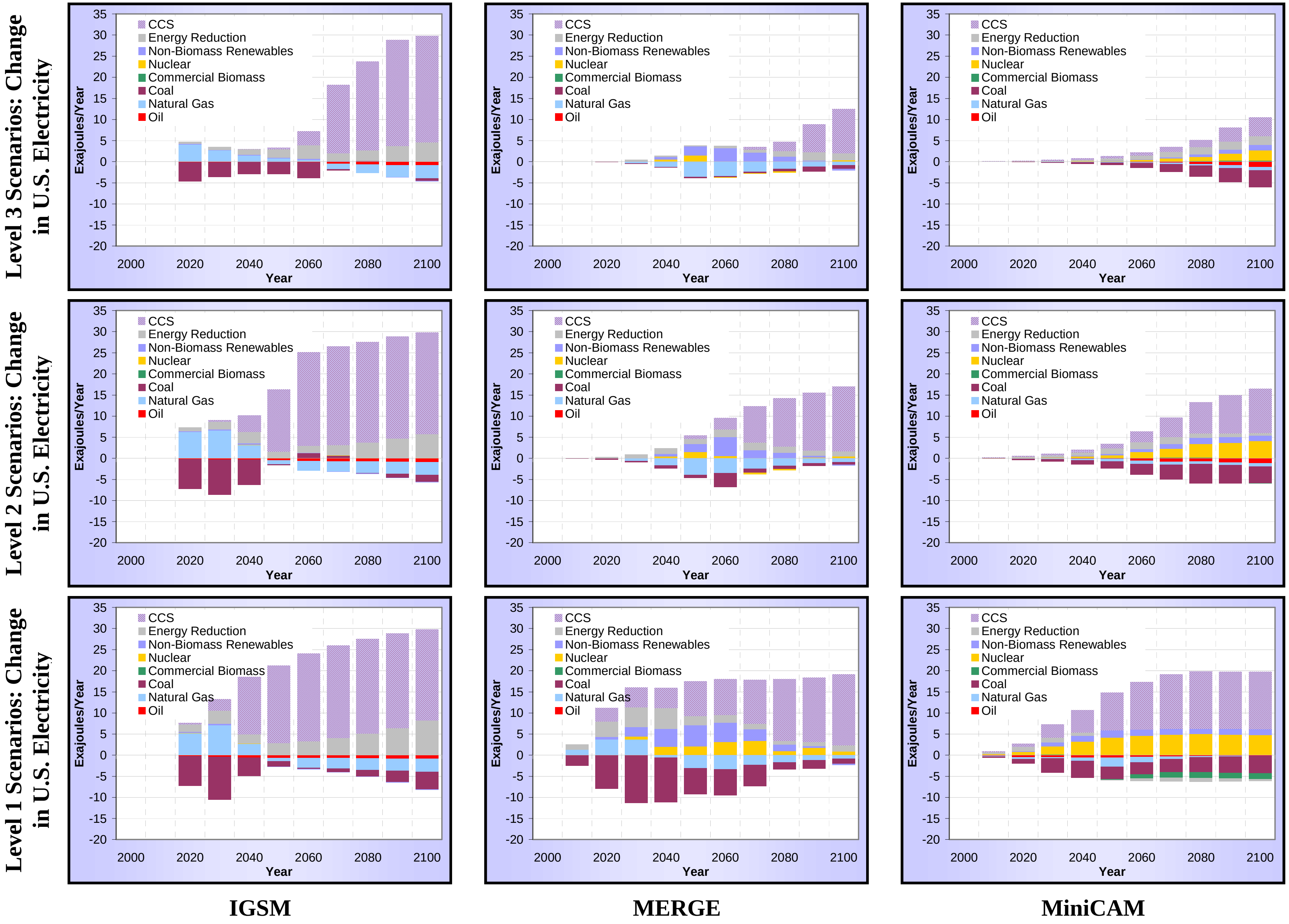

Level 3 Scenarios: Change in U.S. Electricity
Level 2 Scenarios: Change in U.S. Electricity
Level 1 Scenarios: Change in U.S. Electricity
IGSM
MERGE
MiniCAM
CCS
Energy Reduction
Non-Biomass Renewables
Nuclear
Commercial Biomass
Coal
Natural Gas
Oil
Exajoules/Year
35
30
25
20
15
10
5
0
-5
-10
-15
-20
Year
2000
2020
2040
2060
2080
2100

Figure 4.16. Global and U.S. Commercial Biomass Production across Scenarios. Scenarios of the potential for commercial biomass production for the world and the U.S. are similar in magnitude and behavior among the models. Commercial biomass production increases over time in the reference scenarios due in large part to technological improvements in bioenergy crop production and increasing demand for liquid fuels. Stabilization increases the demand for bioenergy crops, causing production to increase more rapidly and to reach higher levels than in the Reference Scenario. Dramatic growth in bioenergy crop production raises important issues concerning the attendant increases in the land that is devoted to these crops, including competition with other agricultural crops, encroachment into unmanaged lands, and water and related resource and environmental impacts.

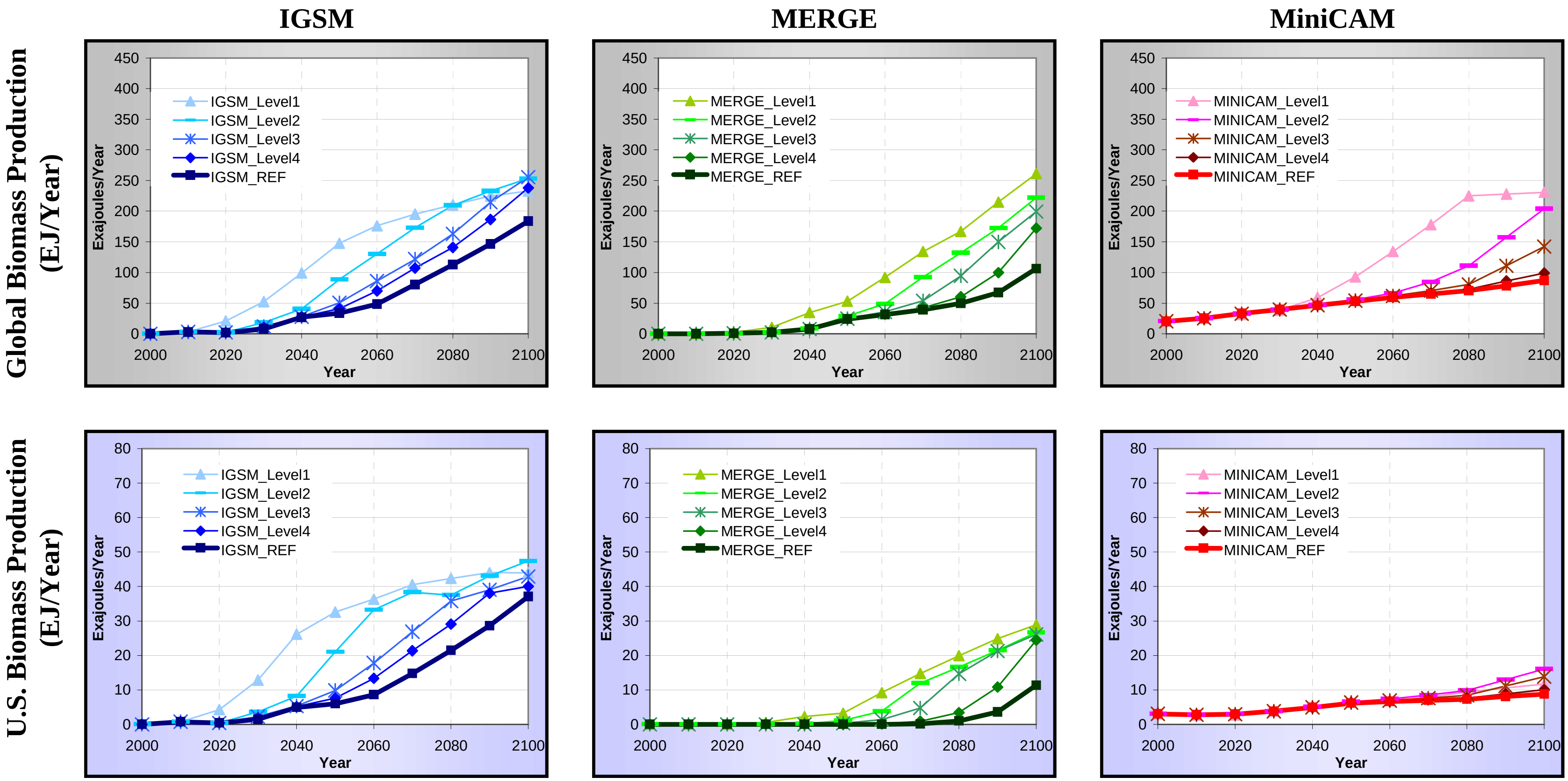


Figure 4.17. Net Terrestrial Carbon Flux to the Atmosphere across Scenarios (GtC/y). The net terrestrial carbon flux to the atmosphere, under reference and stabilization levels, reflects differences in the model structures for processes that remain highly uncertain. MERGE assumes a neutral biosphere. IGSM and MiniCAM generally represent the land as a growing carbon sink, with the exception of the Level 1 MiniCAM simulation, in which increased demand for land for biomass production leads to conversion and carbon loss. This effect is particularly strong prior to 2080 in the Level 1 MiniCAM scenario.

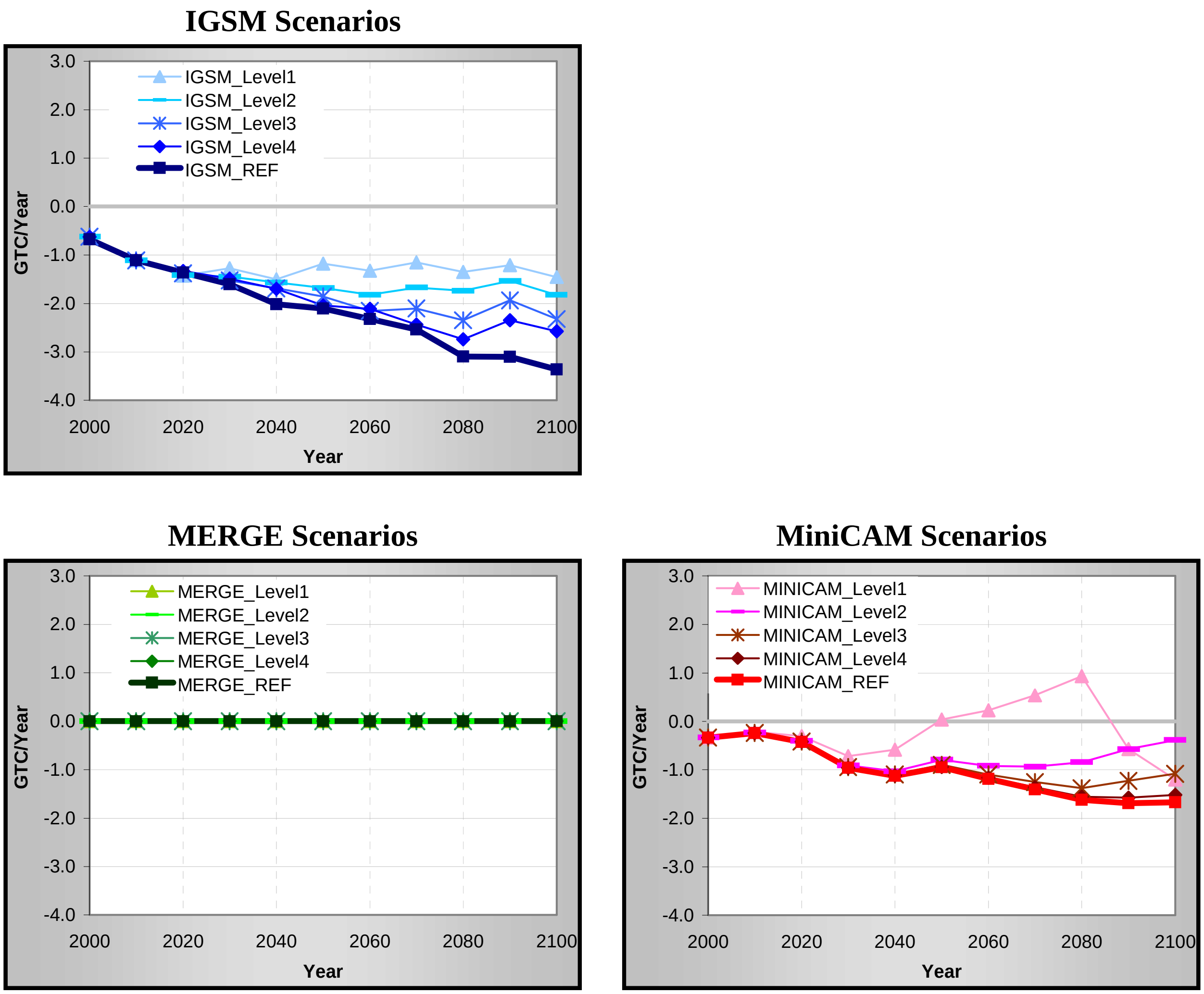


Figure 4.18. Carbon Prices across Stabilization Scenarios ($/tonne C). Stabilization implies an economic penalty for emitting carbon. In all the models, this price rises, by design, over time until stabilization is achieved (or the end-year 2100 is reached), and the prices are higher the more stringent is the stabilization level. There are substantial differences in carbon prices between MERGE and MiniCAM scenarios, on the one hand, and the IGSM scenarios on the other. Differences among the models reflect differences in Reference Scenario emissions and differences in the technologies that might facilitate carbon emissions reductions.

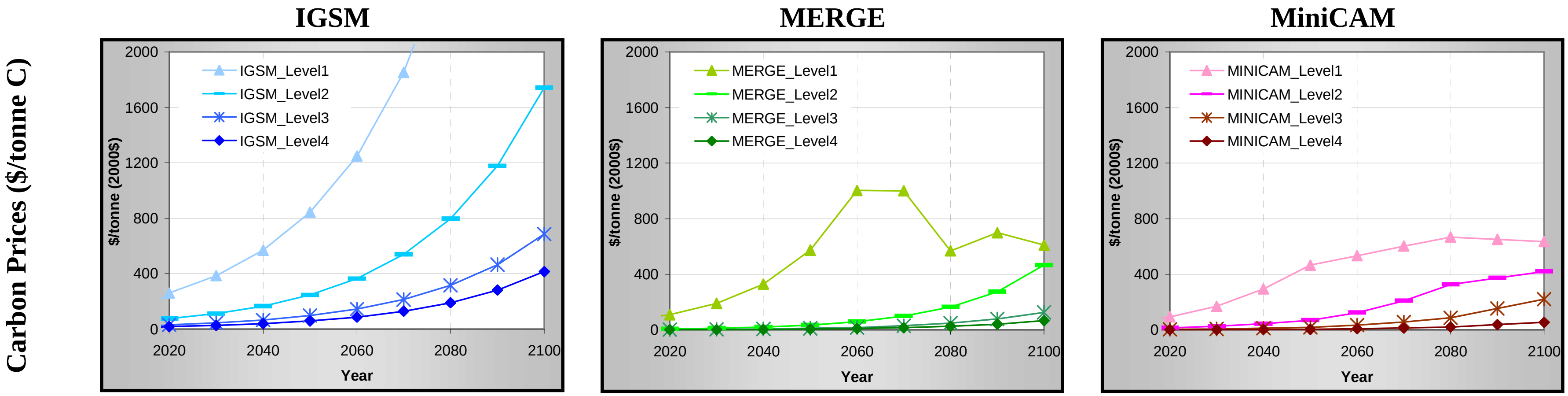
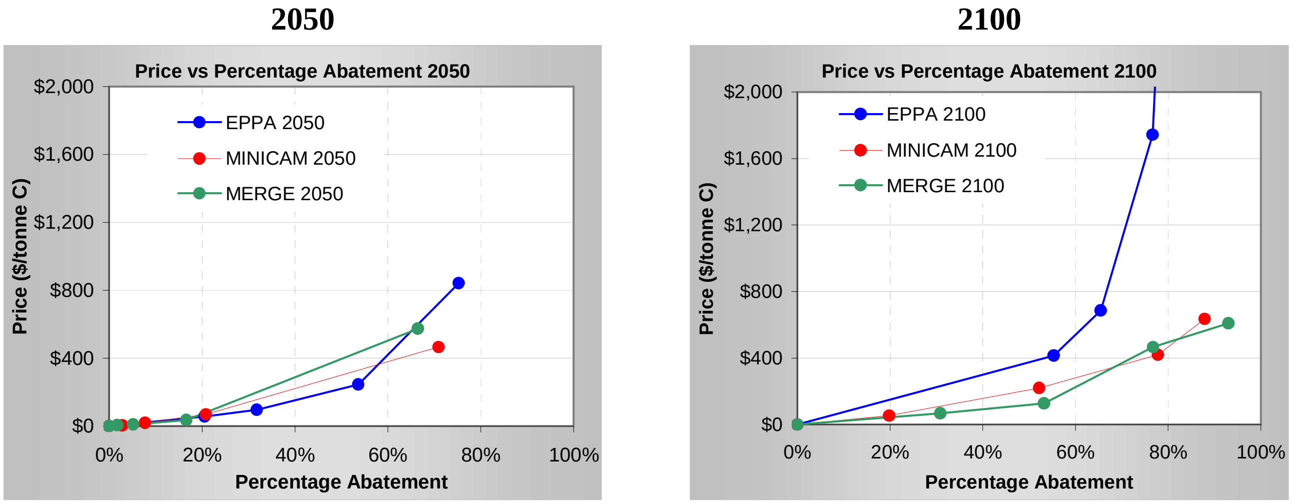


Figure 4.19. Ratio of Relationship Between Carbon Price and Percentage Abatement in 2050 and 2100. The relationship between carbon price and percentage abatement very similar among the models in 2050. In 2100, a given percentage emissions reduction is generally more expensive for IGSM than for either MERGE or MiniCAM. The difference in 2100 is due in large part to different assumptions regarding the technologies available to facilitate emissions reductions late in the century, with the IGSM providing relatively fewer or more costly options than the other two models.



2050

2100

Figure 4.20. Relative Prices of CH_4 and N_2O to Carbon across Scenarios (CH_4 in log scale). Differences in the relative prices of CH_4 and N_2O to carbon reflect different model treatments of this tradeoff, often referred to as “what’ flexibility. MiniCAM set the tradeoff at the CH_4 global warming potential, a constant ratio. MERGE optimized the relative price with respect to the long-run stabilization target. IGSM forced stabilization of each gas independently. IGSM set emissions so that concentrations of CH_4 would stabilize and allowed the CH_4 price path to be determined by changing abatement opportunities. Given N_2O emissions from agriculture, the relative price of N_2O is very high, in part because reference emissions were high. Lower reference scenario emissions of N_2O for MERGE and MiniCAM allowed them to achieve relatively low emissions at lower N_2O prices.

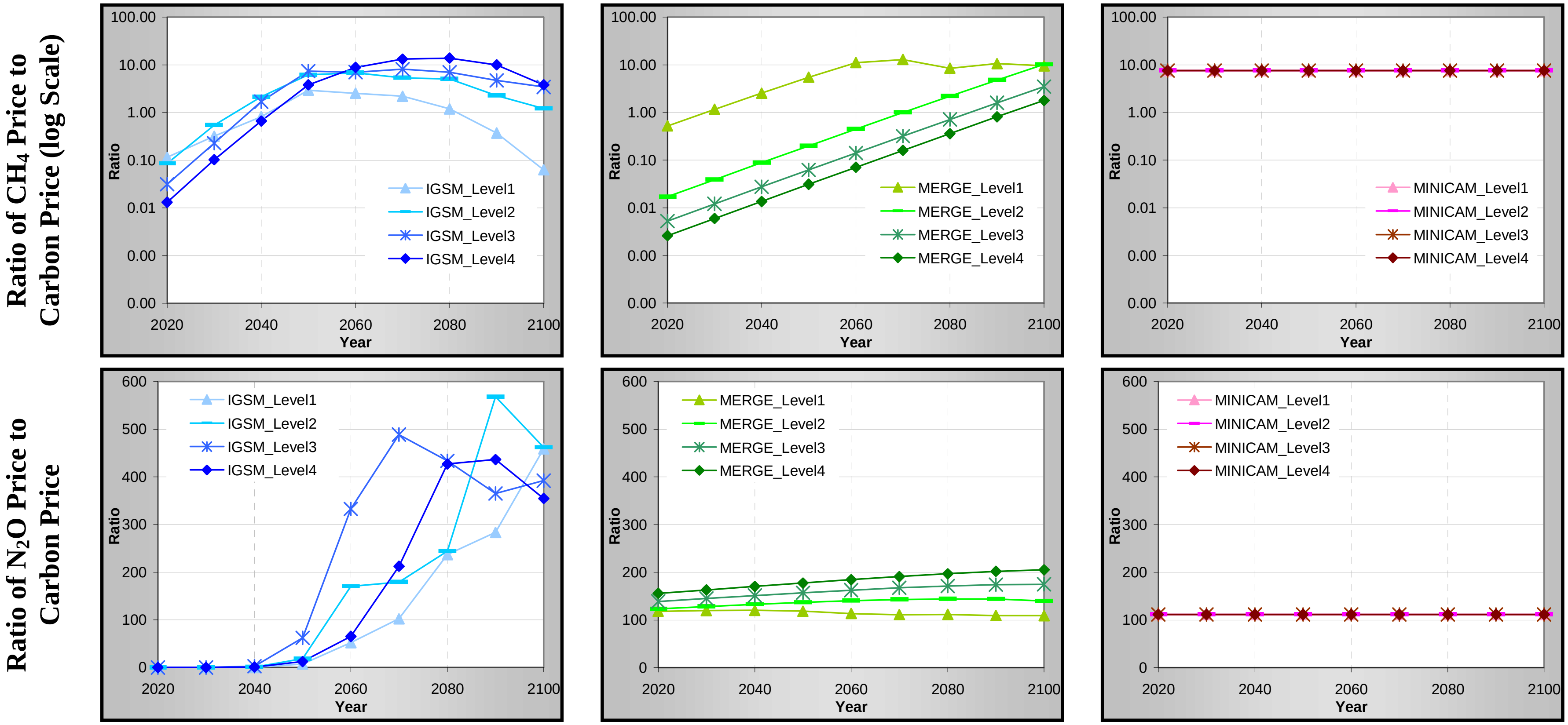
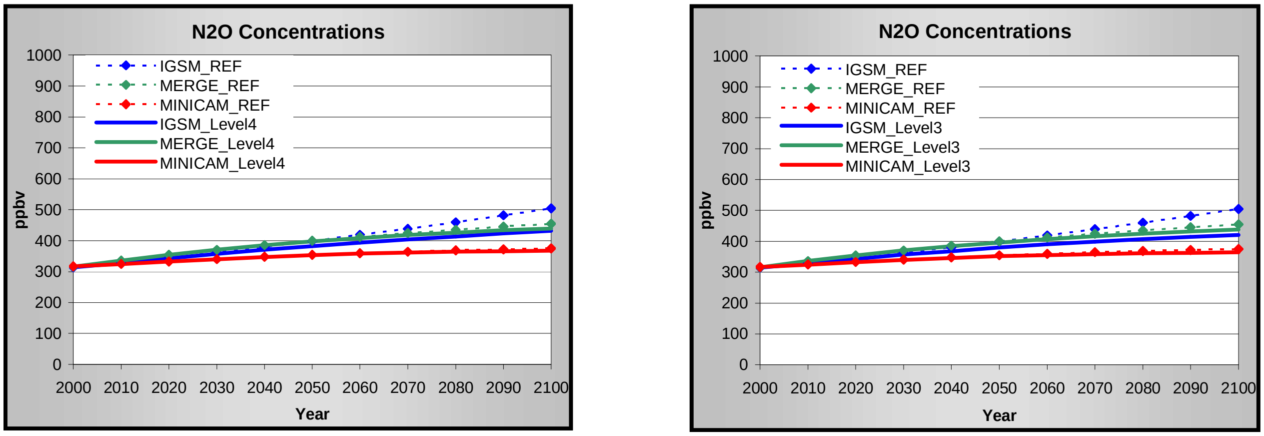
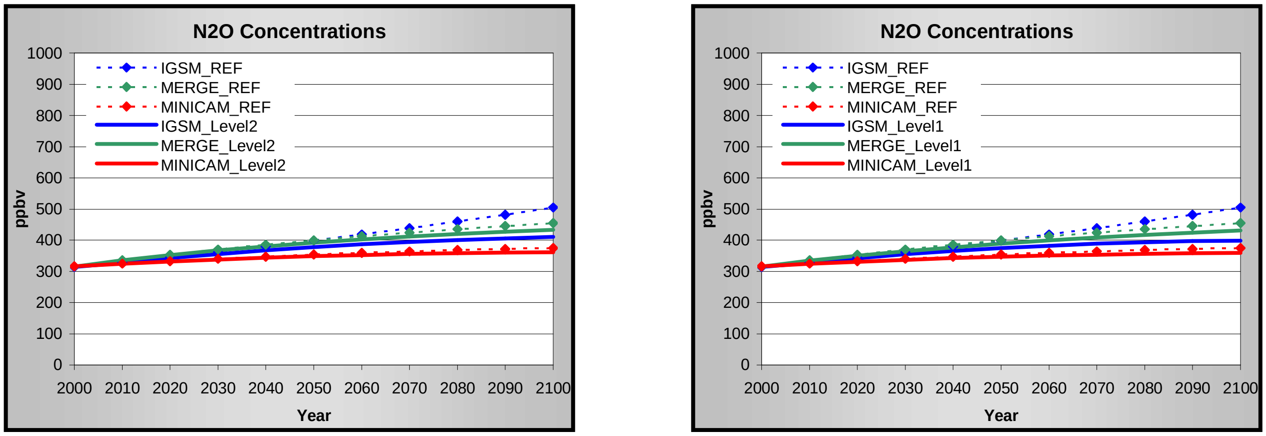


Figure 4.21. N_2O Concentrations across Scenarios (ppbv). Atmospheric concentrations of N_2O range from about 375 ppbv to 500 ppbv in 2100 across the models, with concentrations continuing to rise in the reference. Each modeling team employed a different approach to emissions limitations on N_2O, leading to differences in concentrations between the reference and stabilization cases.



Level 4 Scenarios **Level 3 Scenarios**



Level 2 Scenarios **Level 1 Scenarios**

Figure 4.22. World Oil Price, Reference and Stabilization Scenarios. World oil prices (producer prices) vary considerably in the reference scenario, and reflect the highly uncertain nature of such scenarios, but all three models show that policies to stabilize emissions tend to depress producer prices relative to the reference. Note that producer prices are defined here to not include any cost of carbon permits related to combustion and release of carbon from petroleum products.

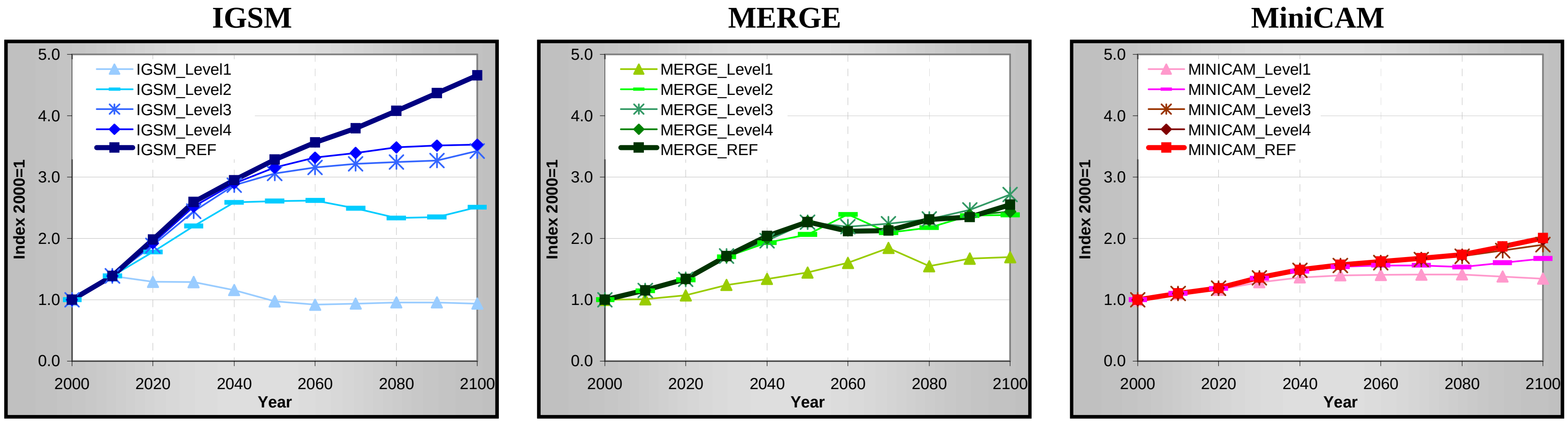


Figure 4.23. United States Mine-mouth Coal Price, Reference and Stabilization Scenarios. United States mine-mouth coal price varies in the reference across the models. IGSM and MiniCAM project coal prices to be depressed by stabilization scenarios, whereas MERGE projects no impact reflecting characterization of coal supply as an inexhaustible single grade such that there is no rent associated with the resource. Prices thus reflect the cost capital, labor, and other inputs that are little affected by the stabilization policy. Note that producer prices are defined here to not include any cost of carbon permits related to combustion and release of carbon from burning coal combustion.

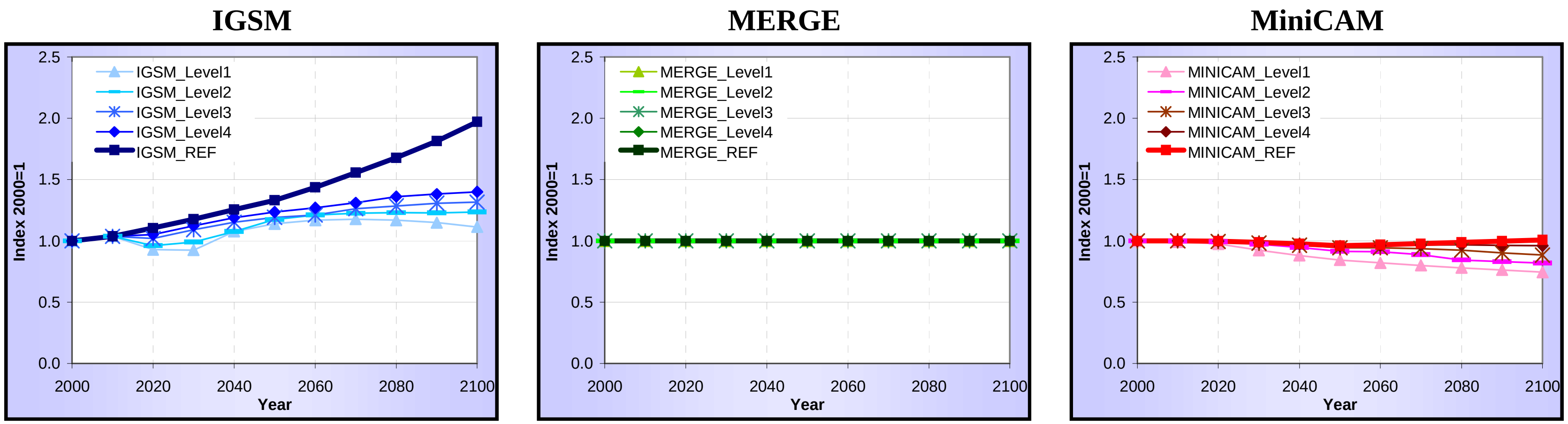


Figure 4.24. United States Natural Gas Producers' Price, Reference and Stabilization Scenarios. United States natural gas producers' prices vary in the reference across the models. MiniCAM and MERGE show little effect on the gas price for stabilization scenarios. IGSM projects that stabilization at Levels 2, 3, and 4 increase the price of gas because of substitution toward gas and away from coal and oil. Gas prices fall relative to reference for Level 1 stabilization because gas demand is depressed because of the tight carbon constraint. Note that producer prices do not include any cost of carbon permits related to combustion and release of carbon from natural gas combustion.

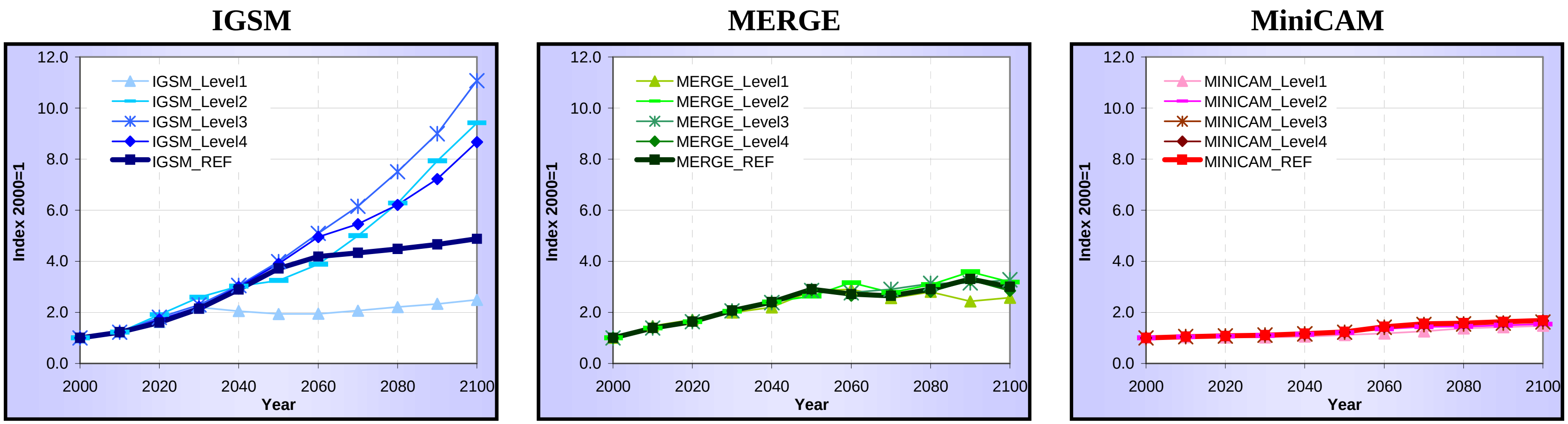

IGSM **MERGE** **MiniCAM**

Figure 4.25. United States Electricity Price, Reference and Stabilization Scenarios. United States electricity prices as projected in the Reference Scenarios to range from little change to about a 50% increase from present levels (IGSM). Under stabilization, producer prices are affected by increasing use of more expensive low- or zero-emissions electricity technologies such as fossil electricity with carbon capture and storage and non-biomass renewables such as solar and wind power. Across the scenarios, rising fossil fuel prices are partially offset by increasing efficiency of fossil electric generation facilities.

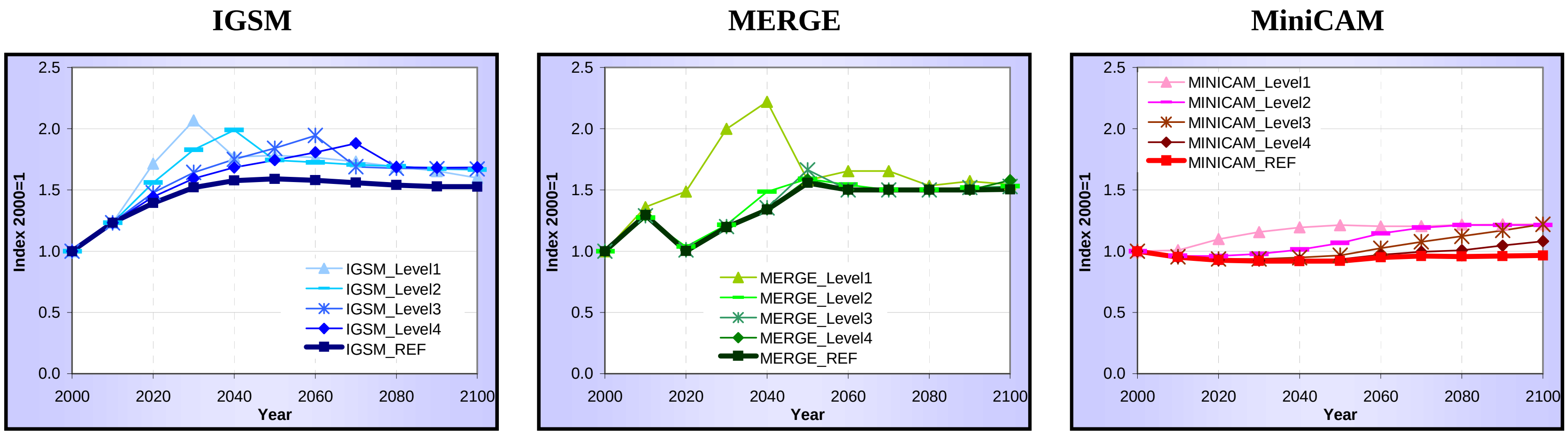
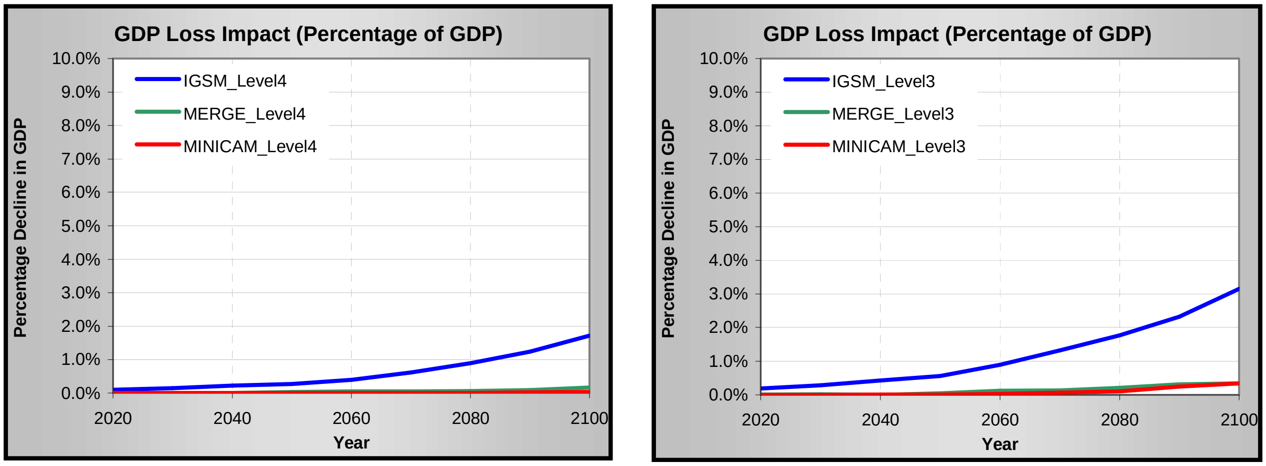
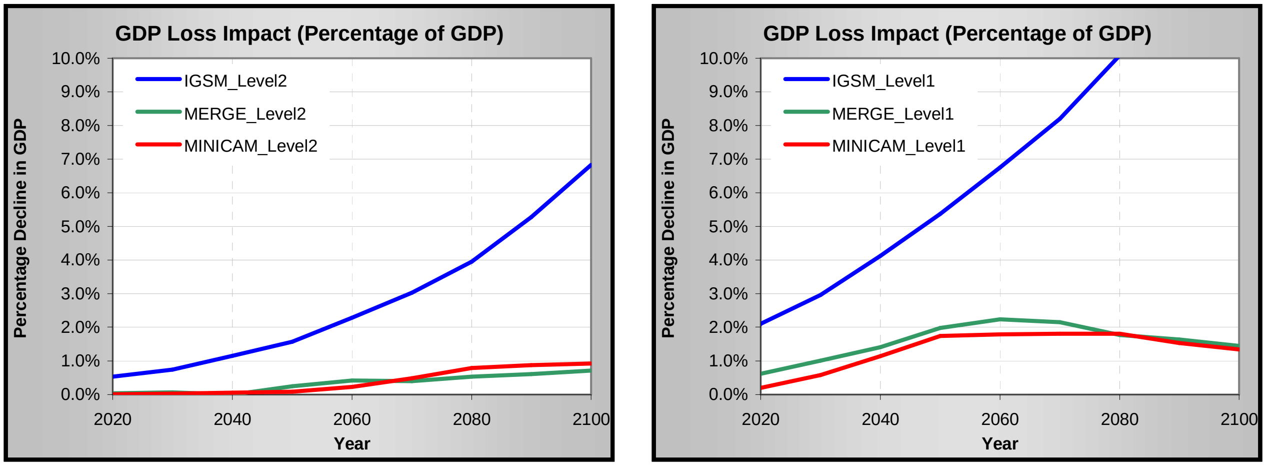


Figure 4.26. Global GDP Impacts of Stabilization across Stabilization Levels (percentage). Stabilization imposes costs on the economy, and stated in terms of Gross World Product (GWP) loss the cost rises over time as ever more stringent emissions restrictions are required. The tighter the stabilization target the higher the cost. Variation is estimates among the models reflect differences in reference scenario emissions, differences in the approaches used to distributed carbon emissions reductions over time, and differences in the cost and availability of low-carbon technologies particularly in the second half of the century.

Level 4 Scenarios **Level 3 Scenarios**



Level 2 Scenarios **Level 1 Scenarios**



5. SUMMARY, APPLICATIONS AND FUTURE DIRECTIONS

5.1. Introduction

Scenarios based on formal, computer-based models, such as those developed here, 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 models such as these 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 may not be the most appropriate for other applications. 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 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 varied clientele implies an equally diverse set of possible needs, and no single scenario exercise can hope to satisfy all. 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 simulations or by probing more deeply into particular issues. The Prospectus for this study does not, however, prescribe such an interactive approach with a focused set of users. Instead, it calls for 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.

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 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 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, and none can be said to have the highest probability of being right. Nor does any single 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.

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 consumption rises substantially in all three reference scenarios, from about 400 EJ/y in 2000 to between 1300 and 1500 EJ/y in 2100. U.S. primary energy production also grows from a little over 1to 2½ times present levels by 2100. This growth occurs despite continued improvements in the efficiency of energy use and production.*

- *All three reference scenarios include a gradual reduction in the relative role of 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 225 EJ to 260 EJ—between roughly half the level of 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 ranges from an increase over current levels of around 50% in the presence of political constraints to an expansion by more than an order of magnitude on the assumption of growth driven strictly by economic considerations.*

- *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 future technological opportunities and the likely effect of controls imposed for non-climate reasons.*

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. At high concentrations projected late in the century, however, chemical, biological and physical processes in the ocean can slow this rate of ocean uptake. The scenarios have ocean uptake in the range of around 2 GtC/y in 2000, rising to about 4-11 GtC/y by 2100. The three models produce more similar ocean behavior in the stabilization scenarios.*

- *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. They project 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, under a changing climate.*

- *GHG concentrations are projected to rise substantially over the century under the 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 at this change by the end of the century.*

5.2.2. Stabilization Scenarios

Important assumptions underlying the stabilization cases concern the flexibility that exists in a policy design, as represented in the model simulation, to seek out least cost abatement options regardless of where they occur, to choose which substances are abated, and to decide when the mitigation occurs. 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 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 are 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 includes 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 stabilize atmospheric conditions. Such emissions limits would shape technology deployment throughout the century and have important economic consequences. The analysis demonstrates that there is no single technology pathway consistent with a given level of radiative forcing; furthermore, there are many plausible pathways of broader economic conditions other than those 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. 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 end-use energy consumption is lower and the energy system relies more heavily on non-fossil energy sources, such as nuclear, solar, wind, biomass, and other renewable energy forms. 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 stabilization levels much more difficult to achieve and (if not restrained for non-climate concerns) yield a 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 level and because of the option to capture and store CO_2.*

- *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, and, in one participating model, the associated impacts of biomass expansion on carbon emissions from changes in land use.*

- *The lower the radiative forcing limit, the more substantial the 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 scale of the emissions reductions required relative to the reference scenario increases over time. In all the stabilization scenarios the major portion of emissions reductions below reference come in the second half of the century though all the models show that near-term emissions reductions are required as well.*

- *The 2100 time horizon of the study limited examination of the ultimate requirements of stabilization. Atmospheric stabilization at any level 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.*

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 of supply, 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 dramatically reduced in all 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 approaches zero.*

The economic effects of stabilization could be substantial although much of this cost is borne later in the century. 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 a price of $100 per ton in 2020 required 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 that they imply vary substantially. Contributing factors are the reference level of emissions and differences in assumptions about the cost and performance of future technologies, especially those employed in the second half of the century. Model differences are indicative of the uncertainties necessarily present in scenarios of the far future.*

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

- *These differences in carbon prices and other model features lead to a wide range of costs among the various stabilization targets. Under the 450 ppmv scenario, for example, estimates of the mid-century reduction in Gross World Product* *(aggregating country figures using market exchange rates) vary 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. As with the GHG prices, the variation in cost in the first 50 years stems mainly from differences in reference emissions, whereas in the second half of the century assumptions about technologies dominate.*

- *As noted earlier, the overall cost levels are strongly influenced by the assumption of immediate global participation combined with "where", "what", and "when" flexibility. Deviations from these assumptions would likely lead to higher cost. The global costs were aggregated using market exchange rates—doing so using purchasing power parity would lead to different global results. Global results would then also depend on how responsibility for reductions were allocated among regions. Thus, these scenarios should not be interpreted as applying beyond the particular conditions assumed.*

- *The projected GHG mitigation would also affect fuel prices. Generally, the producer price for fossil fuels falls as demand 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 reduce cost and overcome existing barriers to adoption, and on the efficiency and effectiveness of the policy instruments applied.

5.3. 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 of these stabilization cases and the underlying reference scenario. There are a variety of possible applications of atmospheric stabilization. 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 scenario, 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 include an estimate of the emissions (or concentrations) of the reflecting and absorbing aerosols. This result could be achieved by the use of sub-models linked to scenario results for energy use by fuel.

The scenarios could also be used as a jumping off point for partial equilibrium analysis of technology development. 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 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 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 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 would be of use. For example, what are the implications of various levels of political constraint on nuclear development, or what would be the effect of similar limits on carbon capture and storage or other technology options? If particular technologies--nuclear, wind, natural gas combined cycle generation, biomass--were assumed to be more or less expensive, how would that affect market penetration and policy cost? How would breakthroughs in one technology area affect cost and other technology developments? Since technology deployment will be influenced by the policy environment, how would the consideration of less optimistic policy regimes affect the results?

5.4.2. Consideration of Less Optimistic Policy Regimes

The discussion in Chapter 4 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. There is little reason to believe that the world is headed toward an international policy architecture that closely resembles that assumed in this study. The assumed international emissions mitigation regime is highly stylized. The results 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 case and lower bound estimates 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 our understanding of the stabilization challenge in areas ranging from technology development to the economics of global mitigation.

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. 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 improved the characterization of land use and land cover and that improved the linkages between energy and economic systems and land use land cover, terrestrial carbon processes, and other bio-geochemical cycles has potentially high payoff.

5.4.4. Inclusion of other Radiatively-Important Substances

The focus here was on the relatively long-lived GHGs but shorter-lived substances like 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.

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.