# Technical Summary

## HIGHLIGHTS OF THE REPORT

### Background

This report presents research from Synthesis and Assessment Product 2.1a of the Climate Change Science Program (CCSP), *Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations*. The scenarios in this research product were designed to stabilize the influence of a suite of greenhouse gases (GHGs) – carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride ($SF_6$) – on the Earth's radiation balance, measured in terms of radiative forcing. Four radiative forcing stabilization levels are considered. The resulting atmospheric concentrations of the largest single contributor, $CO_2$, are roughly 450, 550, 650 and 750 parts per million by volume (ppmv). Responding to the Prospectus for this research product (CCSP 2005), this report focuses on (1) GHG emissions trajectories, (2) global and U.S. energy system implications, and (3) economic implications of stabilization.

This research was conducted using computer-based research tools known as integrated assessment models. Three modeling groups each independently developed a reference scenario, in which all climate policies were assumed to expire in 2012, and then developed four stabilization scenarios as departures from their respective reference scenarios. Idealized emissions-reduction measures – designed to achieve emissions reductions wherever, whenever, and using whichever GHG was most cost effective – were imposed to limit GHG emissions and meet the four radiative forcing stabilization levels. Evidence from previous literature suggests that if less idealized measures were employed to stabilize radiative forcing, the costs could be substantially higher. Further, this research considers only the costs of stabilization; it does not consider the benefits of potential climate change avoided or of possible ancillary benefits of emissions reduction, such as reduced air pollution.

The scenarios in this report are not predictions or best-judgment forecasts from the modeling groups. Rather, they constitute new research intended to advance understanding of the forces that lead to GHG emissions and that shape opportunities to stabilize GHG concentrations and radiative forcing. Although the future is uncertain and the scenarios are strongly dependent on many underlying assumptions, this research provides useful insights for those engaged in climate-related decision making.

### Highlights of the Report

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

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

***In the stabilization scenarios, GHG emissions reductions require a transformation of the global energy system, including reductions in the demand for energy (relative to the reference scenarios) and changes in the mix of energy technologies and fuels. This transformation is more substantial and takes place more quickly at the more stringent stabilization levels.*** Fossil fuel use and energy consumption are reduced in all the stabilization scenarios due to increased consumer prices for fossil fuels. Use of shale oil, tar sands, and synthetic fuels from coal are greatly reduced or, under the most stringent stabilization levels, eliminated. Across the stabilization scenarios, $CO_2$ emissions from electric power generation are reduced at relatively lower prices than $CO_2$ emissions from other sectors, such as transport, industry, and buildings. Emissions are reduced from electric power by increased use of technologies such as $CO_2$ capture and storage (CCS), nuclear energy, and renewable energy. Other sectors respond to rising greenhouse gas prices by reducing demands for fossil fuels; substituting low- or non-emitting energy sources such as bioenergy and low-carbon electricity or hydrogen; and applying CCS where possible.

***Substantial differences in GHG emissions prices and associated economic costs arise among the modeling groups for each stabilization level. These differences are illustrative of some of the unavoidable uncertainties in long-term scenarios.*** Among the most important factors influencing the variation in economic costs are: (1) differences in assumptions – such as those regarding economic growth over the century, the behavior of the oceans and terrestrial biosphere in taking up $CO_2$, and opportunities for reduction in non-$CO_2$ GHG emissions – that determine the amount that $CO_2$ emissions must be reduced to meet the radiative forcing stabilization levels; and (2) differences in assumptions about technologies, particularly in the second half of the century, to shift final demand to low-carbon sources such as biofuels and low-carbon electricity or hydrogen, in transportation, industrial, and buildings end uses. All other things being equal, scenarios with more low-cost technology options and lower required emissions reductions have lower economic costs.

## 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 includes Product 2.1, *Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations and Review of Integrated Scenario Development and Application,* which consists of two parts. This report presents the scenario development component (Product 2.1A); the review of scenario methods (Product 2.1B) is the subject of a separate report (CCSP 2007).

Guidelines for producing these scenarios were set forth in a Prospectus, 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 GHGs. The Prospectus also set forth criteria for the facilities to be used in the analysis. Scenarios developed using three models that meet the Prospectus conditions are reported here.

The scenarios in this report are intended as one of many inputs to public and private discussions regarding climate change and what to do about it, and they may serve as a point of departure for further CCSP and other analyses that might inform these discussions in the future. The possible users of these scenarios are many and diverse. They include climate modelers and the science community; those involved in national public policy formulation; managers of Federal research programs; state and local government officials who face decisions that might be affected by climate change and mitigation measures; and individual firms, non-governmental organizations, and members of the public. Such a varied clientele implies an equally diverse set of possible needs, and no single scenario exercise can hope to fully satisfy all of these needs.

Each of the three modeling groups participating in this research first developed a no-climate policy scenario – referred to as a reference scenario – which serves as baseline for development of alternative scenarios with emissions control. Each modeling group then developed four control scenarios leading to stabilization of radiative forcing at four alternative levels. The resulting scenarios provide insight into questions such as the following:

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

Although each of the models used to develop these scenarios represents the world as a set of interconnected nations and multi-nation regions, as specified in the Prospectus, this report focuses on the U.S. and world characteristics of the scenarios.

With the exception of the stabilization levels themselves and a common hypothesis about international burden sharing, there was no direct coordination among the modeling groups either in the assumptions underlying the reference scenario 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. Although the future is uncertain and the scenarios depend on many underlying assumptions, this research illuminates a range of possible future developments and provides useful insights for those engaged in climate-related decision making.

The scenarios in this report do not constitute a cost-benefit analysis of climate policy. They focus exclusively on the issues associated with reducing emissions to meet various stabilization levels; they do not consider the damages avoided through stabilization or ancillary benefits that could be realized by emissions reductions, such as reductions in local air pollution. Thus, although the scenarios should serve as a useful input to climate-related decision making, they address only one of several components of a benefit-cost analysis of climate policy.

Scenario research such as this continues a tradition of research and analysis that has gone on for over 20 years. This work will be continued and refined as the field advances, new information becomes available, and decision makers raise new questions and issues. Similar work is conducted by modeling groups in Europe and Asia. The 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.

## MODELS USED TO DEVELOP THE SCENARIOS

The Prospectus for this research 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 cen-

tury. In addition, modeling groups 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 Model for Evaluating the Regional and Global Effects (MERGE) of GHG reduction policies developed jointly at Stanford University and the Electric Power Research Institute.
- The MiniCAM Model of the Joint Global Change Research Institute, a partnership between the Pacific Northwest National Laboratory and the University of Maryland.

Each 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. Research using each has appeared widely in peer-reviewed publications.

## APPROACH

As directed by the Prospectus, each of the three modeling groups produced one reference scenario and four stabilization scenarios, for a total of 15 scenarios. First, the reference scenarios were developed under 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 goal, each terminating in 2012 because goals beyond that date have not been identified). Each modeling group developed its own reference scenario. The Prospectus required only that each reference scenario be based on assumptions believed by the participating modeling groups to be *meaningful* and *plausible*. Each of the three reference scenarios is based on a different set of assumptions about how the future might unfold without additional climate policies. These assumptions are not intended as predictions or best-judgment forecasts of the future by the respective modeling groups. Rather, they represent possible paths that the future might follow to serve as a platform for examining how emissions might be reduced to achieve stabilization.

Each group then produced four stabilization scenarios by constraining the models to achieve four alternative radiative forcing levels. Stabilization was defined in terms of the total long-term radiative impact of a suite of GHGs including $CO_2$, $N_2O$, $CH_4$, HFCs, PFCs, and $SF_6$. These are the gases enumerated in the U.S. goal to reduce the intensity of GHG emissions relative to gross domestic product (GDP) as well as the Kyoto Protocol. Other substances with radiative impact, such as gases controlled under the Montreal Protocol, carbon monoxide (CO), ozone ($O_3$), and aerosols were not included in the radiative forcing levels.

The four radiative forcing stabilization scenarios were developed so that the combined radiative forcing from these GHGs since preindustrial times 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. Because radiative forcing was defined relative to preindustrial times, it includes the

**Table TS.1. Greenhouse Gas Concentrations and Forcing.** Concentrations of GHGs have increased since 1750 (preindustrial), altering the radiative energy budget of the Earth's climate system.

| | Preindustrial Concentration (1750) | Current Concentration (1998) | Contribution to Radiative Forcing, (W/m$^2$, 1750 to 1998) |
|---|---|---|---|
| $CO_2$ | 278 ppmv | 365 ppmv | 1.46 |
| CH4 | 700 ppbv | 1745 ppbv | 0.48 |
| $N_2O$ | 270 ppbv | 314 ppbv | 0.15 |
| HFCs, PFCs, $SF_6$ | 0 | various | ≈ 0.02 |
| Total | — | — | ≈ 2.1 |

*Source: IPCC 2001.*

|  | Total Radiative Forcing from GHGs in this Research (W/m$^2$) | Approximate Contribution to Radiative Forcing from non-$CO_2$ GHGs (W/m$^2$) | Approximate Contribution to Radiative Forcing from $CO_2$ (W/m$^2$) | Corresponding $CO_2$ Concentration (ppmv) |
|---|---|---|---|---|
| Level 1 | 3.4 | 0.8 | 2.6 | 450 |
| Level 2 | 4.7 | 1.0 | 3.7 | 550 |
| Level 3 | 5.8 | 1.3 | 4.5 | 650 |
| Level 4 | 6.7 | 1.4 | 5.3 | 750 |
| Year 1998 | ≈ 2.1 | 0.65 | 1.46 | 365 |
| Preindustrial (1750) | — | — | — | 278 |

**Table TS.2. Radiative Forcing Stabilization Levels (W/m$^2$ from preindustrial) and Approximate Resulting $CO_2$ Concentrations (ppmv).** The radiative forcing 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.

roughly 2.1 W/m$^2$ of radiative forcing from these substances that had already occurred from 1750 to 1998 (Table TS.1).

These radiative forcing stabilization levels were chosen so that the associated $CO_2$ concentrations would be roughly 450 ppmv, 550 ppmv, 650 ppmv, and 750 ppmv after accounting for the contributions to radiative forcing from the non-$CO_2$ GHGs (Table TS.2). If these $CO_2$ concentrations were achieved exactly, the radiative forcing from $CO_2$ would be less than the radiative forcing stabilization levels because of the allowance for additional forcing from the non-$CO_2$ GHGs. Thus, the radiative forcing stabilization levels should not be interpreted as the "$CO_2$–equivalent" levels associated with the approximate $CO_2$ concentrations in Table TS.2. Because the stabilization exercises sought least-cost reductions among the gases, any correspondence between radiative forcing levels and $CO_2$ concentrations is necessarily approximate and differs among modeling groups because of differences in the treatment of the forces that influence emissions of GHGs, possibilities for emissions reductions, and tradeoffs between reductions among GHGs.

## OVERVIEW OF THE SCENARIOS

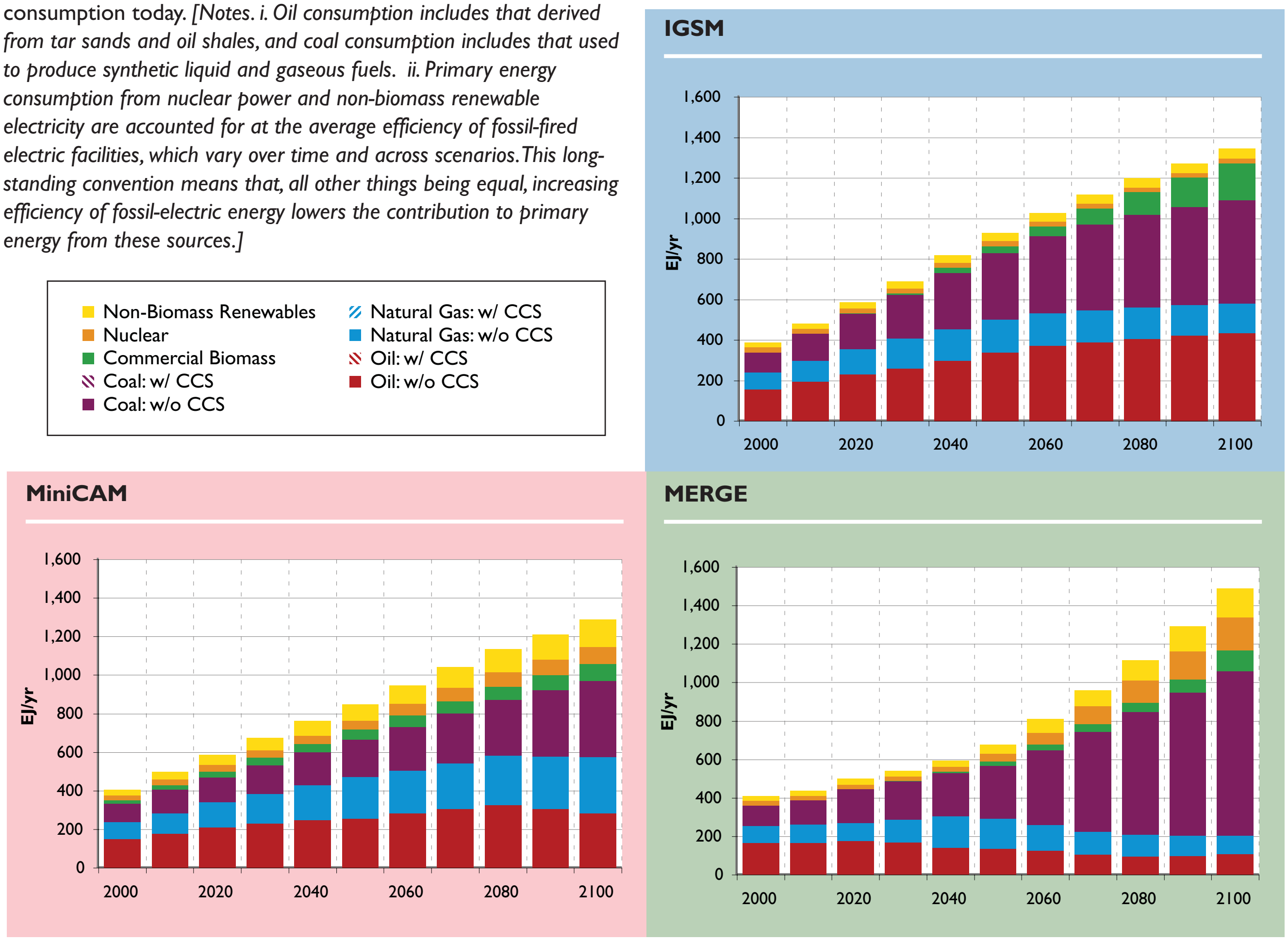
This section provides an overview of the scenarios. The three reference scenarios are discussed in the next section, followed by a discussion of the twelve stabilization scenarios, four from each modeling group.

### Reference Scenarios

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

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

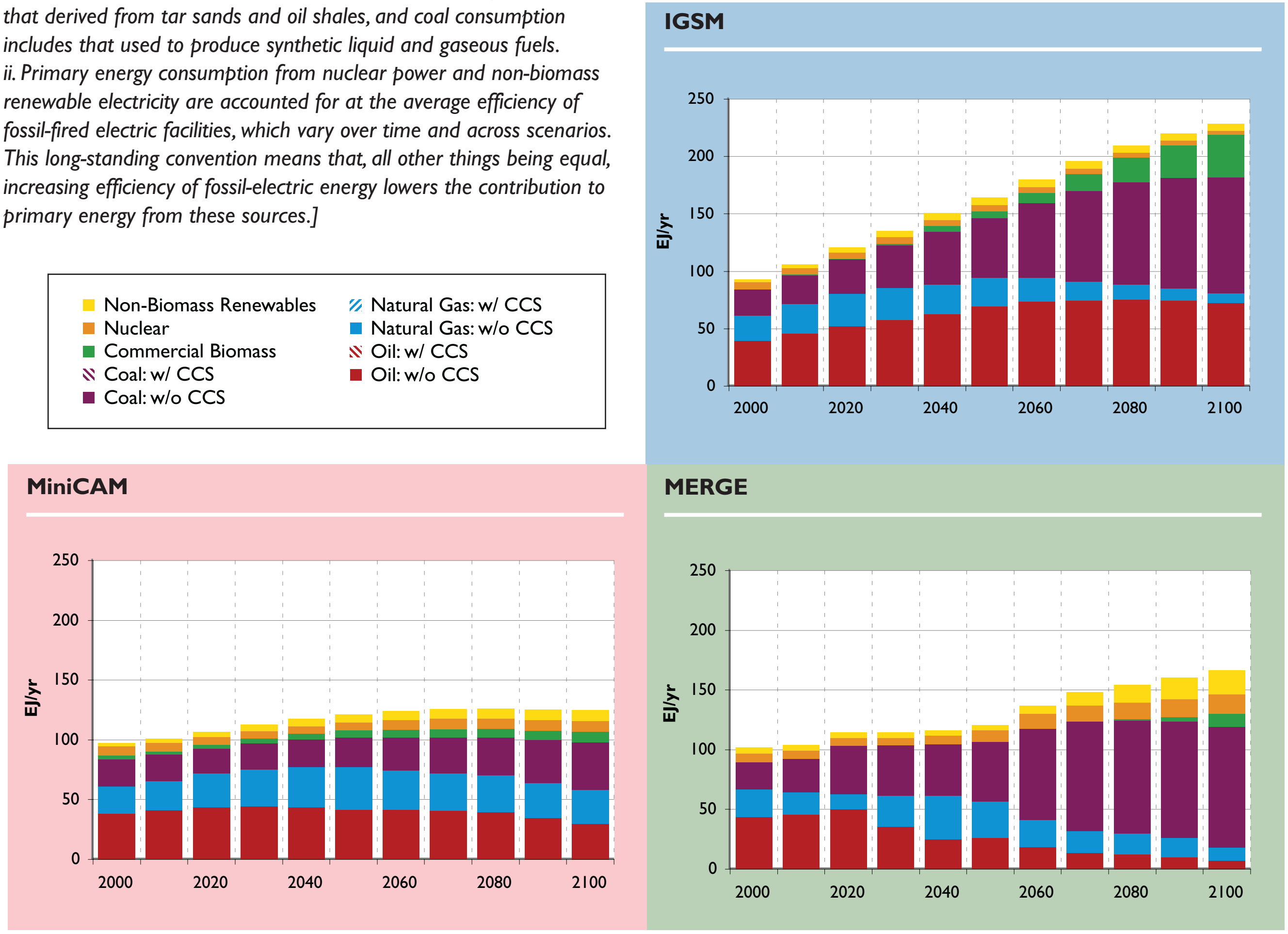
**Figure TS.1. Global Primary Energy Consumption Across Reference Scenarios (EJ/yr).** Global primary energy consumption rises in all three reference scenarios, from about 400 EJ/yr in 2000 to between roughly 1275 EJ/yr and 1500 EJ/yr in 2100. Dependence on conventional oil resources gradually decreases. However, a range of alternative fossil-based resources, such as synthetic fuels from coal and unconventional oil resources (e.g., tar sands and oil shales) are available and become economically viable. Fossil fuels provided almost 90% of global primary energy consumption 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 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/yr to 450 EJ/yr – an amount equaling roughly one-half to a little over global primary energy consumption today. *[Notes. i. Oil consumption includes that derived from tar sands and oil shales, and coal consumption includes that used to produce synthetic liquid and gaseous fuels. ii. Primary energy consumption from nuclear power and non-biomass renewable electricity are accounted for at the average efficiency of fossil-fired electric facilities, which vary over time and across scenarios. This long-standing convention means that, all other things being equal, increasing efficiency of fossil-electric energy lowers the contribution to primary energy from these sources.]*



The three reference scenarios show the implications of this increasing demand and the improved access to energy, with the ranges reflecting the variation among the scenarios from the three modeling groups. Global primary energy consumption rises substantially in all three reference scenarios, from about 400 EJ/yr in 2000 to between roughly 1275 EJ/yr and 1500 EJ/yr in 2100 (Figure TS.1). U.S. primary energy consumption also grows substantially, about 1¼ to 2½ times present levels by 2100 (Figure TS.2). Primary energy growth occurs despite continued improvements in the efficiency of energy use and energy production technologies. For example, the U.S. energy intensity – the ratio of primary energy consumption to economic output – declines 60% to 75% between 2000 and 2100 across the three reference scenarios.

All three reference scenarios include an eventual reduction in the consumption of conventional oil resources. However, in all three, a range of alternative fossil-based resources, such as synthetic fuels from coal and unconventional oil resources (e.g., tar sands and oil shales), are available and become economically viable. Fossil fuels provided almost 90% of global primary energy 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.

**Figure TS.2. U.S. Primary Energy Consumption Across Reference Scenarios (EJ/yr).** U.S. primary energy consumption rises in all three reference scenarios, to roughly 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 in the reference scenarios. *[Notes. i. Oil consumption includes that derived from tar sands and oil shales, and coal consumption includes that used to produce synthetic liquid and gaseous fuels. ii. Primary energy consumption from nuclear power and non-biomass renewable electricity are accounted for at the average efficiency of fossil-fired electric facilities, which vary over time and across scenarios. This long-standing convention means that, all other things being equal, increasing efficiency of fossil-electric energy lowers the contribution to primary energy from these sources.]*



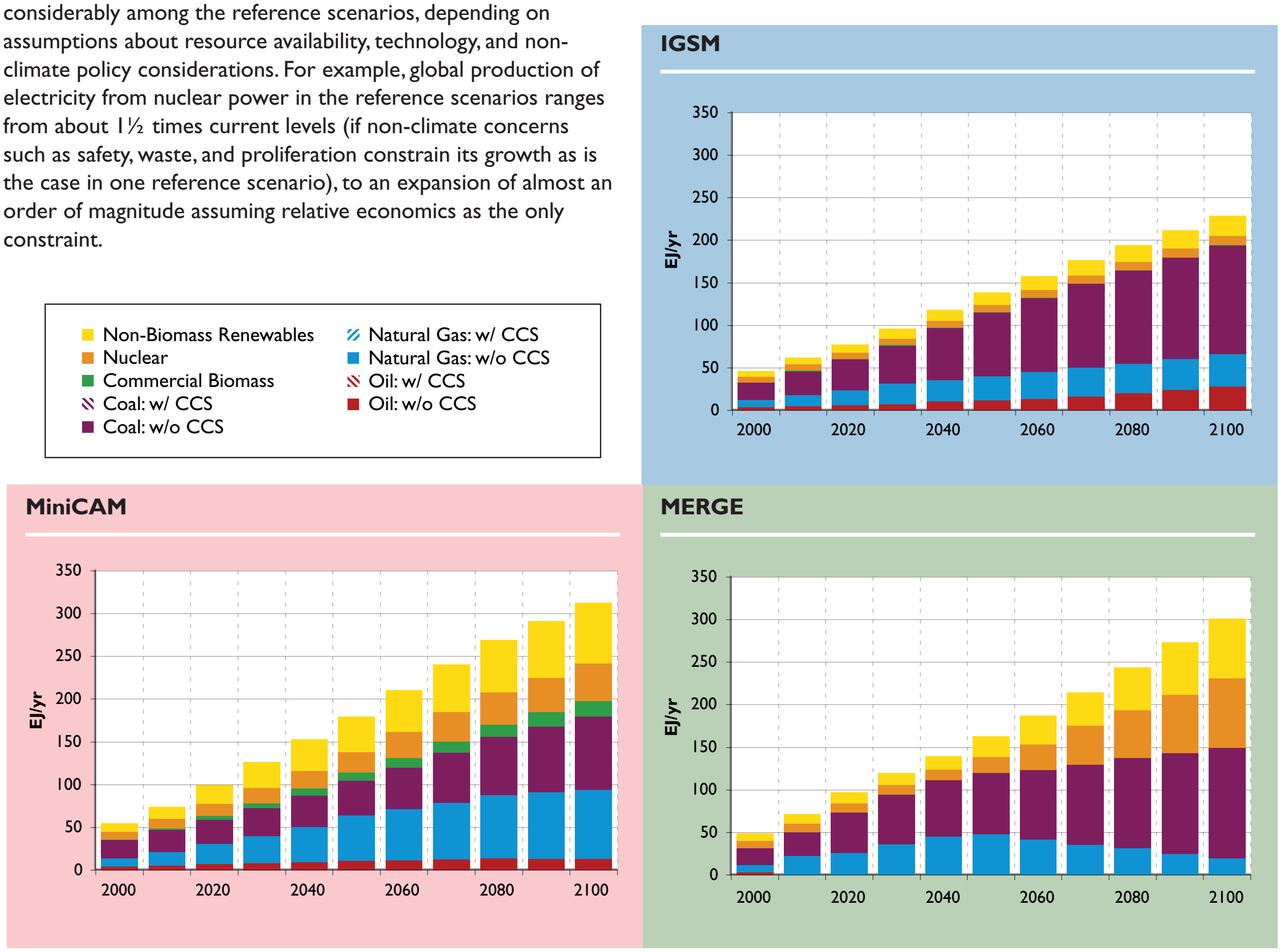
However, non-fossil fuel energy use also grows over the century in all three reference scenarios. Contributions to primary energy consumption in 2100 range from 250 EJ to 450 EJ – an amount equaling roughly ½ times to a little over global primary energy consumption today. Despite this growth, these sources never supplant fossil fuels, although they provide an increasing share of the total, particularly in the second half of the century.

Consistent with the characteristics of primary energy consumption, global and U.S. electricity production continues to rely on coal, although the contribution of coal varies among the reference scenarios (Figure TS.3 and Figure TS.4). The contribution of renewable and nuclear energy varies considerably in the different reference scenarios, depending on resource availability, technology, and non-climate policy considerations. For example, global nuclear generation in the reference scenarios ranges from about 1½ times current levels (if non-climate concerns such as safety, waste, and proliferation constrain its growth as is the case in one reference scenario), to an expansion of almost an order of magnitude assuming relative economics as the only constraint.

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

As a combined result of all these influences, $CO_2$ emissions from fossil fuel combustion and

**Figure TS.3. Global Electricity Production Across Reference Scenarios (EJ/yr).** Global electricity production grows to over four times production levels 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 renewable energy and nuclear power varies considerably among the reference scenarios, depending on assumptions about resource availability, technology, and non-climate policy considerations. For example, global production of electricity from nuclear power in the reference scenarios ranges from about 1½ times current levels (if non-climate concerns such as safety, waste, and proliferation constrain its growth as is the case in one reference scenario), to an expansion of almost an order of magnitude assuming relative economics as the only constraint.



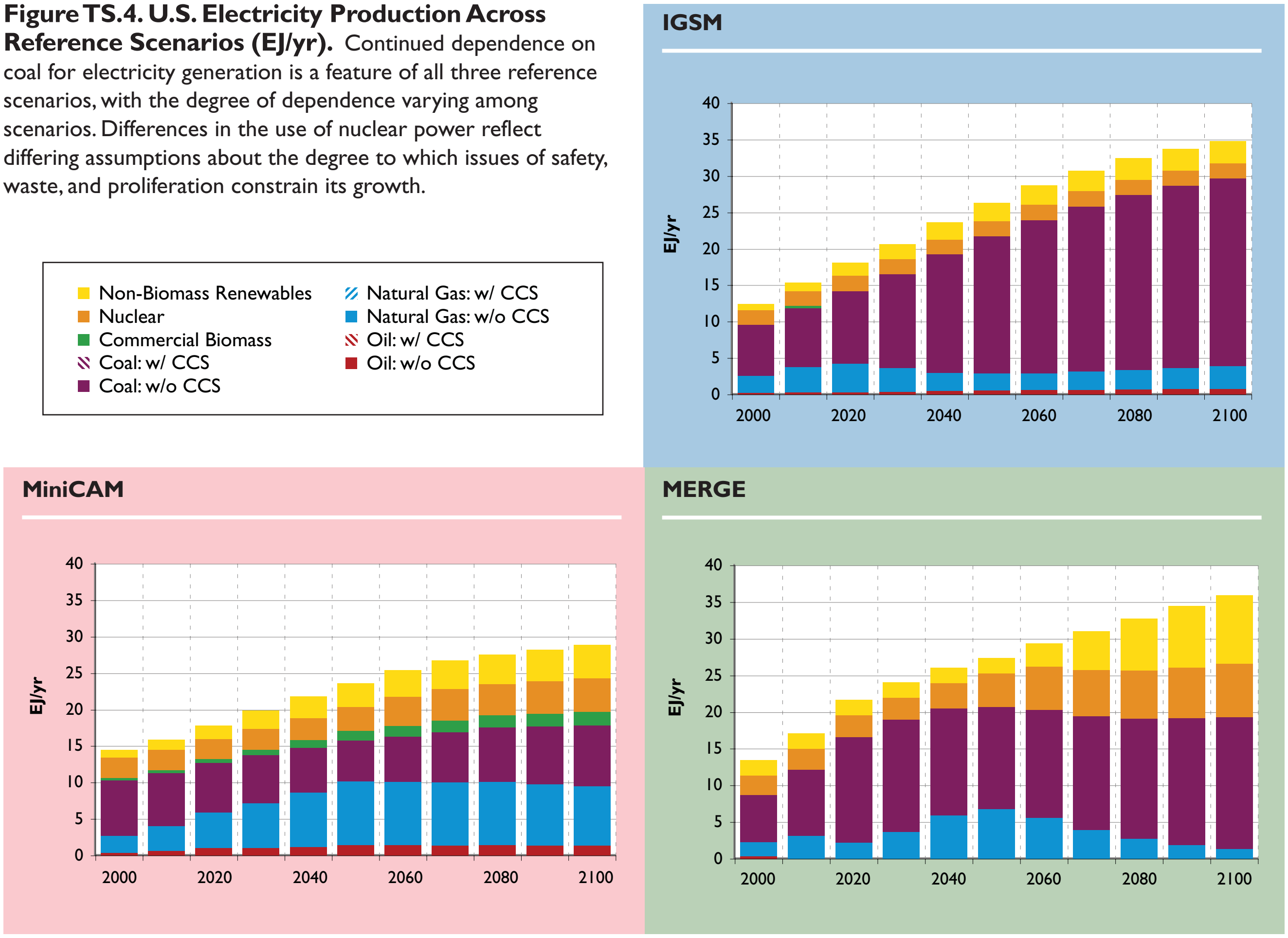
industrial processes in the reference scenarios increase from approximately 7 gigatonne carbon per year (GtC/yr) in 2000 to between 22.5 GtC/yr and 24.0 GtC/yr in 2100; that is, roughly 3 to 3½ times current levels (Figure TS.5). (Note that one tonne C is equivalent to 3.67 tonnes $CO_2$. See Box 3.2 for more on converting between units of carbon and units of $CO_2$.)

It is instructive to see how emissions are divided between industrialized countries (Annex 1) and developing countries (Non-Annex 1). Developing country emissions overtake those of developed countries in the 2020 to 2030 timeframe in the reference scenarios (Figure TS.6). 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 would still be necessary for stabilization.

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

Two of the three participating models include sub-models of the exchange of $CO_2$ with the terrestrial biosphere, including the net uptake by plants and soils and the emissions from deforestation. In the reference scenarios from these

**Figure TS.4. U.S. Electricity Production Across Reference Scenarios (EJ/yr).** Continued dependence on coal for electricity generation is a feature of all three reference scenarios, with the degree of dependence varying among scenarios. Differences in the use of nuclear power reflect differing assumptions about the degree to which issues of safety, waste, and proliferation constrain its growth.



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

Although this Technical Summary focuses on the most important anthropogenic GHG, $CO_2$, the scenarios considered a number of other GHGs ($CH_4$ , $N_2O$ $SF_6$, 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 differing assumptions about technological opportunities and about whether current emissions rates will be reduced significantly for non-climate reasons, such as air pollution control and/or higher natural gas prices that would further stimulate the capture of $CH_4$ emissions for its fuel value.

Increases in emissions from the global energy system and other human activities lead to higher atmospheric GHG concentrations and radiative forcing. These increases are 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 ppmv to 900 ppmv, up from 365 ppmv in 1998. $CH_4$ concentrations in 2100 range from 2000 ppbv to 4000 ppbv, up from 1745 ppbv in 1998, and $N_2O$ concentrations in 2100 range from about 375 ppbv to 500 ppbv, up from 314 ppbv in 1998.

As a result, radiative forcing in 2100 ranges from 6.4 W/m$^2$ to 8.6 W/m$^2$ from preindustrial, up from a little over 2 W/m$^2$ today. The non-$CO_2$

**Figure TS.5. Global Emissions of $CO_2$ from Fossil Fuels and Industrial Sources [$CO_2$ from land-use change excluded] Across Reference Scenarios (GtC/yr).** 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 24.0 GtC/yr.

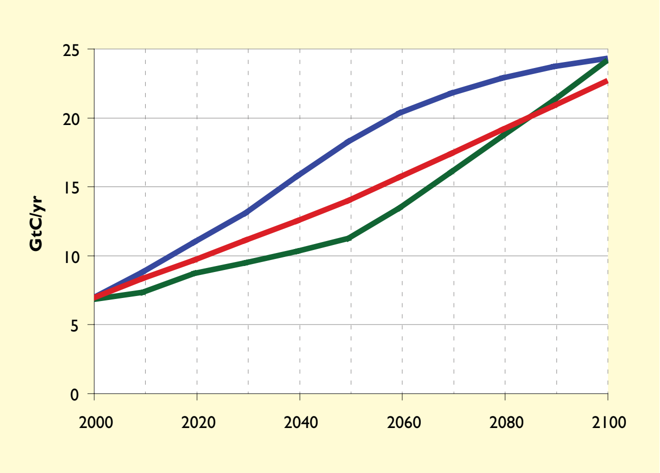
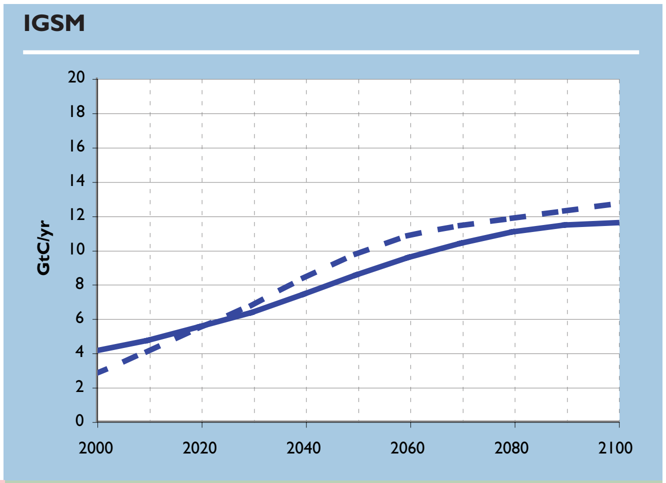


**Figure TS.6. Global Emissions of Fossil Fuel and Industrial $CO_2$ by Annex I and Non-Annex I Countries Across Reference Scenarios (GtC/yr).** Emissions of fossil fuel and industrial $CO_2$ from the Non-Annex I countries exceed those from the Annex I countries in all three reference scenarios by 2030 or earlier. Non-Annex I emissions continue to grow rapidly in two of the reference scenarios, such that their emissions are on the order of twice the level of Annex I by 2100. Emissions do not continue to diverge in the third reference scenario, due in part to relatively slower economic growth in Non-Annex I regions, faster growth in Annex I, and increased emissions in Annex I as they become producers and exporters of shale oil, tar sands, and synthetic fuels from coal.



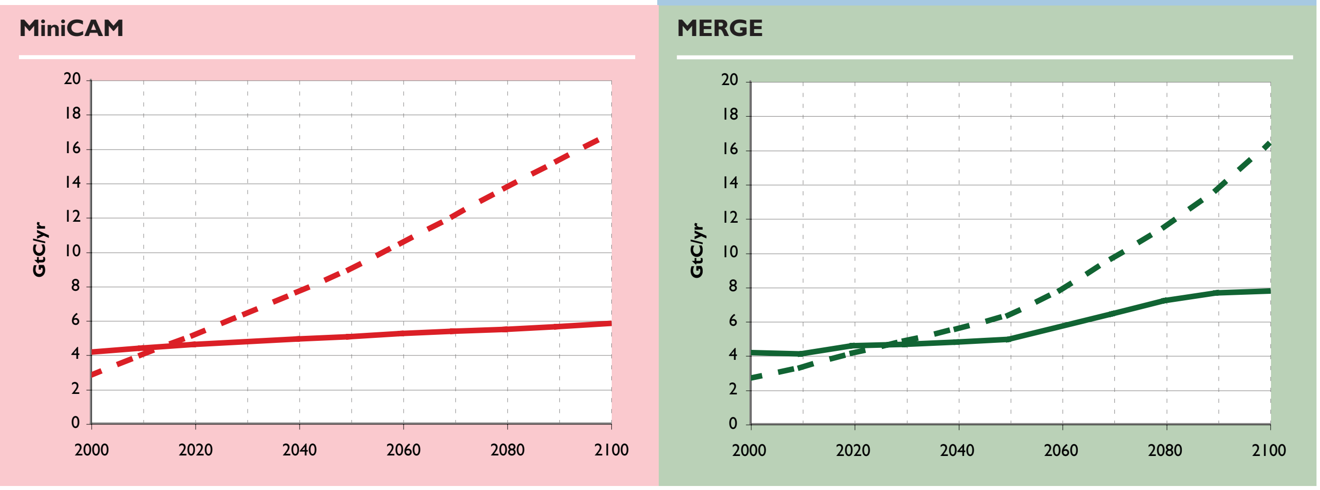


**Figure TS.7. Radiative Forcing by Gas Across Reference Scenarios (W/m$^2$ from preindustrial).** $CO_2$ accounts for 75% to 80% of the radiative forcing in 2100 in the three reference scenarios. Total radiative forcing in 2100 from all the GHGs considered in this research ranges from about 6.4 W/m$^2$ to 8.6 W/m$^2$.

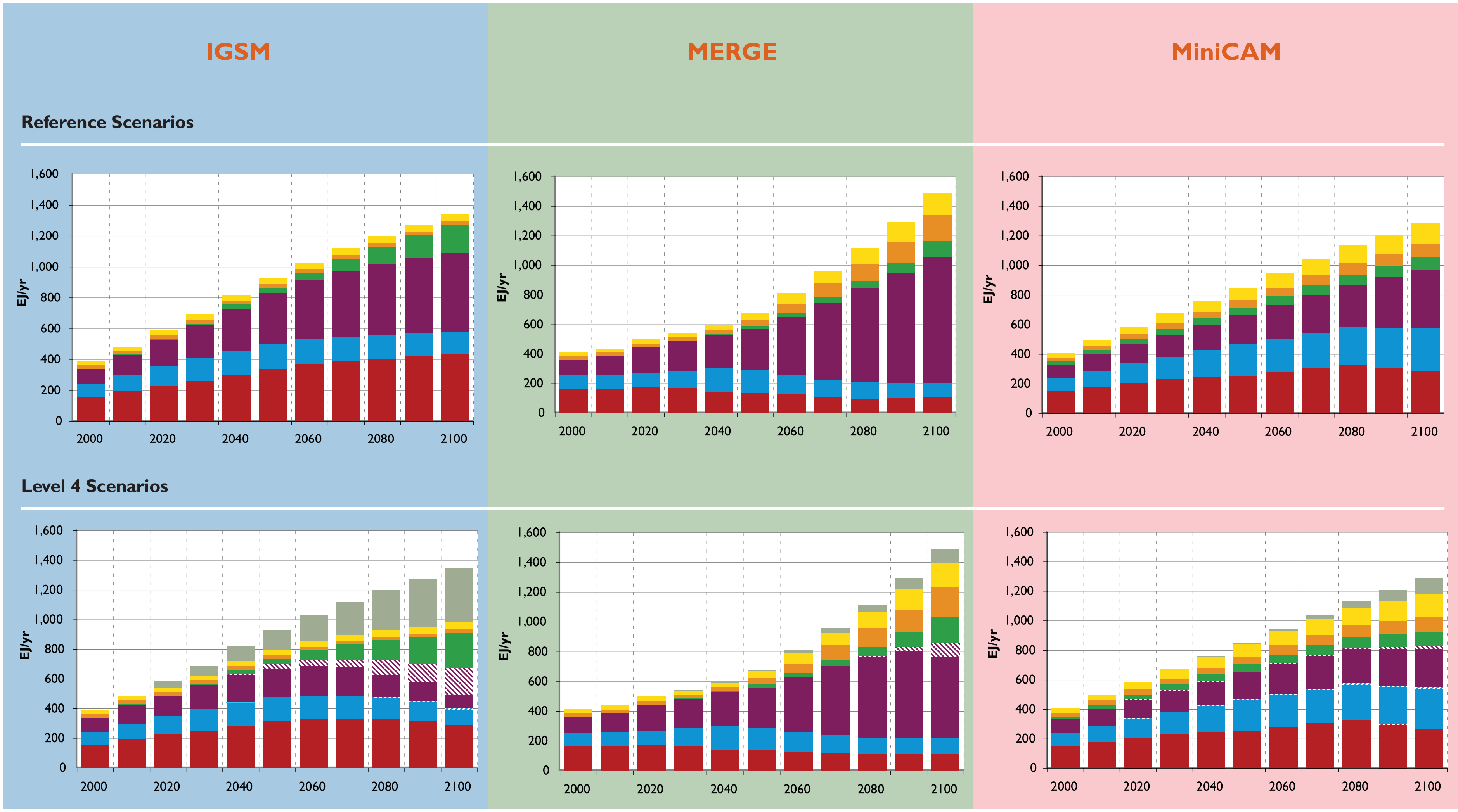
GHGs account for about 20% to 25% of radiative forcing by the end of the century (Figure TS.7).

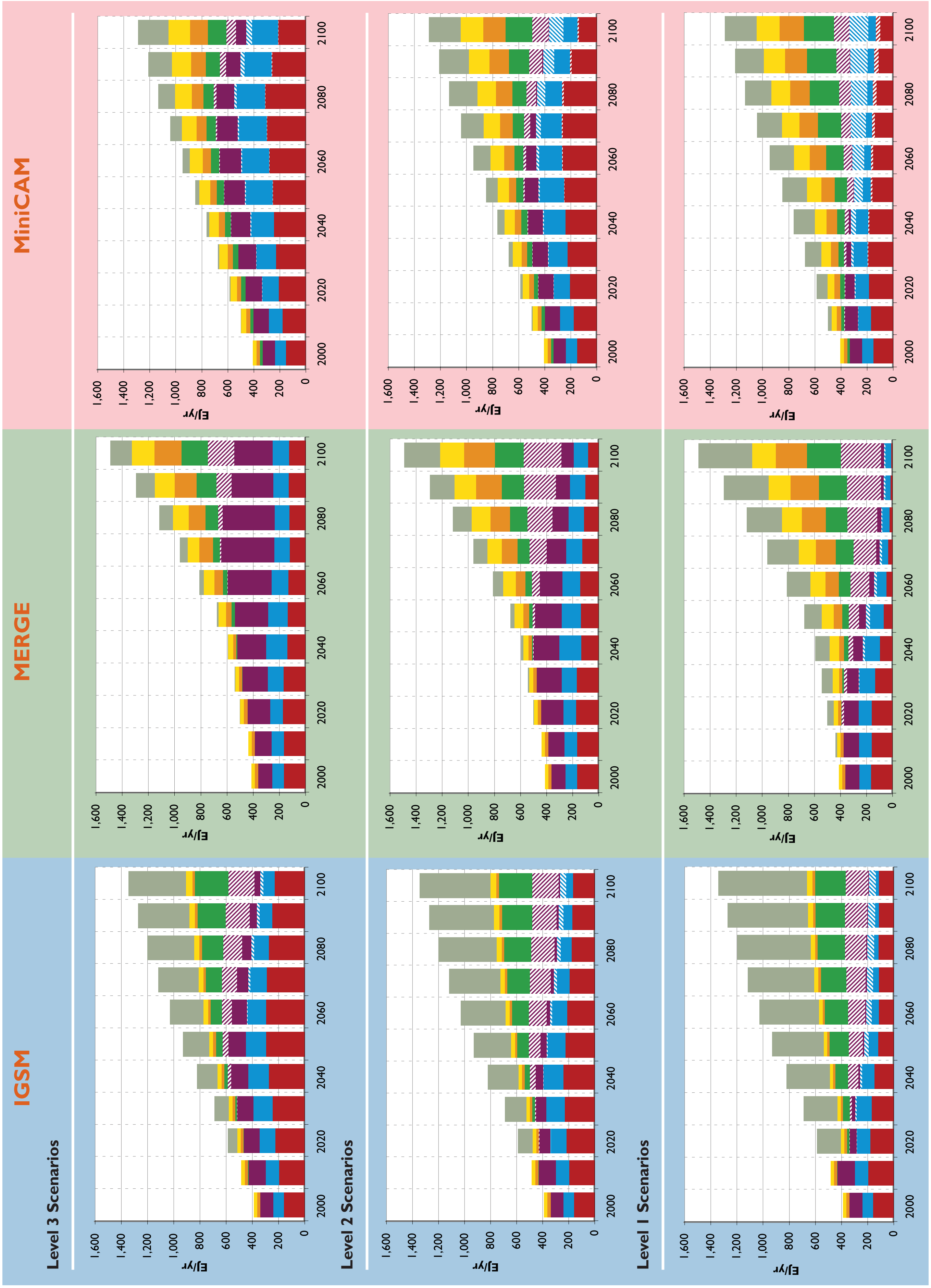
## Stabilization Scenarios

Important assumptions underlying the stabilization scenarios include the flexibility that exists in a policy design, as represented by the modeling groups, to seek out least cost options for emissions control regardless of where they occur, what substances are controlled, or when they occur. This set of conditions is referred to as *where*, *what*, and *when* flexibility. Equal marginal costs of abatement among regions, across time (taking into account discount rates and the lifetimes of substances), and among substances (taking into account their relative warming potential and different lifetimes) will, under specified conditions, lead to least-cost abatement. Each modeling group applied an economic instrument that priced GHGs in a manner consistent with the group's interpretation of *where*, *what* and *when* flexibility. The economic characteristics of the scenarios therefore 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 based on each modeling group's interpretation of *when* flexibility, with the effect of linking emissions mitigation efforts over the time horizon of the scenarios; and (3) stabilization of radiative forcing is achieved by combining control of all GHGs, with differences in how modeling groups compared them (*what* flexibility).

Although these assumptions are convenient for analytical purposes, to gain an impression of the implications of stabilization, they are idealized versions of possible outcomes. For the abatement costs in these scenarios to be representative of actual abatement costs would require, among other things, that a negotiated international agreement include these flexibility mechanisms. Failure in that regard could have a

**Figure TS.8. Global Primary Energy Consumption by Fuel Across Scenarios (EJ/yr).** The global energy system undergoes a significant transformation in the stabilization scenarios from all three modeling groups. This transformation begins earlier the more stringent the radiative forcing stabilization level, and would continue into the next century for all stabilization levels. The transformation includes: reduction in energy use, increased use of carbon-free sources of energy such as biomass, other renewables, and nuclear power; and the addition of CCS. The contribution of each of these varies among the models reflecting different assumptions about cost and performance, policy, and resource limits. *[Notes. i. Oil consumption includes that derived from tar sands and oil shales, and coal consumption includes that used to produce synthetic liquid and gaseous fuels. ii. Primary energy consumption from nuclear power and non-biomass renewable electricity are accounted for at the average efficiency of fossil-fired electric facilities, which vary over time and across scenarios. This long-standing convention means that, all other things being equal, increasing efficiency of fossil-electric energy lowers the contribution to primary energy from these sources.]*




IGSM
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Level 3 Scenarios
Level 2 Scenarios
Level 1 Scenarios
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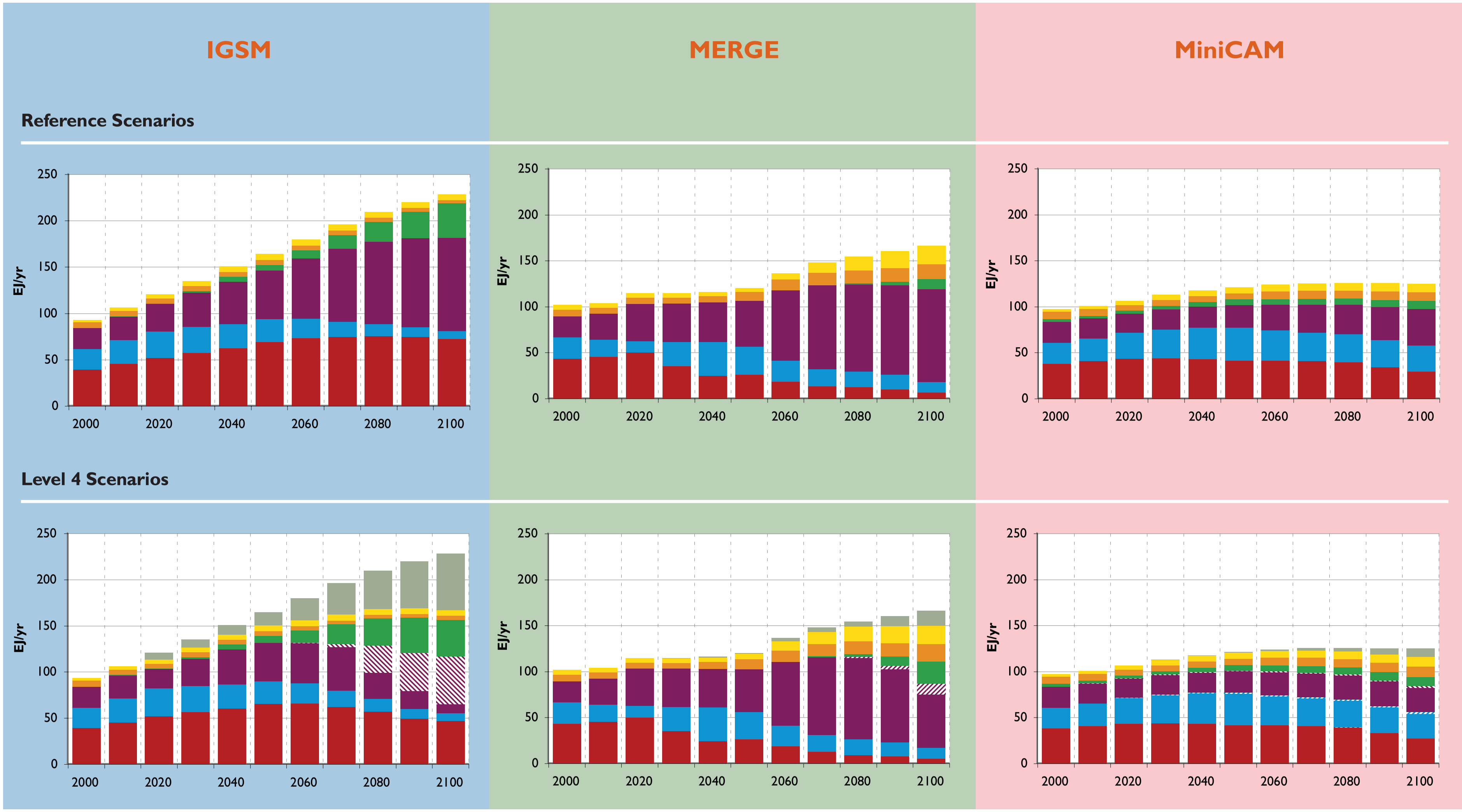
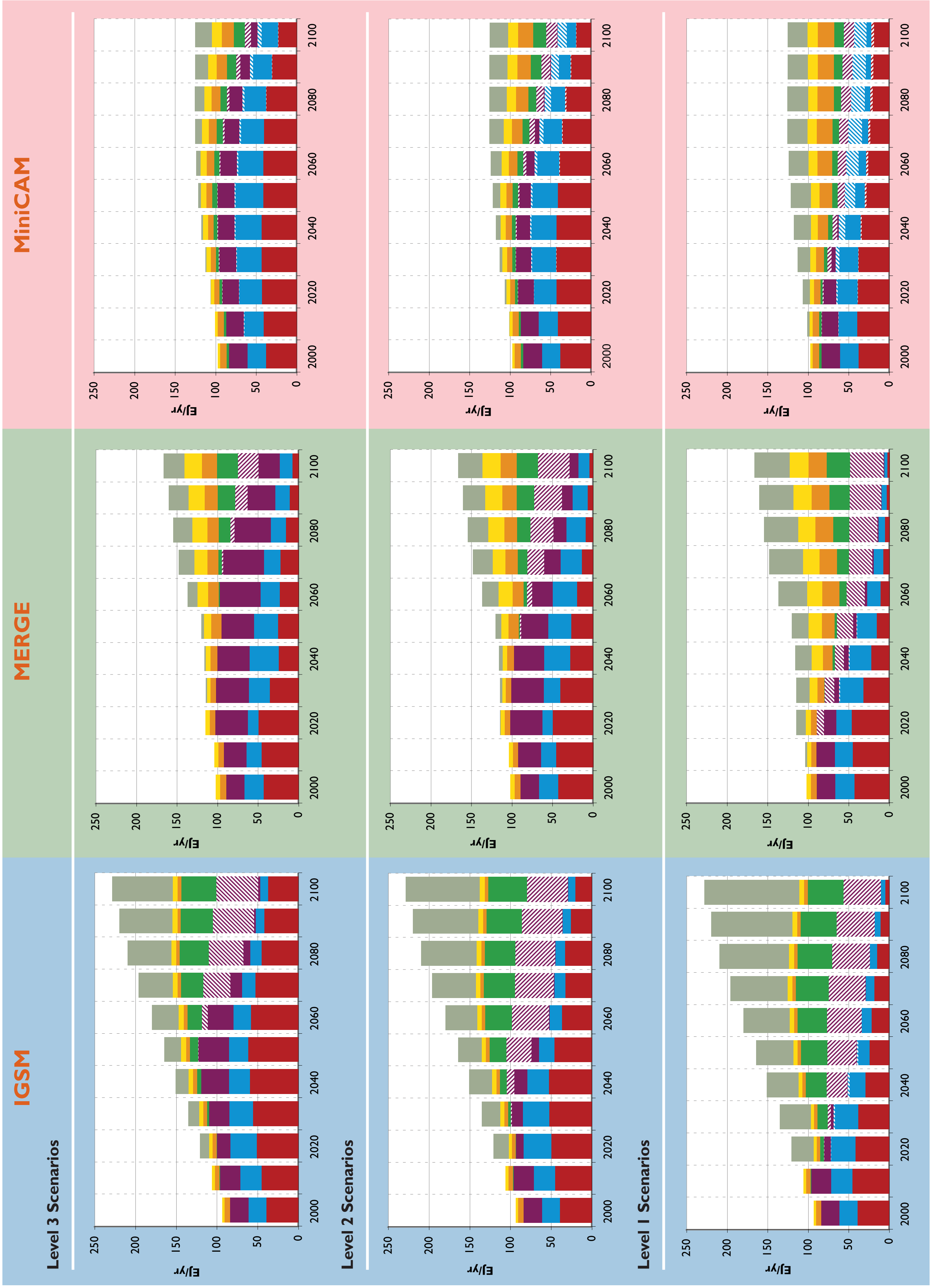
**Figure TS.9. U.S. Primary Energy Consumption by Fuel Across Scenarios (EJ/yr).** The U.S. energy system undergoes a significant transformation in the stabilization scenarios similar to the transformation in the global energy system. One difference, not obvious in this figure, is the transformation 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. The third (MiniCAM) includes an intermediate mix of both. *[Notes. i. Oil consumption includes that derived from tar sands and oil shales, and coal consumption includes that used to produce synthetic liquid and gaseous fuels. ii. Primary energy consumption from nuclear power and non-biomass renewable electricity are accounted for at the average efficiency of fossil-fired electric facilities, which vary over time and across scenarios. This long-standing convention means that, all other things being equal, increasing efficiency of fossil-electric energy lowers the contribution to primary energy from these sources.]*




IGSM
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Level 3 Scenarios
Level 2 Scenarios
Level 1 Scenarios
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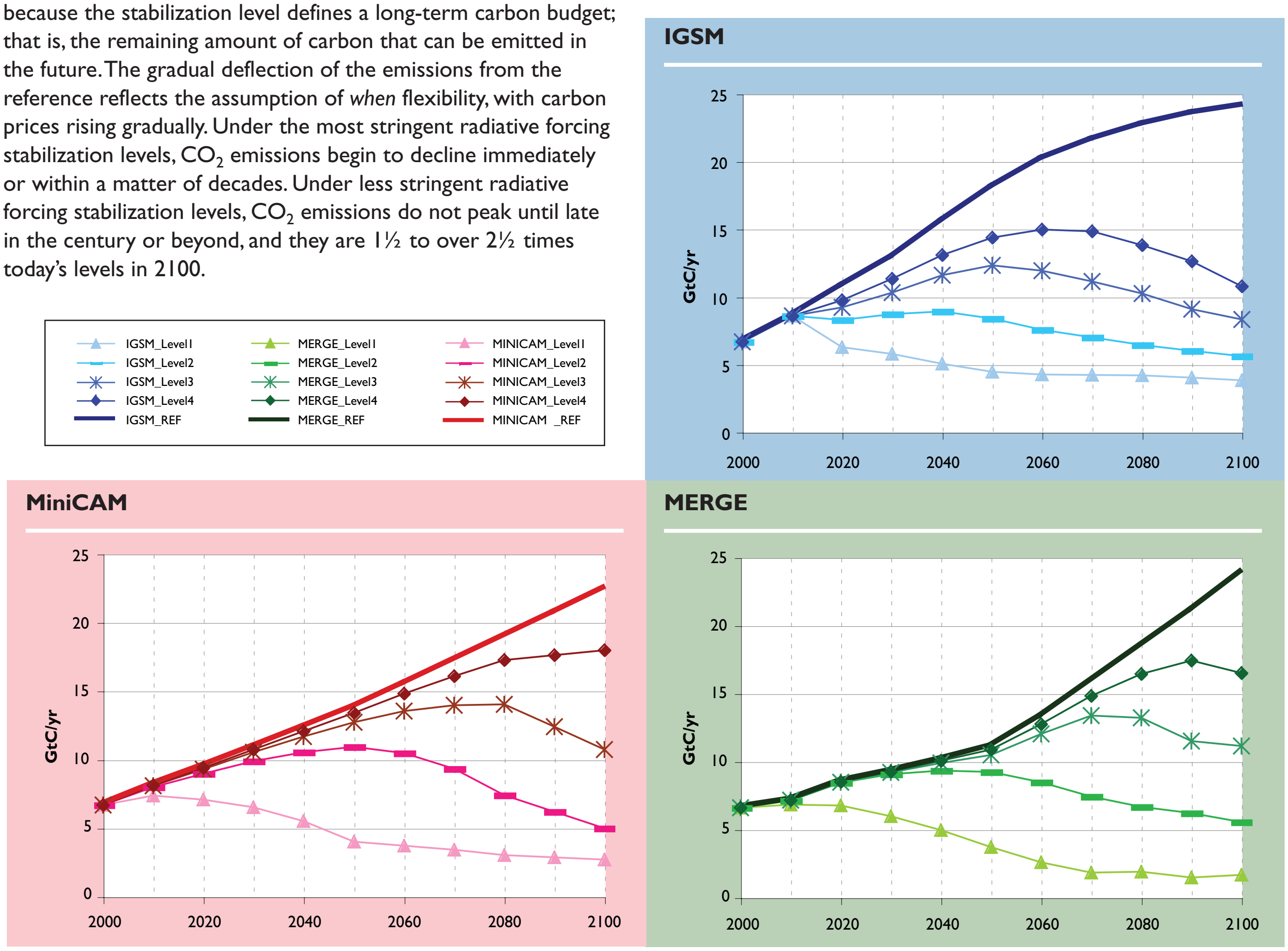
**Figure TS.10 Global Emissions of $CO_2$ from Fossil and other Industrial Sources Across Scenarios (GtC/yr).** The tighter the constraint on radiative forcing, the faster carbon emissions must decline from those in the reference scenarios. This is because the stabilization level defines a long-term 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. Under the most stringent radiative forcing stabilization levels, $CO_2$ emissions begin to decline immediately or within a matter of decades. Under less stringent radiative forcing stabilization levels, $CO_2$ emissions do not peak until late in the century or beyond, and they are 1½ to over 2½ times today's levels in 2100.



substantial effect on the difficulty of achieving any of the stabilization levels considered in this research. For example, a delay in the participation of some large countries would require greater effort by the others, and policies that impose differential burdens on different sectors without mechanisms to allow for equalizing marginal costs across sectors can result in a many-fold increase in the cost of any environmental gain. Therefore, *it is important to view these result as scenarios under specified conditions, not as predictions or best-judgment forecasts of the most likely outcome within the national and international political system.* Further, none of the scenarios considered the extent to which variation from these least-cost rules might be improved upon given interactions with existing taxes, technology spillovers, or other non-market externalities.

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

Stabilization of radiative forcing at the levels examined in this research would require a substantially different energy system globally, and in the U.S., than what emerges in the reference scenarios. The degree and timing of change in the global energy system depends on the level at which radiative forcing is stabilized (Figure TS.8 and Figure TS.9). The lower the radiative forcing stabilization level, the larger the scale of change in the global energy system relative to the reference scenario required over the coming century and the sooner those changes would need to occur.

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

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

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

Increased use is made of biomass energy crops in all the stabilization scenarios, the contribution of which is ultimately limited by competition with agriculture and forestry. One modeling group examined the importance of valuing terrestrial carbon similarly to the way fossil fuel carbon is valued in stabilization scenarios. It was found that 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 carbon in terrestrial systems.

Across the stabilization scenarios, the scale of the emissions reductions required relative to the reference scenario increases over time, with the bulk of emissions reductions taking place in the second half of the century. But emissions reductions occur in the first half of the century in every stabilization scenario (Figure TS.10).

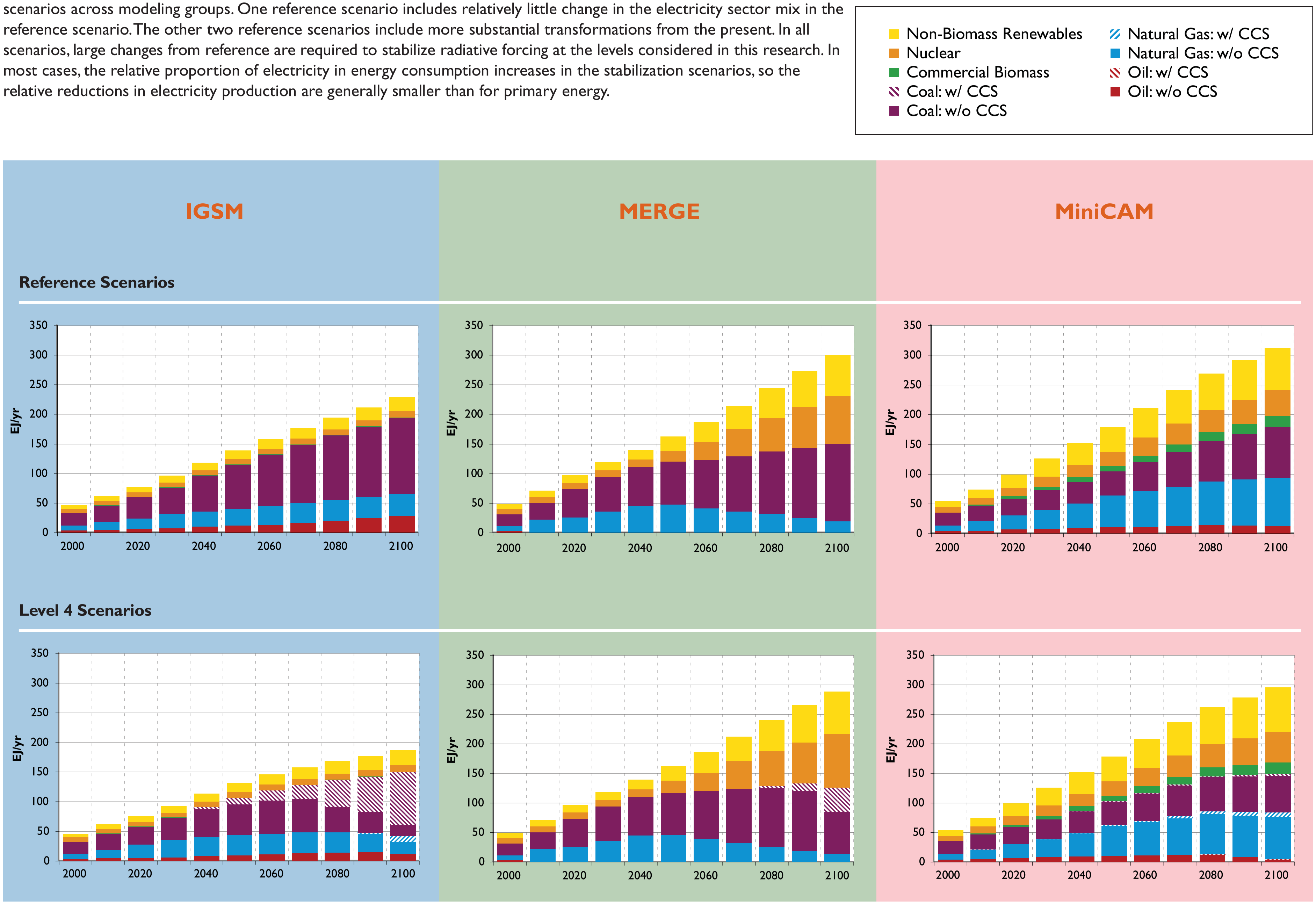
The 2100 time horizon of this research limited examination of the ultimate stabilization requirements. Further reductions in $CO_2$ emissions after 2100 would be required in all of the stabilization scenarios, because stabilization of radiative forcing at any of the levels considered in this research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

Fuel sources and electricity generation technologies change substantially, both globally and in the U.S., in the stabilization scenarios compared to the reference scenarios. There are a variety of technological options in the electricity sector that reduce carbon emissions in these scenarios (Figure TS.11 and Figure TS.12).

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

The economic effects of stabilization are substantial in many of the stabilization scenarios, although much of this cost is borne later in the century. As noted earlier, each of the modeling groups assumed that a global policy was implemented after 2012, with universal participation by the world's nations, and that the time path of reductions approximated a least-cost solution.

**Figure TS.11. Global Electricity Production by Fuel Across Scenarios (EJ/yr).** Various electricity technology options could be competitive in the future, and different assumptions regarding their relative economic viability, reliability, and resource availability lead to considerably different scenarios of the global electricity sector in reference and stabilization scenarios across modeling groups. One reference scenario includes relatively little change in the electricity sector mix in the reference scenario. The other two reference scenarios include more substantial transformations from the present. In all scenarios, large changes from reference are required to stabilize radiative forcing at the levels considered in this research. In most cases, the relative proportion of electricity in energy consumption increases in the stabilization scenarios, so the relative reductions in electricity production are generally smaller than for primary energy.



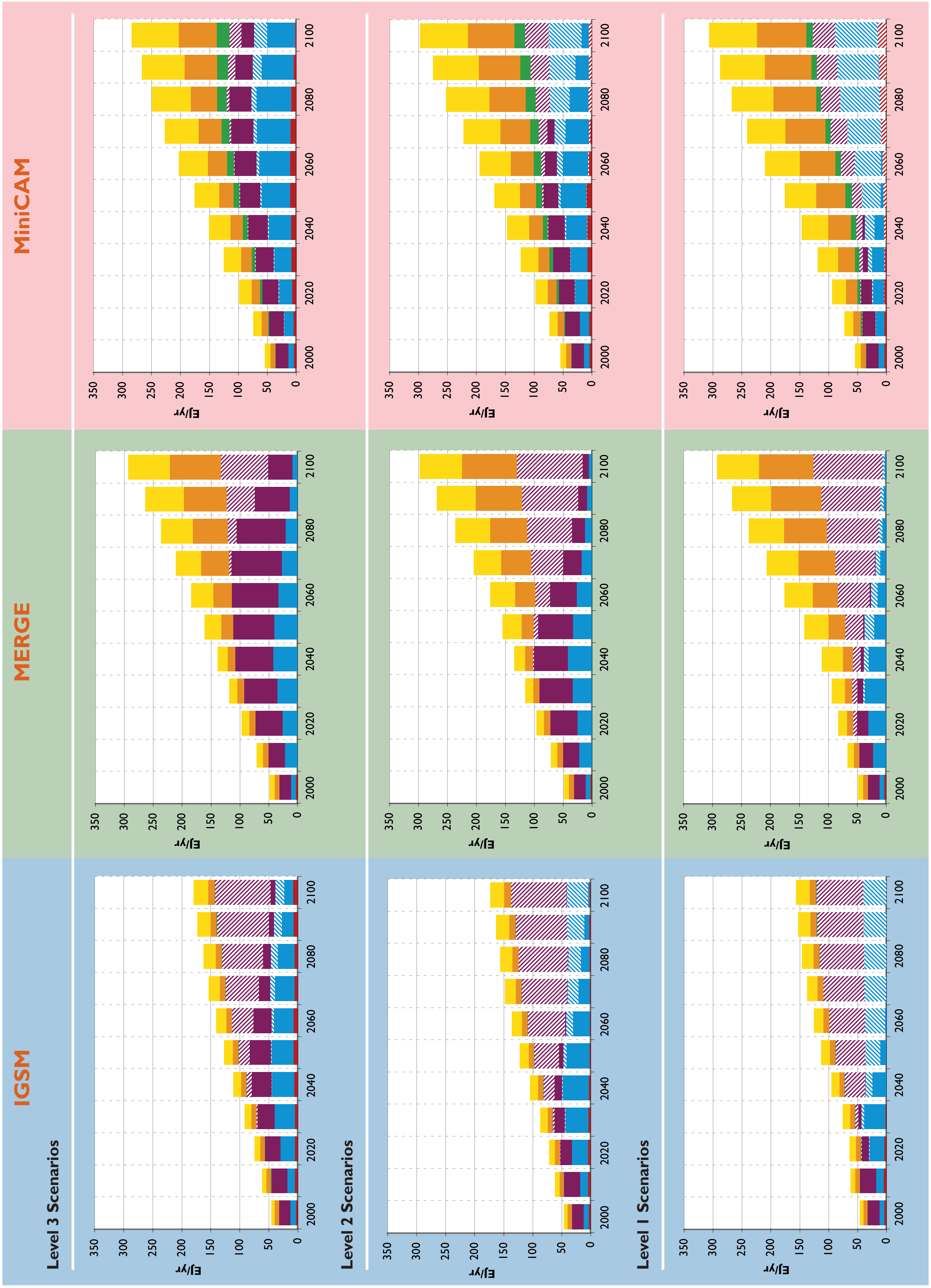

IGSM
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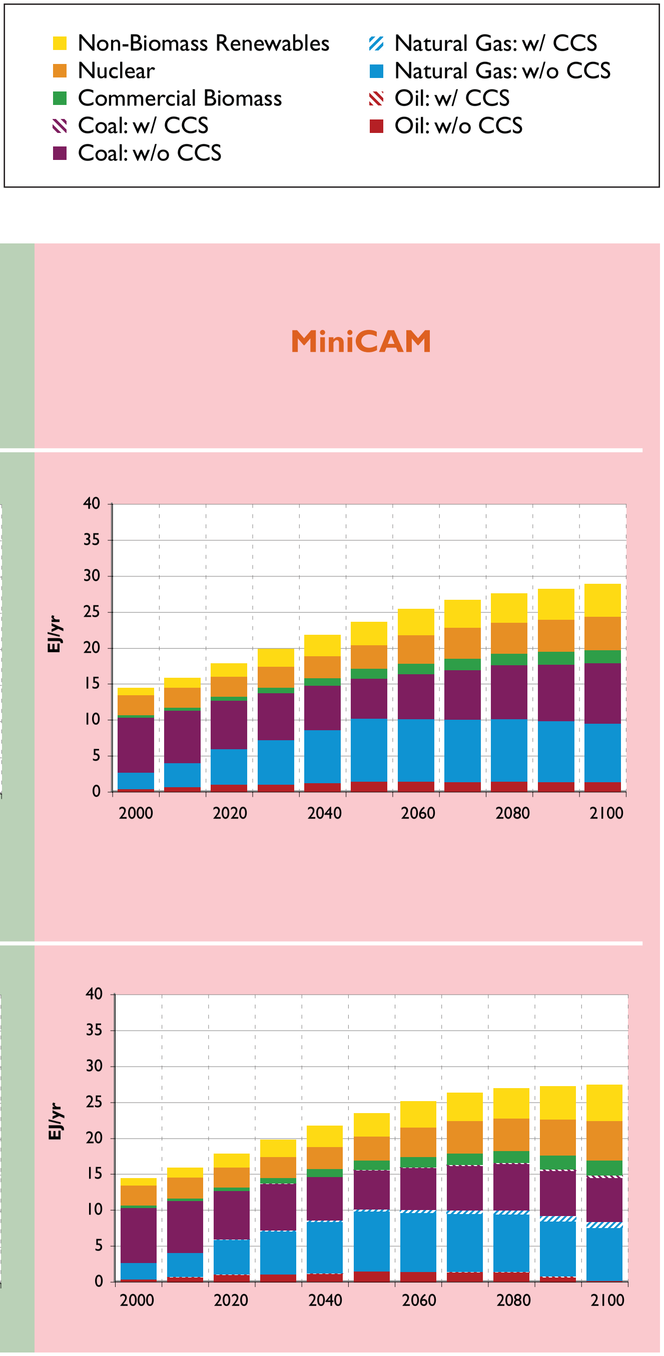
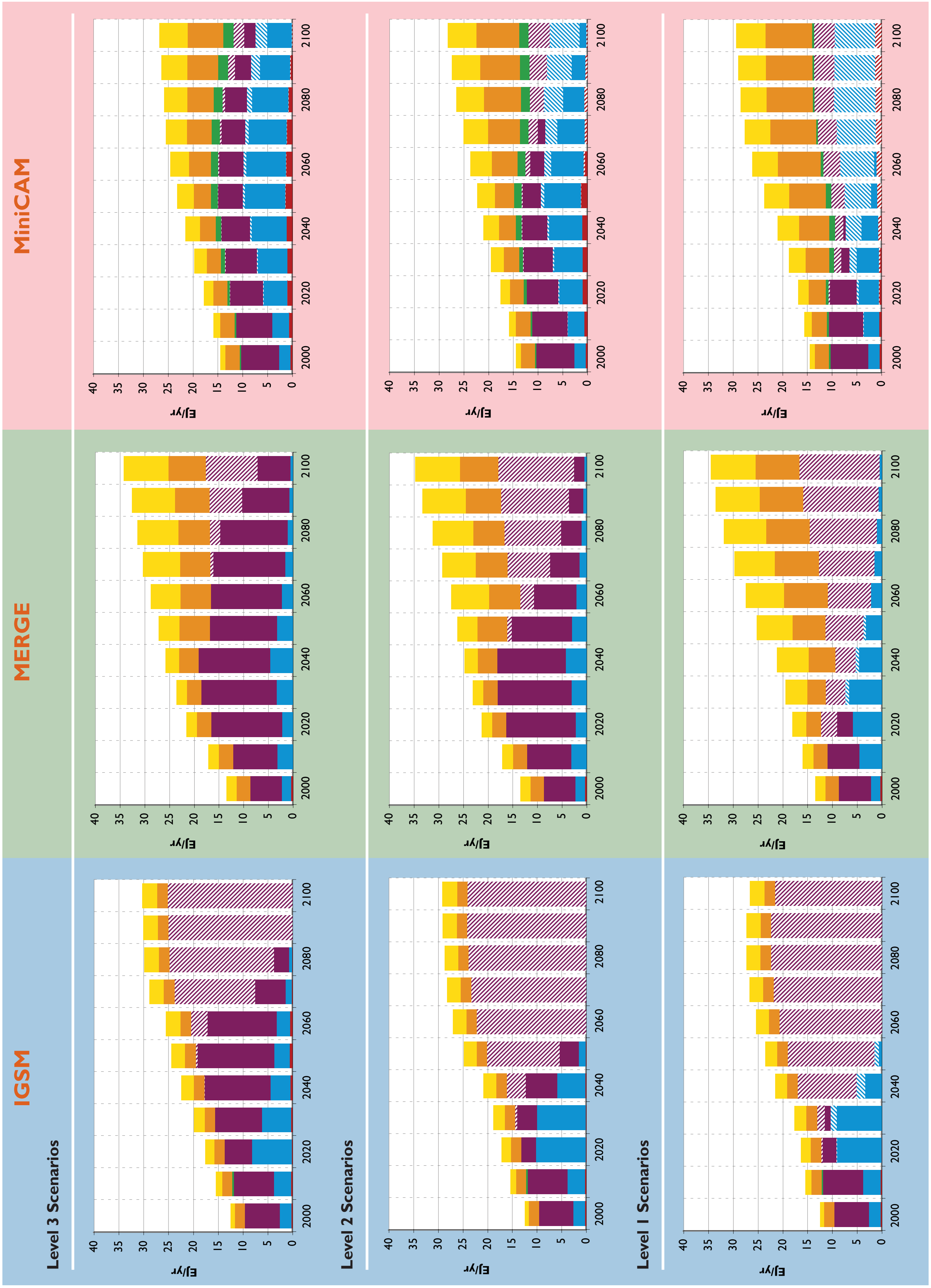
**Figure TS.12. U.S. Electricity Production by Fuel Across Scenarios (EJ/yr).** U.S. electricity generation sources and technologies are substantially transformed to meet the four radiative forcing stabilization levels. CCS figures in the stabilization scenarios from all three modeling groups, but the contribution of other sources and technologies and the total amount of electricity used differ substantially. In most cases, the relative proportion of electricity in energy consumption increases in the stabilization scenarios, so the relative reductions in electricity production are generally smaller than for primary energy. In one scenario (MiniCAM Level 1), electricity production in the U.S. increases under stabilization in the second half of the century.

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Level 3 Scenarios
Level 2 Scenarios
Level 1 Scenarios
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**Table TS.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 |

These assumptions of where, when, and *what* flexibility lower the economic consequences of stabilization relative to what they might be with other implementation approaches.

The stabilization scenarios follow a pattern where, in most scenarios, the carbon price rises steadily over time (Table TS.3), providing an opportunity for the energy system to adjust gradually. Although the general shape of the carbon price trajectory over time is similar across the models, the carbon prices vary substantially across the models. For example, for the less stringent stabilization levels two of the modeling groups produced scenarios with carbon prices of $10 or below per tonne of carbon in 2020, with carbon prices rising to roughly $100 per tonne in 2020 at the most stringent stabilization level. The scenarios from the third modeling group show 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. (Note that $100/tonne C is equivalent to $27/tonne $CO_2$. See Box 3.2 for more on converting between units of carbon and units of $CO_2$.)

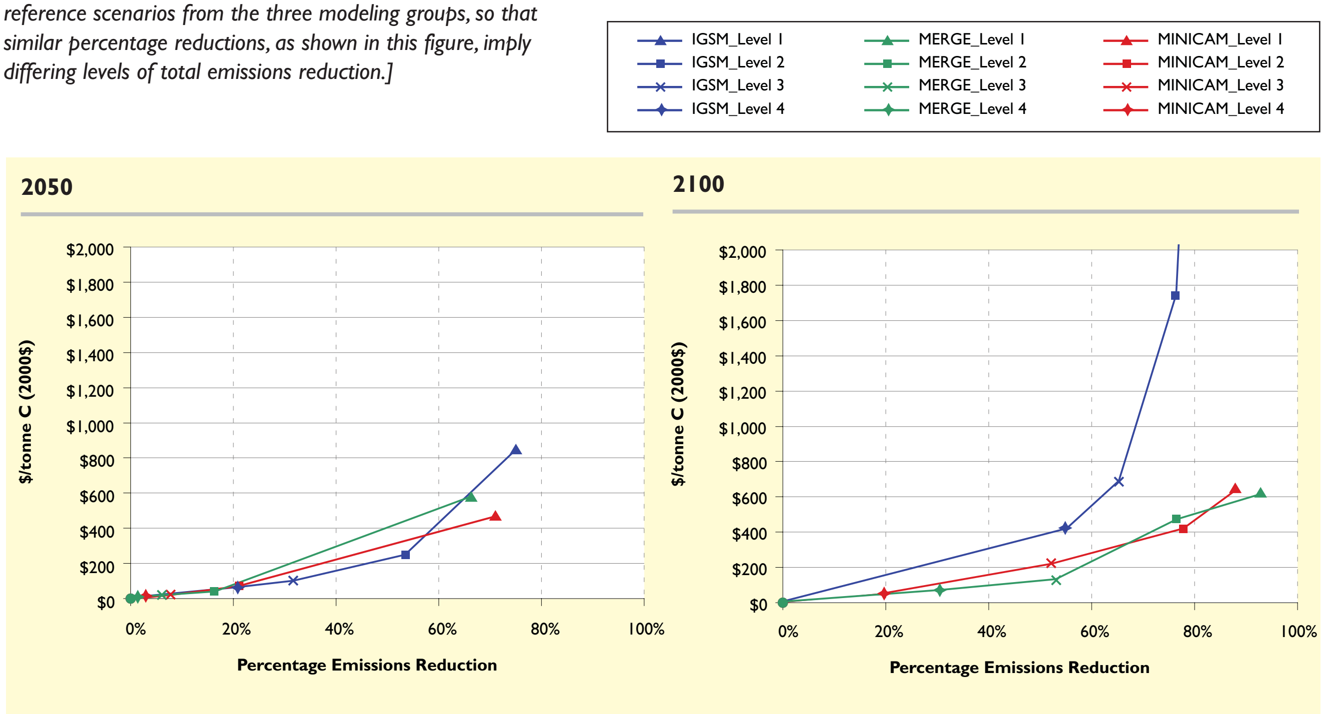
These differences in carbon prices, along with other model features, lead to similar variation in the costs of stabilization. Under the most stringent radiative forcing stabilization level, for example, gross world product (aggregating country figures using market exchange rates) is reduced in 2050 by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

The variation in carbon prices and reductions in gross world product is attributable to many factors, but two are most prominent. First, the amount that $CO_2$ emissions must be reduced to achieve stabilization differs between the scenarios from the different modeling groups (Table TS.4), because of differing assumptions regarding economic growth and other factors that determine emissions in the reference sce-

**Table TS.4. Cumulative Emissions Reductions from the Reference Scenarios Across Models in the Stabilization Scenarios (GtC through 2100)**

| | IGSM | MERGE | MiniCAM |
|---|---|---|---|
| Level 4 | 472 | 112 | 97 |
| Level 3 | 674 | 258 | 267 |
| Level 2 | 932 | 520 | 541 |
| Level 1 | 1172 | 899 | 934 |

**Figure TS.13. Relationship Between Carbon Price and Percentage Emissions Reductions in 2050 and 2100.** The relationship between carbon price and percentage reduction in emissions is similar among the models in 2050. In 2100, the relationship between carbon price and percentage reduction in emissions diverges across the models, due in large part to different assumptions regarding the technologies available to facilitate emissions reductions late in the century. *[Note. $CO_2$ emissions vary across the reference scenarios from the three modeling groups, so that similar percentage reductions, as shown in this figure, imply differing levels of total emissions reduction.]*



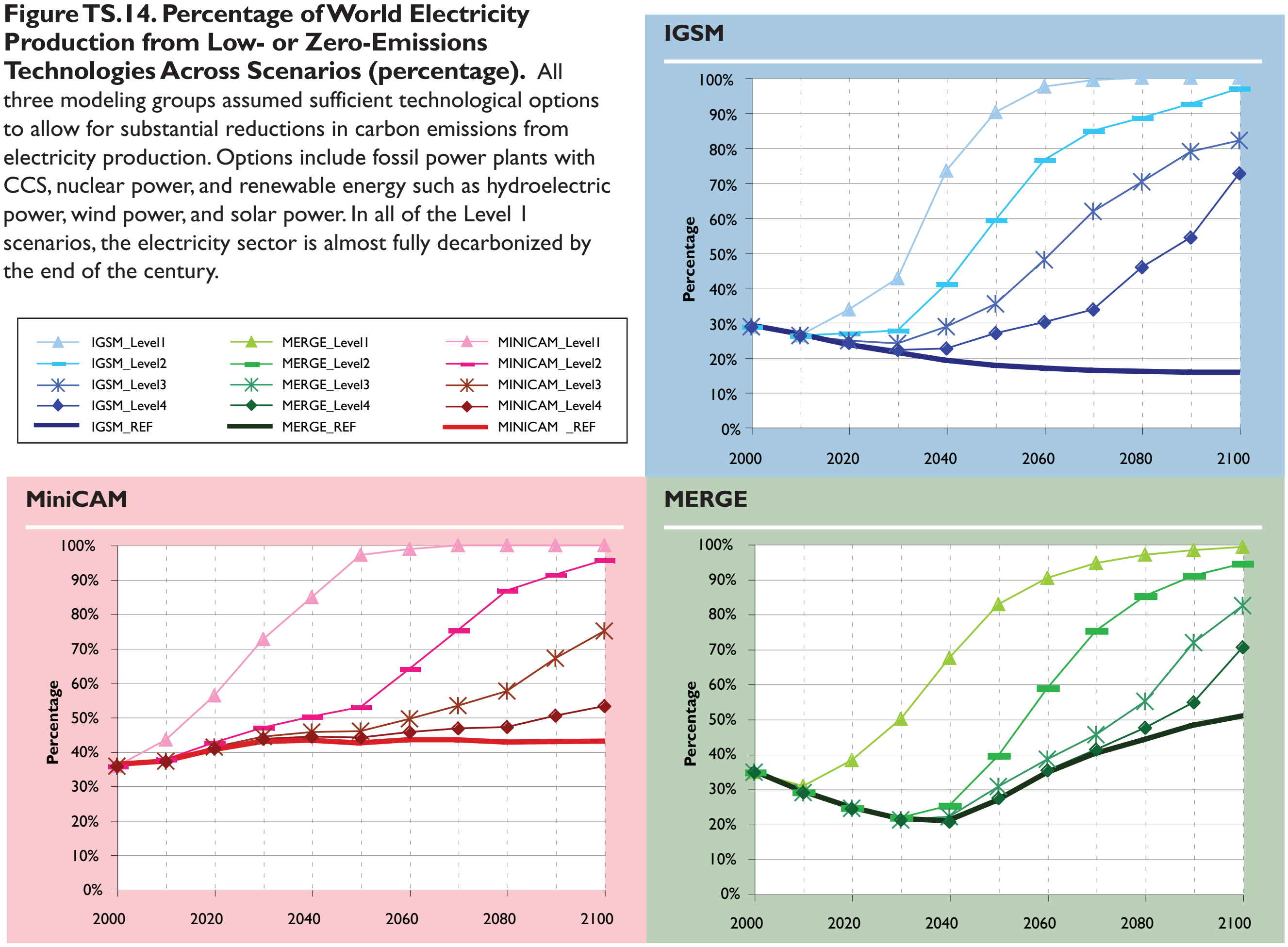
narios; levels of $CO_2$ uptake by the oceans and terrestrial biosphere; and availability of control for non-$CO_2$ GHGs.

Second, the modeling groups chose different assumptions regarding the technologies available for emissions reductions, particularly in the second half of the century. Most prominent are differences in assumptions about technologies to shift final energy demand to low-carbon sources such as biofuels and low-carbon electricity or hydrogen, in transportation, industrial and buildings end uses. The differences in technological assumptions among the modeling groups is reflected in the relationship between carbon prices and percentage abatement (Figure TS.13), a form of marginal abatement cost curve, for the three models in 2050 and 2100. The scenarios from the three modeling groups exhibit very similar behavior through 2050, but different assumptions about technological options lead to a divergence among the models by 2100.

In all of the scenarios, emissions reductions in electric power sector come at relatively lower prices than in other sectors (e.g. buildings, industry, and transport) so that the electricity sector is essentially decarbonized in the most stringent scenarios from all three modeling groups (Figure TS.14). At somewhat higher cost, other sectors can respond to rising carbon prices by reducing demands for fossil fuels, applying CCS technologies where possible, and substituting low-carbon energy sources such as bioenergy and low-carbon electricity or hydrogen. The amount of electricity used per unit of total primary energy increases in all of the stabilization scenarios (Figure TS.15), but those scenarios with the highest relative use of electricity tend to exhibit lower stabilization costs in part because of the larger role of decarbonized power generation. Assumptions regarding costs and performance of technologies to facilitate these adjustments, particularly in the post-2050 period, play an important role in determining stabilization costs.

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

**Figure TS.14. Percentage of World Electricity Production from Low- or Zero-Emissions Technologies Across Scenarios (percentage).** All three modeling groups assumed sufficient technological options to allow for substantial reductions in carbon emissions from electricity production. Options include fossil power plants with CCS, nuclear power, and renewable energy such as hydroelectric power, wind power, and solar power. In all of the Level 1 scenarios, the electricity sector is almost fully decarbonized by the end of the century.



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

Constraints on GHG emissions also affect fuel prices. Generally, producer prices for fossil fuels fall as demand for them is depressed by the stabilization measures. Consumers of fossil fuels, on the other hand, pay for fuel plus a carbon price if the $CO_2$ emissions are freely released to the atmosphere (Table TS.5). Therefore, consumer costs of energy rise with more stringent stabilization levels in these scenarios.

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 technologies for reducing non-$CO_2$ emissions allow a given radiative forcing stabilization level to be met with greater radiative forcing from $CO_2$ and, all other things being equal, less extensive changes to the energy system. Differences in GHG 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 in the scenarios from one of the modeling groups 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 in the scenarios

**Figure TS.15. Ratio of Global Electricity Production to Primary Energy Consumption Across Scenarios.** Efforts to constrain $CO_2$ emissions result in increased use of electricity as a fraction of total primary energy in the scenarios from all three modeling groups. This is because all three modeling groups assumed lower-cost technology options for reductions in emissions from electricity production than for substitution away from fossil fuels in direct uses such as transportation. The scenarios from two of the modeling groups (MERGE and MiniCAM) generally include greater electrification than the scenarios from the third modeling group (IGSM). Greater opportunities to electrify reduce the economic impacts of stabilization. *[Note. Primary energy consumption from nuclear power and non-biomass renewable electricity are accounted for at the average efficiency of fossil-fired electric facilities, which vary over time and across scenarios.]*

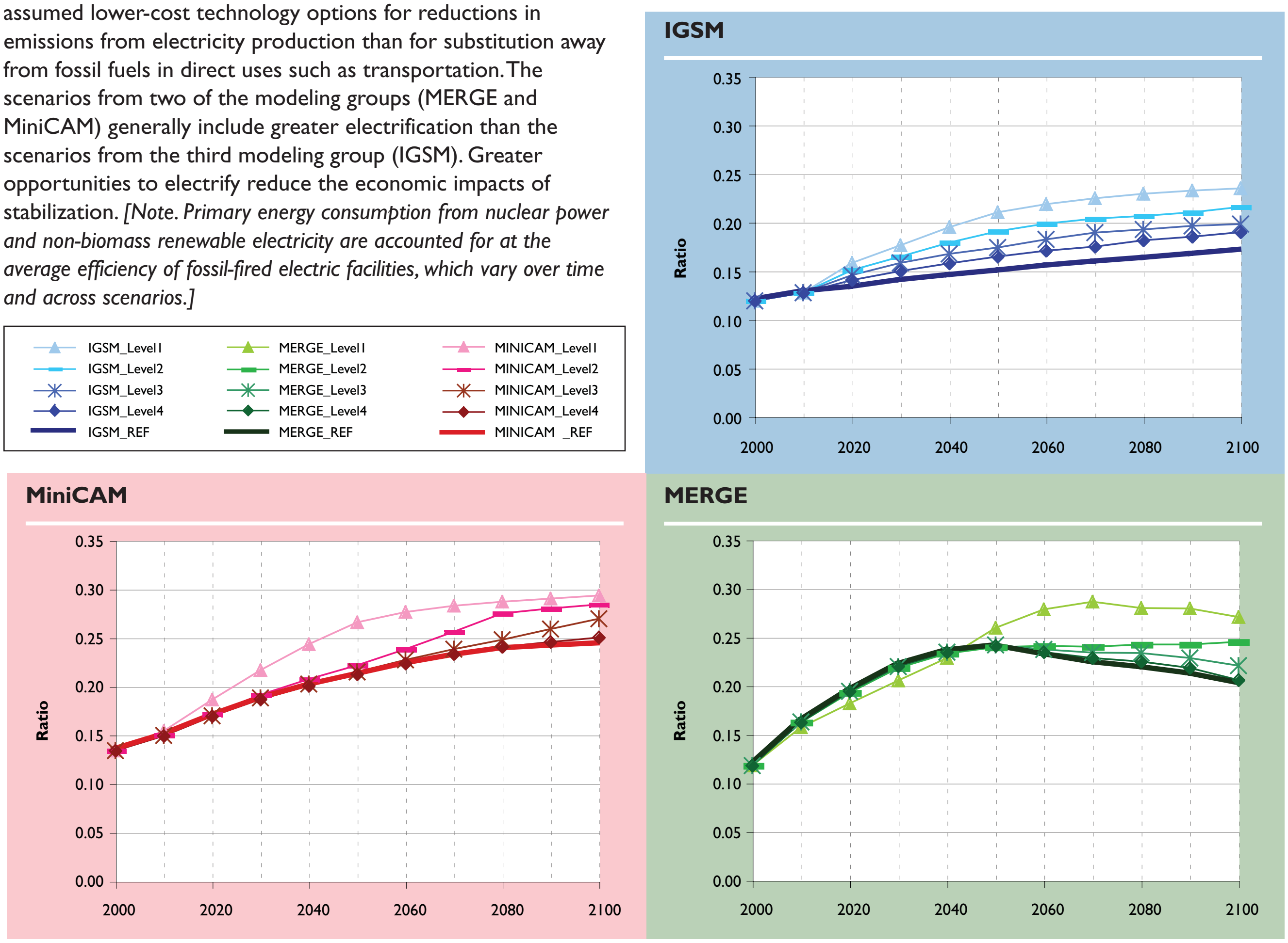
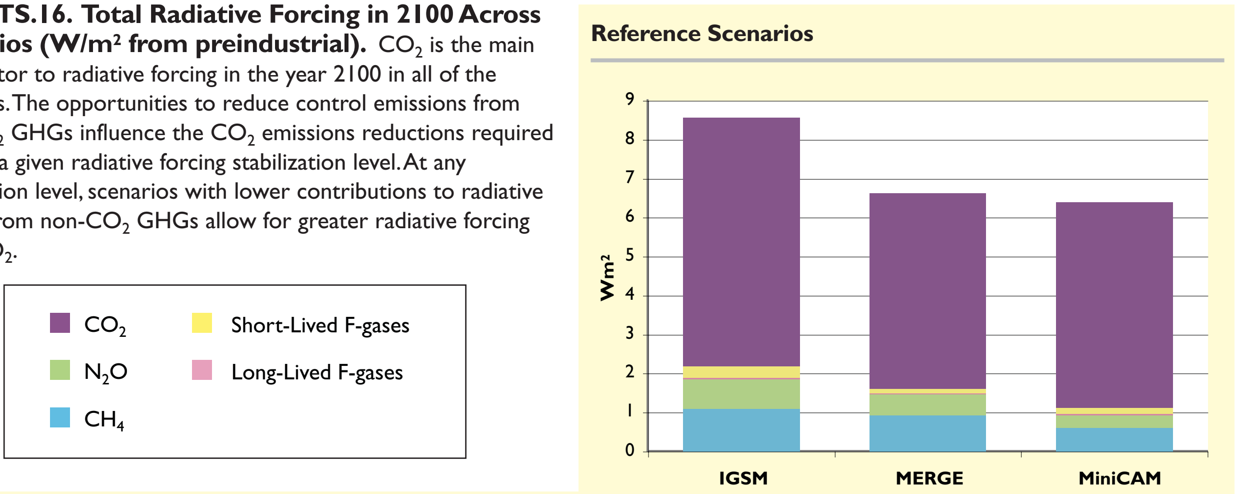


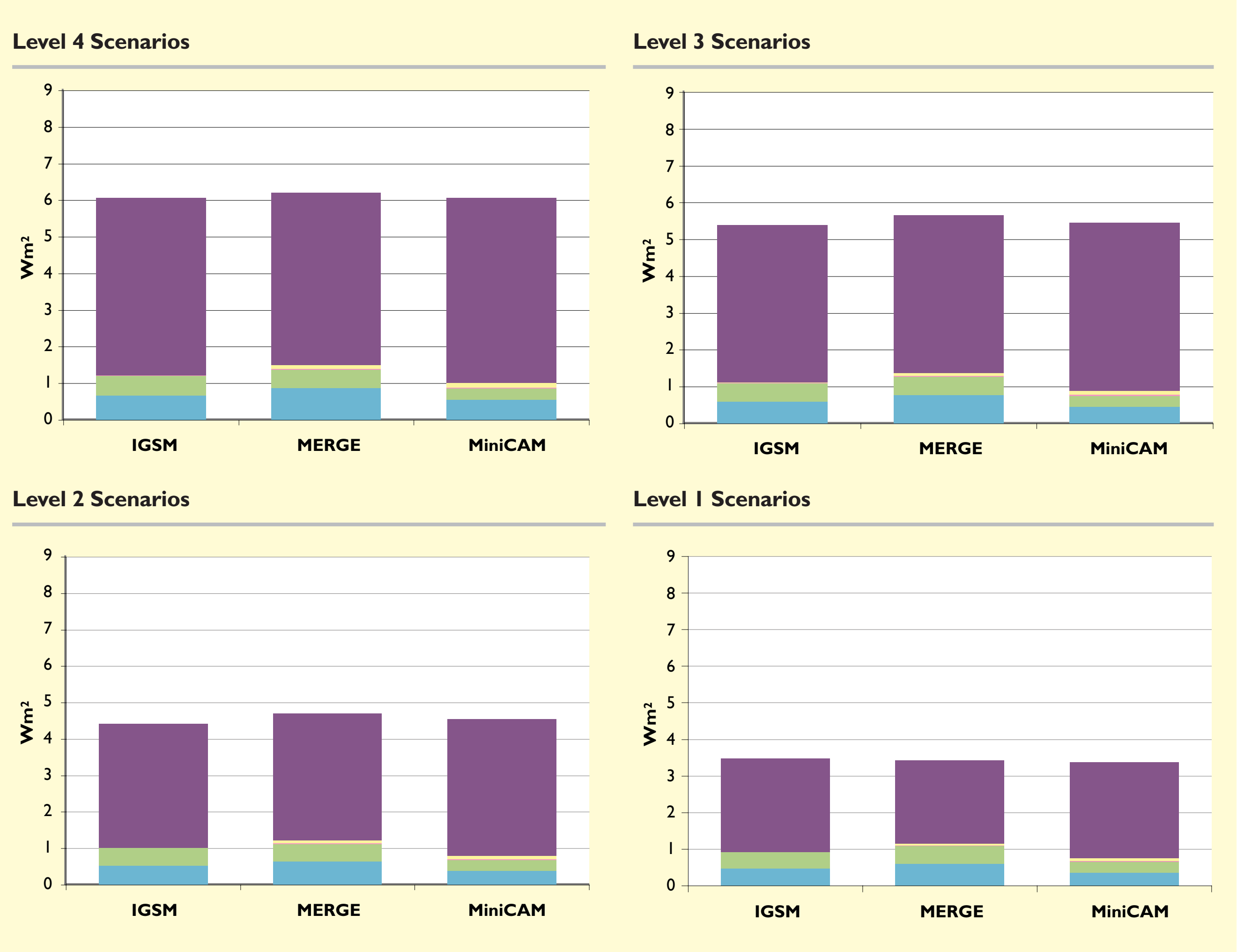
**Table TS.5. Relationship Between a $100/tonne Carbon Price and Fuel Prices.** (In most cases, stabilization depresses producer prices and so the percentage rise in the fuel cost seen by consumers would be less than indicated here. The change in producer price is highly scenario- and model-dependent.)

| 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 U.S. average prices for the 4th quarter of 2005 as reported in DOE 2006.*

**Figure TS.16. Total Radiative Forcing in 2100 Across Scenarios (W/m² from preindustrial).** $CO_2$ is the main contributor to radiative forcing in the year 2100 in all of the scenarios. The opportunities to reduce control emissions from non-$CO_2$ GHGs influence the $CO_2$ emissions reductions required to meet a given radiative forcing stabilization level. At any stabilization level, scenarios with lower contributions to radiative forcing from non-$CO_2$ GHGs allow for greater radiative forcing from $CO_2$.





from the other two modeling groups, higher levels of $CO_2$ are still consistent with the overall radiative forcing levels (Figure TS. 16).

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

## USING THE SCENARIOS AND FUTURE WORK

The scenarios in this report are intended as one of many inputs to public and private discussions regarding the threat of climate change, and they are also intended to serve as a point of departure for further CCSP and other analyses. A range of such analyses are possible. For example, the scenarios could be applied as the basis for assessing the climate implications of alternative stabilization levels, and then follow-on studies of potential climate impacts. They might also be used in studies exploring possible technology cost and performance goals, using information from the scenarios on energy prices and technology deployment levels. Similarly, the scenarios might inform analyses of the non-climate environmental implications of implementing potential new energy sources at a large scale. Another possibility is that the scenarios could serve as an input to a more complete analysis of the economic effects of stabilizing at the different radiative forcing levels, such as 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, such as effects on air pollution). The scenarios could also be compared against past and future scenarios analyses.

The scenarios in this report represent 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 needs for additional research and analysis are elaborated in Chapter 5.

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# CHAPTER 1

# Introduction and Overview

## 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 scenarios created in the scenario-development component of Product 2.1; the review of scenario methods is the subject of a separate report (CCSP 2007). The guidelines for the development of these scenarios are set forth in the *Final Prospectus for Synthesis and Assessment Product 2.1* (CCSP 2005). Consistent with the Prospectus and the nature of the climate change issue, these scenarios were developed using long-term models of global energy-agriculture-land-use-economy systems coupled to models of global atmospheric composition and radiation.

This report discusses the overall design of scenarios (Chapter 1); describes the key features of the participating models (Chapter 2); presents and compares the newly prepared scenarios (Chapters 3 and 4); and discusses emerging insights from these new scenarios, the uses and limitations of the scenarios, and avenues for further research (Chapter 5). Scenario details are available in a separate data archive.

The scenarios in this report are intended as one of many inputs to public and private discussions regarding climate change and what to do about it, and they may also serve as a point of departure for further Climate Change Science Program (CCSP) and other analyses that might inform these discussions in the future. The possible users of these scenarios are many and diverse. They include climate modelers and the science community; those involved in national public policy formulation; managers of Federal research programs; state and local government officials who face decisions that might be affected by climate change and mitigation measures; and individual firms, non-governmental organizations, and members of the public. Such a varied clientele implies an equally diverse set of possible needs, and no single scenario research product can hope to fully satisfy all of these needs. The Prospectus for this research highlighted three particular areas in which the scenarios might provide valuable insights: