CHAPTER 4

Stabilization Scenarios

In these scenarios, stabilizing radiative forcing at levels ranging from 3.4 W/m^2 to 6.7 W/m^2 above preindustrial levels (Level 1 to Level 4) implies significant changes to the world's energy and agriculture systems and leads to lower global economic output. Although all the stabilization scenarios require changes in the world's energy and agricultural systems, the three modeling groups produced scenarios with differing conceptions of how these changes might occur. The economic implications vary considerably among the scenarios, depending on the amount that emissions must be reduced and the evolution of technology, particularly in the post-2050 period.

INTRODUCTION

In Chapter 3, each modeling group developed scenarios of long-term GHG emissions associated with changes in key characteristics, such as demographics, economic growth, and technology. This chapter describes how such developments might affect or be affected by limits on radiative forcing. It illustrates that society's response to a limit on radiative forcing can take many paths, reflecting factors shaping the reference scenario and the availability and performance of emissions-reducing technologies. Control of GHG emissions requires changes in the global energy, economic, agriculture, and land-use systems.

It should be emphasized that the four radiative forcing stabilization levels considered in this research and detailed in Table 1.2 were chosen for illustrative purposes only. They reflect neither a preference nor a recommendation. In all the stabilization scenarios, it was assumed that radiative forcing would not be allowed to overshoot the radiative forcing levels along the path to long-term stabilization. Given this assumption, each modeling group had to make further decisions regarding the means of meeting these radiative forcing limits. Section 4.2 compares the approaches of the three modeling groups. 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 the measures to achieve the various radiative forcing stabilization levels in these scenarios.

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 stabilization scenarios
- The timing of participation in stabilization scenarios
- Policy instrument assumptions in stabilization scenarios.

In two areas, the groups employed different approaches:

- The timing of CO_2 emissions mitigation
- Non-CO_2 emissions mitigation.

Climate Policies in the Stabilization Scenarios

For the stabilization scenarios, each modeling group assumed that, as in the reference scenarios, the U.S. will achieve its goal of reducing GHG emissions intensity (the ratio of GHG emissions to GDP) by 18% by 2012, although implementation of this goal was left to the judgment of each modeling group. Also, the Kyoto Protocol participants were assumed to achieve their commitments through the first commitment period, 2008 to 2012. In the reference scenarios, 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.

Participation in Stabilization Scenarios

For the stabilization scenarios, it was assumed that policies to limit the change in radiative forcing would be applied globally after 2012, as directed by the Prospectus. Although it seems unlikely that all countries would simultaneously join such a global agreement, and the economic costs of stabilization would be greater with less-than-universal participation, the assumption that all countries participate does provide a useful benchmark.

Policy Instrument Assumptions in Stabilization Scenarios

Note that the issue of economic efficiency applies across both space and time. All of the scenarios assume an economically efficient allocation of reductions among nations in each time period, that is, across space. Thus, in these scenarios, GHG emissions in all regions and across all sectors of the economy were controlled 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 individual GHGs differ across the models. The implied ability to access emissions reduction opportunities wherever they are cheapest is sometimes referred to as *where* flexibility (Richels et al. 1996).

Timing of CO_2 Emissions Mitigation

The cost of stabilizing radiative forcing to any given level depends on the timing of the associated emissions reductions. There is a strong economic argument that costs will be lower if emissions reductions 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 (Wigley et al. 1996).

Although 100 years is a very long time horizon for economic scenarios, it is not long enough to fully evaluate stabilization goals. For several of the radiative forcing stabilization levels, the scenarios are only approaching stabilization in 2100; radiative forcing is below the long-term stabilization levels and still rising, but the rate of increase is slowing. Stabilizing radiative forcing and associated atmospheric GHG concentrations requires that any emissions be completely offset by uptake or destruction processes. Because ocean and terrestrial uptake of CO_2 is subject to saturation and system inertia, at least for the approximate CO_2 concentration levels considered in this research, 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. Although there is some flexibility in the inter-temporal allocation of emissions, this allocation is inherently constrained by the carbon cycle. Given that anthropogenic CO_2 emissions rise with time in all three of the reference scenarios, the degree of CO_2 emissions reduction also increases steadily with time in the stabilization scenarios.

Different approaches were used by the modeling groups to determine the profile of emissions reductions over time and how the different GHGs contribute to meeting the radiative forcing stabilization levels. A major reason for the difference is the structure of the models. MERGE is an inter-temporal optimization model and is able to solve for the cost-minimizing allocation of emissions reductions across GHGs and over time to meet a given radiative forcing stabilization level. It thus offers insights regarding the optimal path of emissions reductions. A positive discount rate will lead to a gradual phase-in of emissions reductions, and the tradeoff among GHGs is endogenously calculated based on the contribution each makes toward the long-term goal (Manne and Richels 2001). The changing relative prices of GHGs over time can be interpreted as an optimal trading index for the GHGs 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 (IPCC 2001). Furthermore, economically efficient indices for the relative importance of GHG emissions reductions 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 GHG. However, the choice of price paths over time used in the stabilization scenarios for the IGSM and MiniCAM modeling groups take 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.

In the MiniCAM stabilization scenarios, the rate of increase in the carbon price was set equal to the rate of interest plus the average rate of carbon removal from the atmosphere by natural systems. This approach follows Peck and Wan (1996) and yields a resulting carbon price path similar in structure to that obtained in the MERGE scenarios. 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, total costs cannot be reduced by making emissions mitigation either earlier or later.

As is the case in the MERGE scenarios, the exponential increase in the price of CO_2 continues until such time as radiative forcing is stabilized in the MiniCAM stabilization scenarios. 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 relevant in the Level 3 or Level 4 scenarios because stabilization is not reached until after the end of the twenty-first century.

The IGSM scenarios are based on a carbon price path that rises 4% per year. The initial carbon price is set to achieve the required concentrations and radiative 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 reduce emissions now or later would compare the expected return on that emissions reduction 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, investments in emissions reductions would yield a higher return than investments elsewhere in the economy, so that the entity would invest more in emissions reductions 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 emissions reductions. 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 emissions reductions through time.

Timing of Non-CO_2 Emissions Mitigation

Like CO_2, the contribution of non-CO_2 GHGs 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 emissions reductions. Each of the three modeling groups used its own approach to model control of non-CO_2 GHGs. As noted above, MERGE employs an inter-temporal optimization approach. The price of each GHG was determined so as to minimize the cost of stabilizing radiative forcing at each level. Thus, the price of each GHG was constant across regions at any point in time, but varied over time so as to minimize the cost of achieving each stabilization level.

In the MiniCAM stabilization scenarios, non-CO_2 GHG prices were tied 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. The IGSM stabilization scenarios are based on the same approach as MiniCAM stabilization scenarios for determining 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 scenarios 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 in the IGSM scenarios implies that near-term emissions reductions result in economic benefit, an approach consistent with a view that there are risks associated with levels of radiative forcing below the long-term stabilization levels. This approach is different than that followed in the MERGE scenarios, where any value of CH_4 emissions reductions is derived only from the extent to which it contributes to meeting the long-term stabilization level. In the MERGE stabilization scenarios, reductions of emissions of short-lived species like CH_4 have very little consequence for a radiative forcing stabilization level that will not be reached for many decades, so the optimized result places little value on reducing emissions of short-lived species until the stabilization level is approached. A full analysis of the resulting climate change and its effects would be required to select between the approaches used in the MERGE and IGSM scenarios. The different stabilization paths in the scenarios from these two models provide a range of plausible scenarios for non-CO_2 GHG stabilization. The MiniCAM scenarios yield an intermediate result.

IMPLICATIONS FOR RADIATIVE FORCING, GREENHOUSE GAS CONCENTRATIONS, AND EMISSIONS

Despite significantly different radiative forcing levels in the reference scenarios, radiative forcing relative to preindustrial levels in 2100 is similar across models in all four stabilization scenarios. CO_2 concentrations are also similar in 2100 across the models. Scenarios with higher CO_2 concentrations for a given stabilization level generally have lower concentrations and emissions of non-CO_2 GHGs, trading off reductions in these substances to make up for higher forcing from CO_2.

All three modeling groups produced scenarios in which emissions reductions below levels in the reference scenarios were much smaller between 2000 and 2050 than between 2050 and 2100. With one exception at the least stringent stabilization level, the stabilization scenarios were characterized by a peak and decline in global CO_2 emissions in the twenty-first century. In the most stringent scenarios, CO_2 emissions begin to decline immediately or within a matter of decades.

Table 4.1. Radiative Forcing in the Year 2100 Across Scenarios

		Radiative Forcing in 2100 (W/m^{-2} from preindustrial)		
Stabilization Level	**Long-Term Radiative Forcing Limit (W/m^2 from preindustrial)**	**IGSM**	**MERGE**	**MiniCAM**
Reference	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

Implications for Radiative Forcing

Given that all the models were constrained to the same radiative forcing stabilization levels, radiative forcing from preindustrial for the year 2100 is similar across the models (Table 4.1).[1] The differences across the models between the long-term stabilization levels and the radiative forcing levels in 2100 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. For Levels 3 and 4, each modeling group 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.

The radiative forcing stabilization paths are shown in Figure 4.1. Even though they reflect different criteria used to allocate emissions reductions over time, the paths are very similar across models. The radiative forcing paths are dominated by radiative forcing associated with CO_2 concentrations, which in turn are driven by cumulative emissions. Thus, even fairly different time profiles of CO_2 emissions can yield relatively little difference in concentrations and radiative forcing.

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

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 shown in Table 4.3. Because the stabilization levels were specified in terms of total radiative forcing from the multiple GHGs, it is possible to meet those levels while varying from the approximate CO_2 concentration levels used to construct them (Table 1.2). That means CO_2 concentrations in 2100 differ across models for any stabilization level. For example, the CO_2 concentrations in the MiniCAM stabilization scenarios are generally higher than in IGSM and MERGE stabilization scenarios. Consequently, CH_4 and N_2O concentrations are systematically lower as can be seen in Figure 4.4 and Figure 4.5.

Differences in the GHG concentrations among the scenarios from the three models reflect differences in the way that tradeoffs were made among gases and differences in assumed emissions reduction opportunities for non-CO_2 GHGs compared to CO_2.

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[1] The IGSM exceeds the Level 1 target by 0.1 W/m^2, which is a negligible difference that results from the iterative process required to achieve a radiative forcing target.

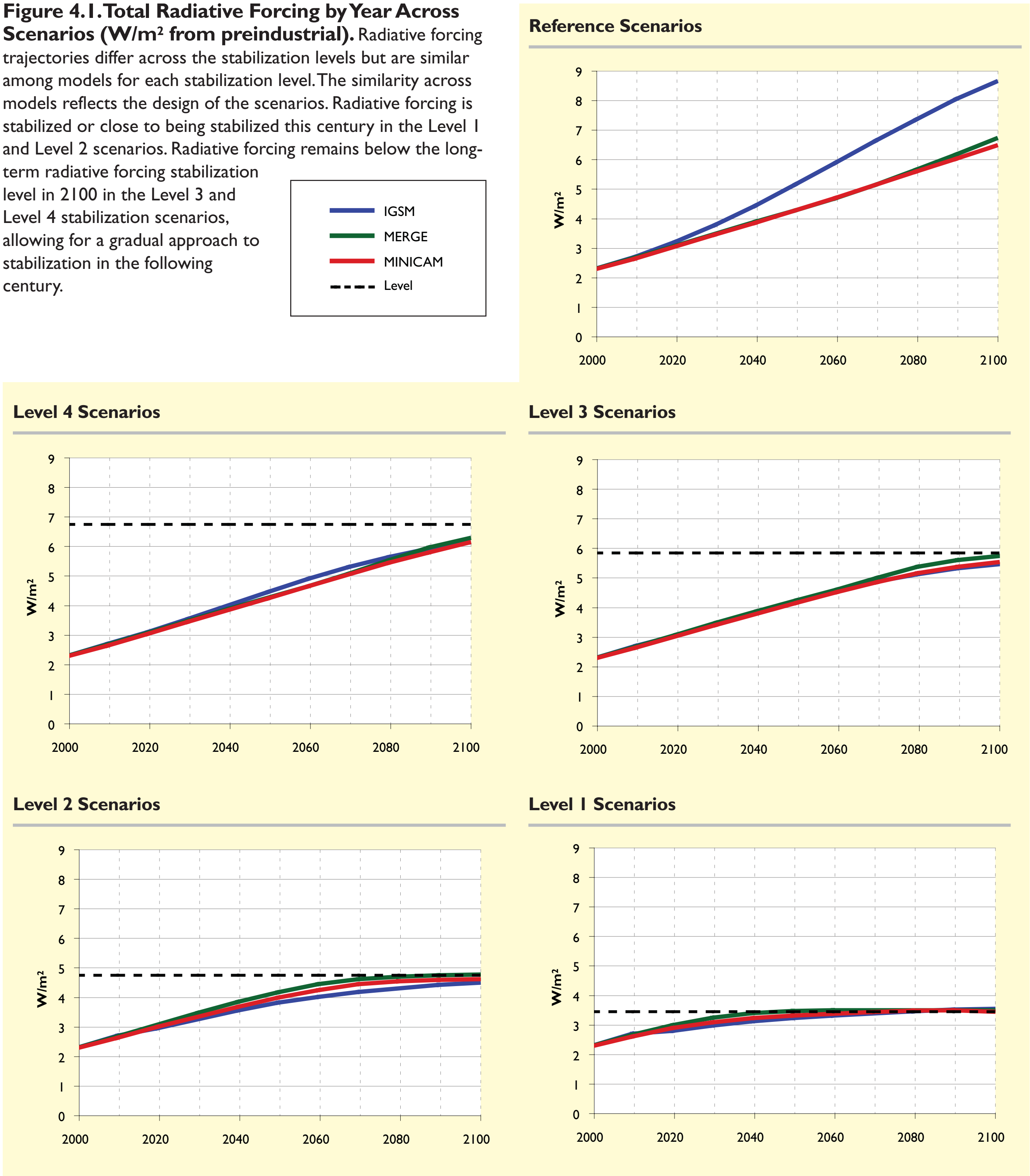


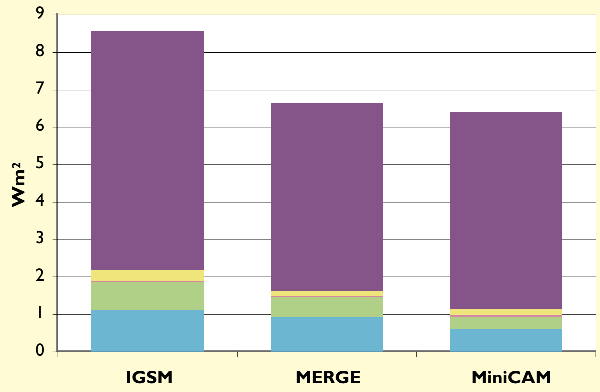
Figure 4.1. Total Radiative Forcing by Year Across Scenarios (W/m² from preindustrial). Radiative forcing trajectories differ across the stabilization levels but are similar among models for each stabilization level. The similarity across models reflects the design of the scenarios. Radiative forcing is stabilized or close to being stabilized this century in the Level 1 and Level 2 scenarios. Radiative forcing remains below the long-term radiative forcing stabilization level in 2100 in the Level 3 and Level 4 stabilization scenarios, allowing for a gradual approach to stabilization in the following century.

Approximate stabilization of CO_2 concentrations occurs by 2100 in all the Level 1 and Level 2 scenarios, but concentrations are still increasing in 2100 for the Level 3 and Level 4 scenarios, 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 levels do not change the nature of long-term changes in emissions required in the global economy; they only delay when the emissions reductions must be achieved.

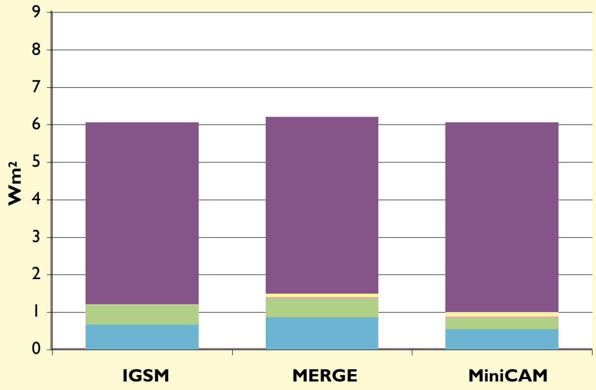
Figure 4.2. Total Radiative Forcing by Gas in 2100 Across Scenarios (W/m² from preindustrial). CO_2 is the main contributor to radiative forcing by the end of the century in the scenarios from all three modeling groups. The IGSM reference scenario has the highest contribution from non-CO_2 GHGs among the three models. The MERGE stabilization scenarios have the highest contribution from non-CO_2 GHGs among the three models, implying greater non-CO_2 control efforts in the IGSM scenarios than in the MERGE scenarios. Contributions from non-CO_2 GHGs are lowest in the MiniCAM scenarios, reflecting, in part, assumptions about control of these substances for non-climate reasons.

🟪 CO_2
🟨 Short-Lived F-gases
🟩 N_2O
▨ Long-Lived F-gases
🟦 CH_4

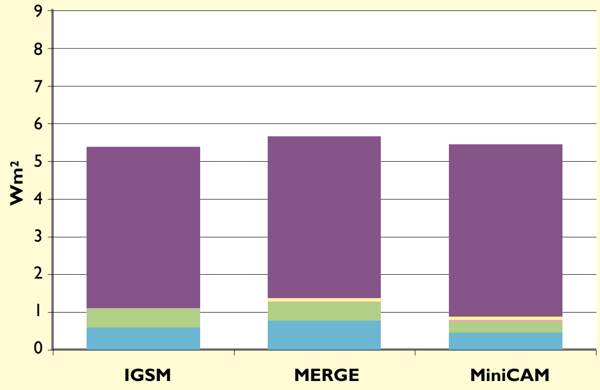
Reference Scenarios



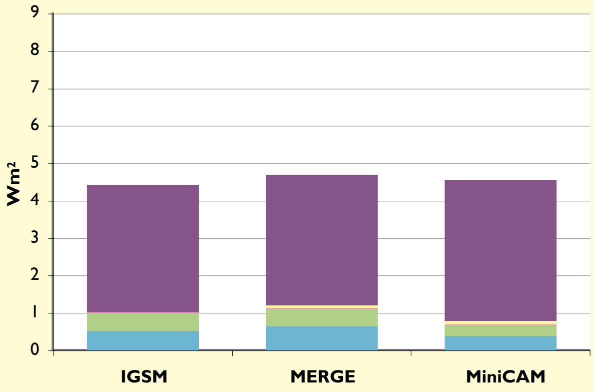
Level 4 Scenarios



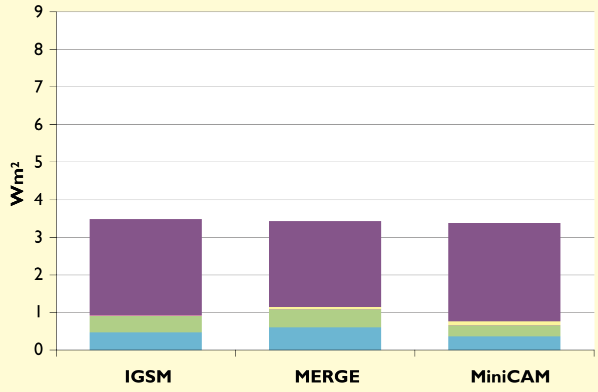
Level 3 Scenarios



Level 2 Scenarios

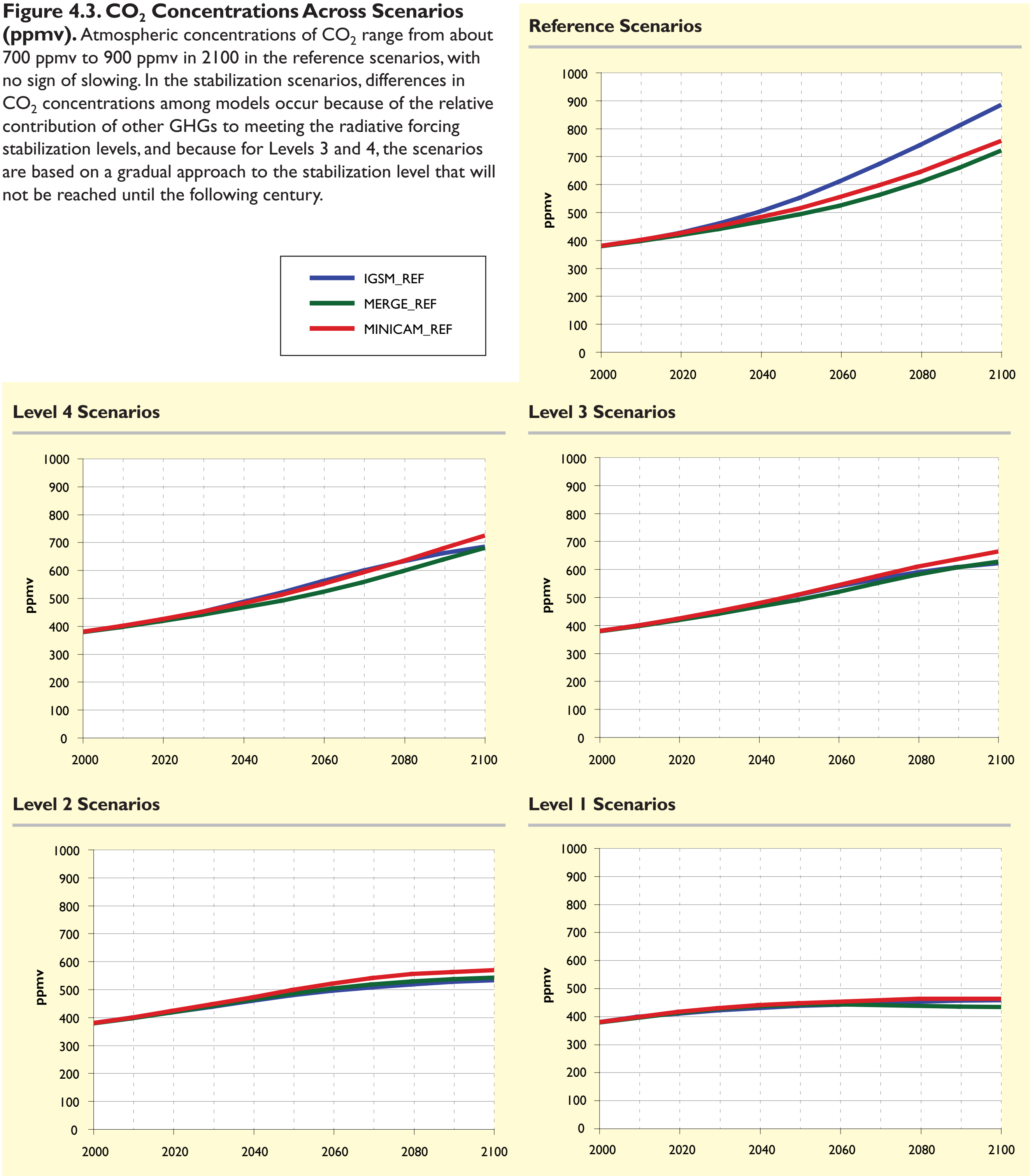


Level 1 Scenarios



In all the stabilization scenarios, as the rise in atmospheric concentrations slows, 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 the scenarios from the three modeling groups, as shown in Figure 4.6. Ocean uptake is smallest in the IGSM scenarios. The MERGE scenarios have the highest uptake for the least stringent stabilization levels, and the MiniCAM and MERGE scenarios are almost identical under the most stringent stabilization levels.

Figure 4.3. CO$_2$ Concentrations Across Scenarios (ppmv). Atmospheric concentrations of CO$_2$ range from about 700 ppmv to 900 ppmv in 2100 in the reference scenarios, with no sign of slowing. In the stabilization scenarios, differences in CO$_2$ concentrations among models occur because of the relative contribution of other GHGs to meeting the radiative forcing stabilization levels, and because for Levels 3 and 4, the scenarios are based on 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

Implications for Greenhouse Gas Emissions

Implications for Global CO$_2$ Emissions

Global CO$_2$ emissions begin declining immediately after 2010 or in a matter of decades in all three Level 1 stabilization scenarios (Figure 4.7). The constraint is so tight that there is relatively little room for variation among models.

All three modeling groups show continued emissions growth throughout the first half of the twenty-first century for Level 4, the least stringent stabilization levels, and the MiniCAM

Table 4.2. CO_2 Concentrations in the Year 2100 Across Scenarios (ppmv). The approximate CO_2 concentrations were used as a guide to develop the radiative forcing stabilization levels. The scenarios were required to meet the total radiative forcing limits. The CO_2 concentrations in the scenarios do not exactly match these approximations and differ among the 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.

		CO_2 Concentration in 2100 (ppmv)		
Level	**Approximate Long-Term CO_2 Concentration Limit (ppmv)**	**IGSM**	**MERGE**	**MiniCAM**
Reference	—	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

Figure 4.4. CH_4 Concentrations Across Scenarios (ppbv). Differences among the models in CH_4 concentrations are larger than differences in CO_2 concentrations. These differences stem from differences in reference scenarios, assumptions about options for emissions reductions, and the methods used by the modeling groups for determining the relative emissions reductions among different GHGs. Reductions in non-CO_2 GHG emissions in the MiniCAM stabilization scenarios are based on 100-year GWPs. The MERGE stabilization scenarios are based on intertemporal optimization, leading to relatively little value for controlling CH_4 emissions until the stabilization level is approached due to the relatively short lifetime of CH_4. The IGSM stabilization scenarios are based on independent stabilization of CH_4.

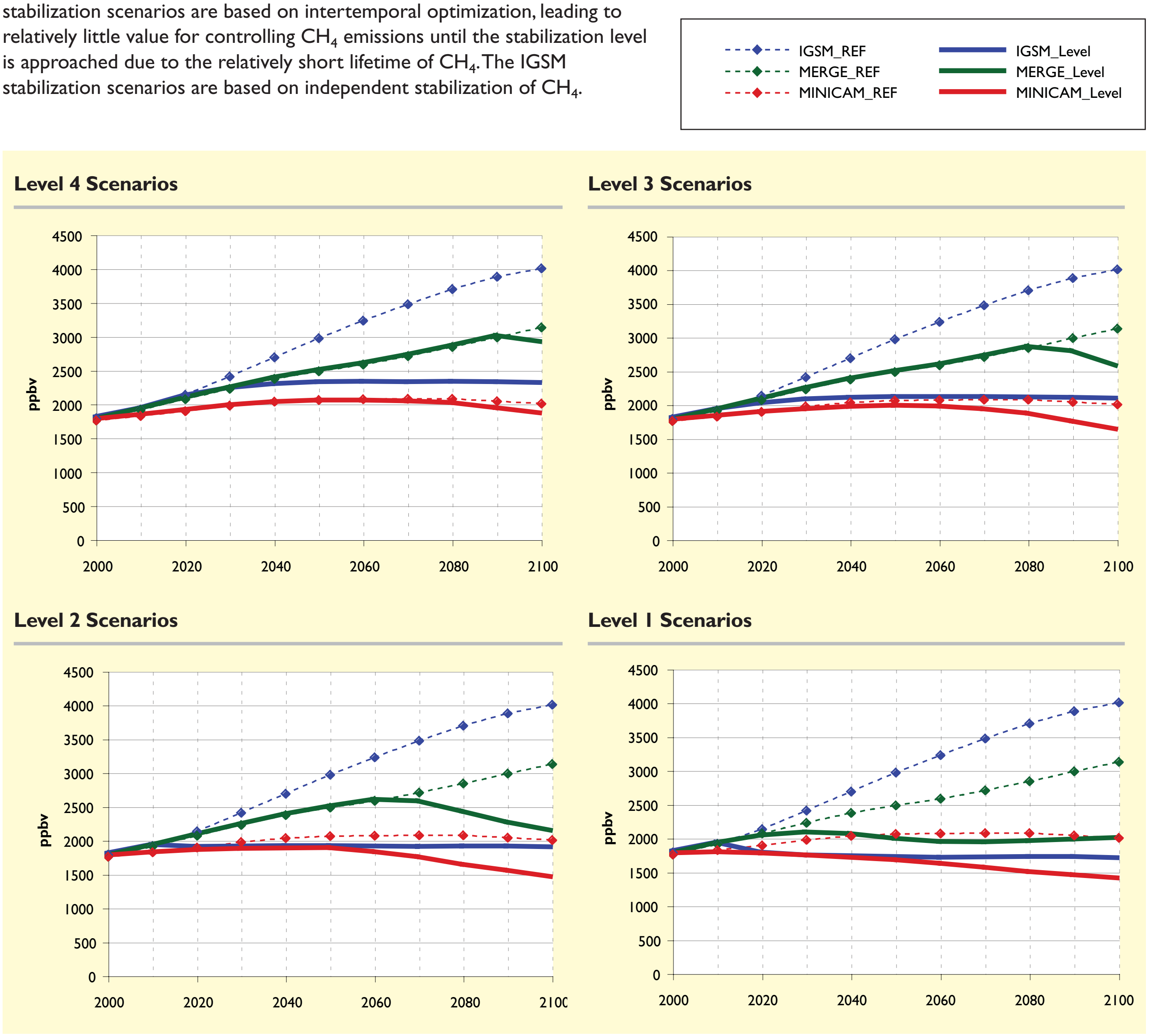
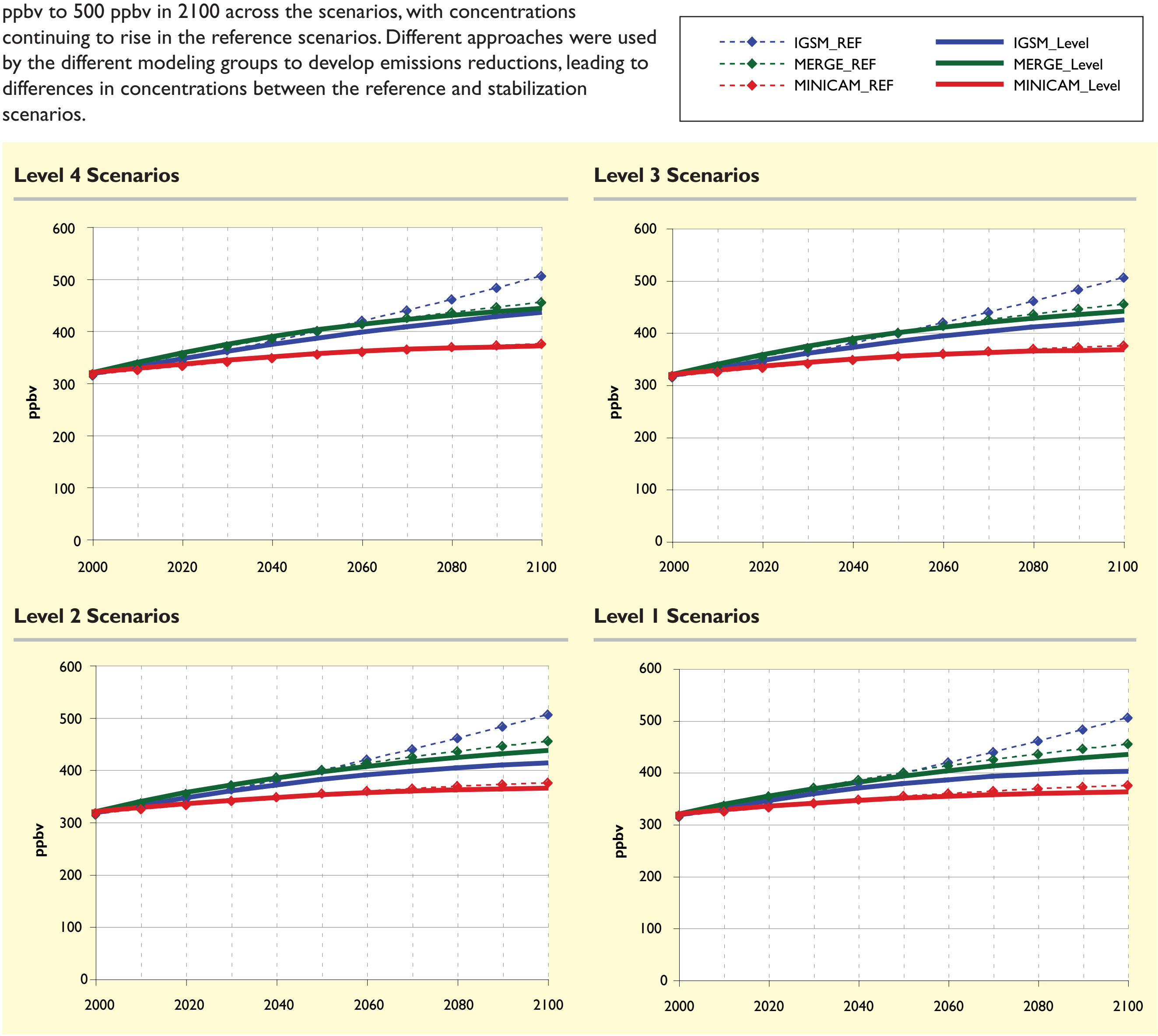


Figure 4.5. N_2O Concentrations Across Scenarios (ppbv). Atmospheric concentrations of N_2O range from about 375 ppbv to 500 ppbv in 2100 across the scenarios, with concentrations continuing to rise in the reference scenarios. Different approaches were used by the different modeling groups to develop emissions reductions, leading to differences in concentrations between the reference and stabilization scenarios.

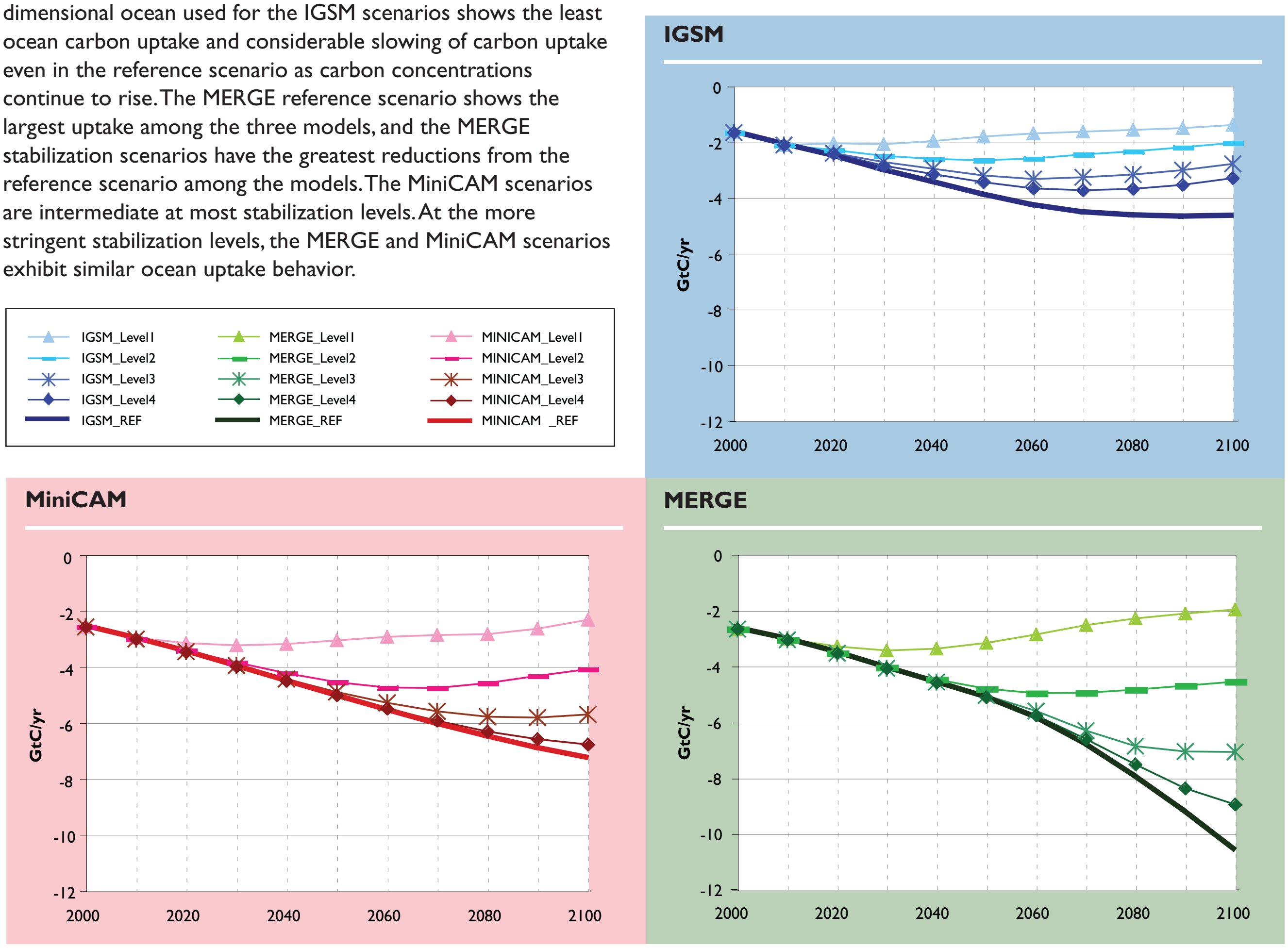


Level 4 scenario exhibits increasing emissions throughout the century, although emissions are approaching a peak by 2100.

The stabilization scenarios from all three modeling groups 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 stabilization level, 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 from all three modeling groups. Even for Level 1, where the limit on radiative forcing is the tightest and near-term mitigation most urgent, 75% or more of the emissions reduction below reference scenario occurs in the second half of the century. While this is partly a result of the *when* flexibility assumption, continuing emissions growth in the reference scenarios means that the percentage reduction increases over time.

All three of the modeling groups constructed reference scenarios in which Non-Annex 1 emissions were a larger fraction of the global total in the future than at present (Figure 3.16).

Figure 4.6. Ocean CO_2 Uptake Across Scenarios (GtC/yr, expressed in terms of net emissions). Oceans have taken up approximately one half of anthropogenic emissions of CO_2 since preindustrial times, and future ocean behavior is an important determinant of atmospheric concentrations. The three-dimensional ocean used for the IGSM scenarios shows the least ocean carbon uptake and considerable slowing of carbon uptake even in the reference scenario as carbon concentrations continue to rise. The MERGE reference scenario shows the largest uptake among the three models, and the MERGE stabilization scenarios have the greatest reductions from the reference scenario among the models. The MiniCAM scenarios are intermediate at most stabilization levels. At the more stringent stabilization levels, the MERGE and MiniCAM scenarios exhibit similar ocean uptake behavior.



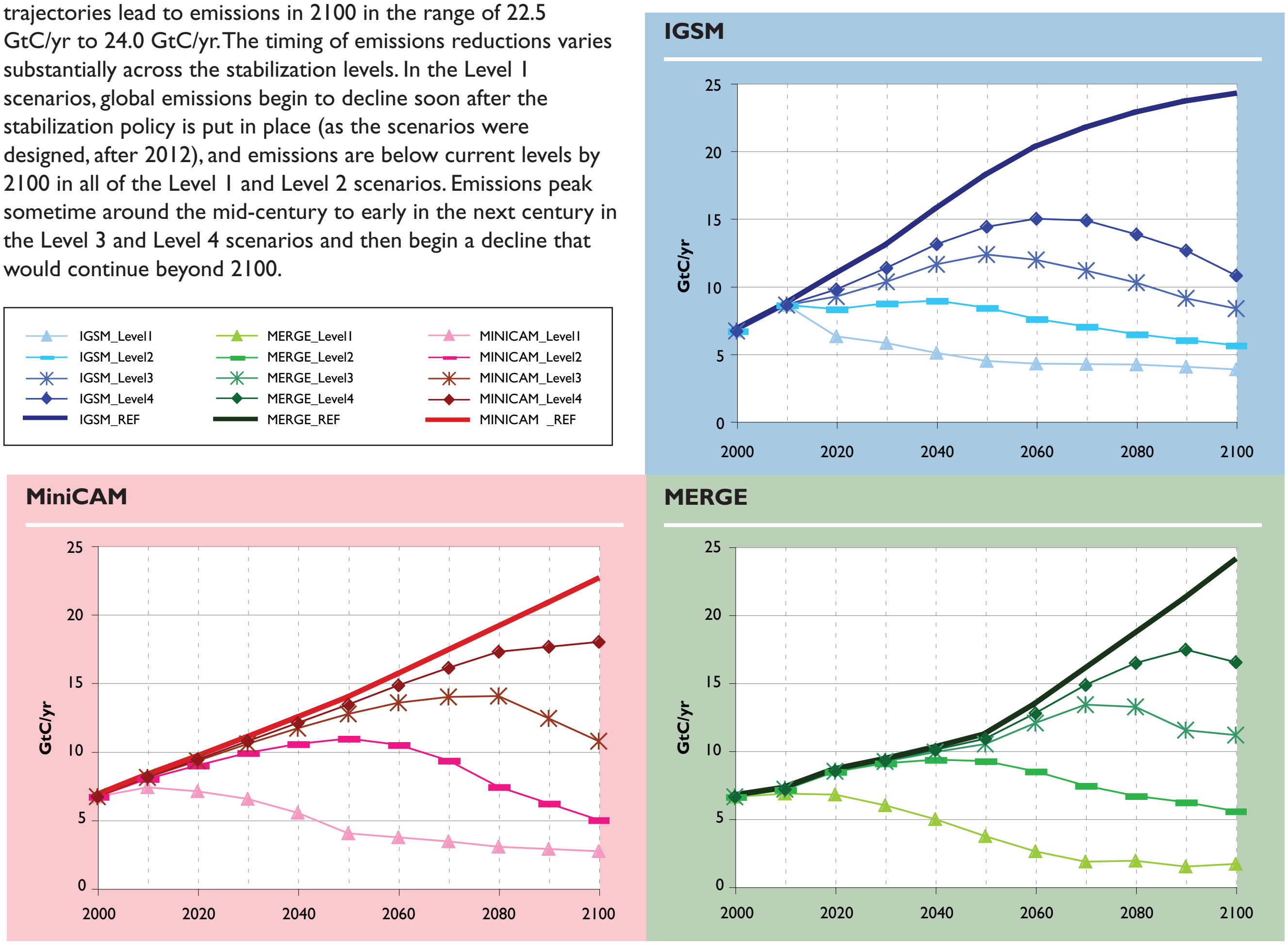
Because the stabilization scenarios are based on the assumption that all regions of the world face the same price of GHG emissions and have access to the same general set of technologies for mitigation, the resulting distribution of emissions mitigation between Annex I and Non-Annex I regions generally reflects the distribution of reference scenario emissions among them. So, when radiative forcing is restricted to Level 1, 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 scenario 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, emissions reductions occur separately from and mostly independent of the distribution of the economic burdens of reduction.

IMPLICATIONS FOR NON-CO_2 GREENHOUSE GAS EMISSIONS

The stabilization properties of the non-CO_2 GHGs differ due to their lifetimes (as determined by chemical reactions in the atmosphere), technologies for reducing emissions, and natural sources. CH_4 has a relatively short lifetime, and anthropogenic sources are a big part of CH_4 emissions. If anthropogenic emissions are kept constant, an approximate equilibrium between oxidation and net emissions will be established relatively quickly and concentrations will stabilize. The same is true for the relatively short-lived HFCs.

CH_4 emissions under stabilization are systematically lower the more stringent the stabilization level, as can be seen in Figure 4.8. The MiniCAM scenarios have the lowest CH_4 emis-

Figure 4.7. Fossil Fuel and Industrial CO_2 Emissions Across Scenarios (GtC/yr). Fossil fuel CO_2 emissions vary among the reference scenarios, but the three differing emissions trajectories lead to emissions in 2100 in the range of 22.5 GtC/yr to 24.0 GtC/yr. The timing of emissions reductions varies substantially across the stabilization levels. In the Level 1 scenarios, global emissions begin to decline soon after the stabilization policy is put in place (as the scenarios were designed, after 2012), and emissions are below current levels by 2100 in all of 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 2100.

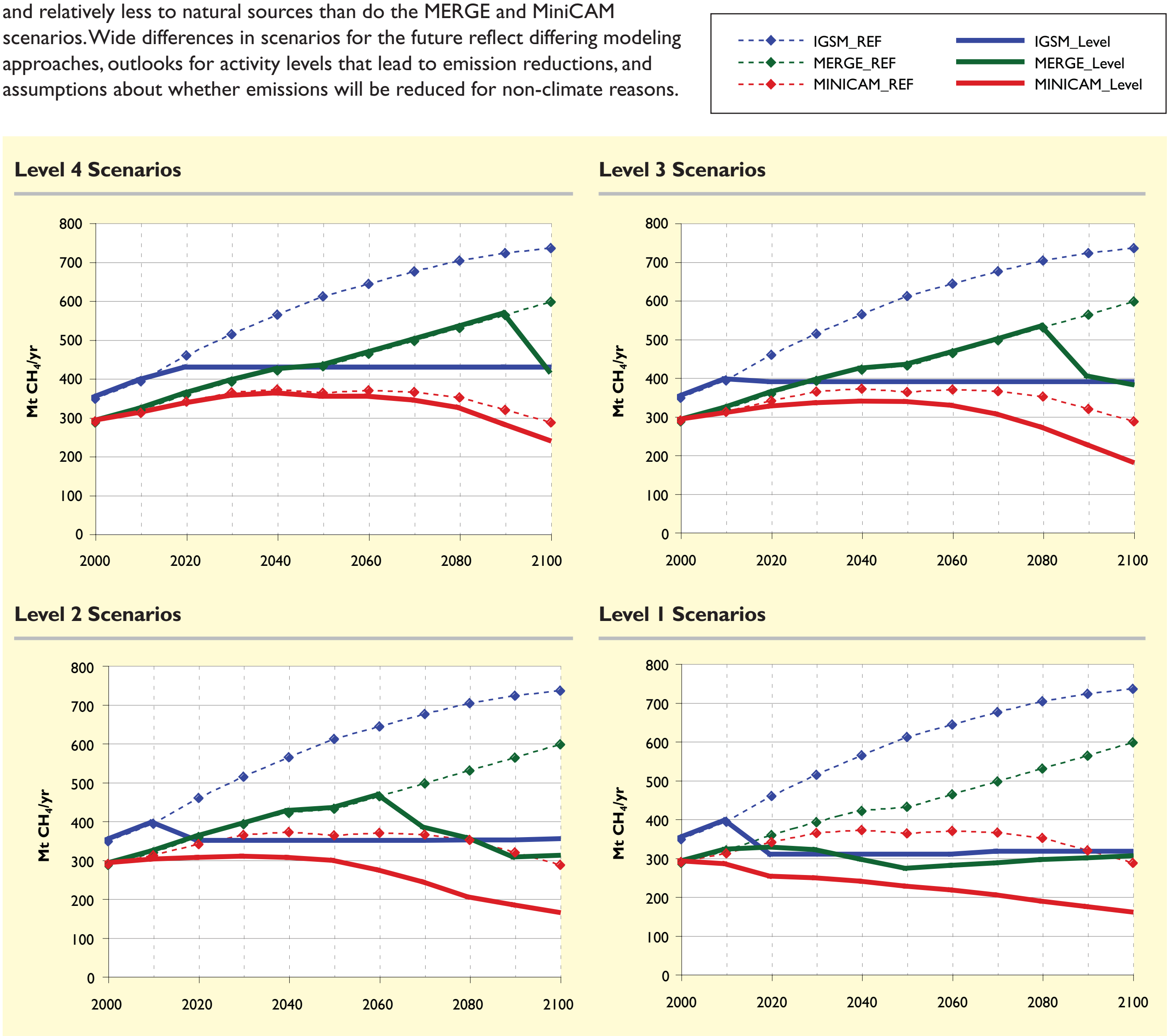


sions among the models in the reference scenario and the stabilization scenarios. The assumed policy environment for CH_4 control is also important. Despite the fact that the IGSM reference scenario has higher reference CH_4 emissions than the MERGE reference scenario, the MERGE stabilization scenarios have higher emissions under stabilization in several instances. The reason is that the MERGE intertemporal optimization approach leads to a low relative price for CH_4 emissions in the near term, which grows rapidly relative to CO_2, favoring strong reductions of CH_4 emissions only toward the end of the century, whereas CH_4 emissions were controlled based on quantitative limits in the IGSM stabilization scenarios, and these limits lead to substantial reduction early in the century. Thus, emissions in the MERGE stabilization scenarios sometimes exceed those in the IGSM stabilization scenarios until the relative CH_4 price rises sufficiently to induce substantial emissions reductions.

The very long-lived gases are nearly indestructible, thus for stabilization their emissions must be very near zero. Based on the assumptions used by all three modeling groups, it is possible, at reasonable cost, to achieve substantial reductions in long-lived gas emissions. While these substances are important, their emissions are not as difficult to reduce 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 shown in Figure 4.9, although these differences are smaller than those for CH_4.

Figure 4.8. CH_4 Emissions Across Scenarios (Mt CH_4/yr). Emissions of anthropogenic CH_4 vary widely across the models, including differences in year 2000 emissions that reflect uncertainty about these emissions. With current concentrations and destruction rates relatively well known, the difference in current levels means that IGSM scenarios ascribe relatively more to anthropogenic sources and relatively less to natural sources than do the MERGE and MiniCAM scenarios. Wide differences in scenarios for the future reflect differing modeling approaches, outlooks for activity levels that lead to emission reductions, and assumptions about whether emissions will be reduced for non-climate reasons.



Level 4 Scenarios

Level 3 Scenarios

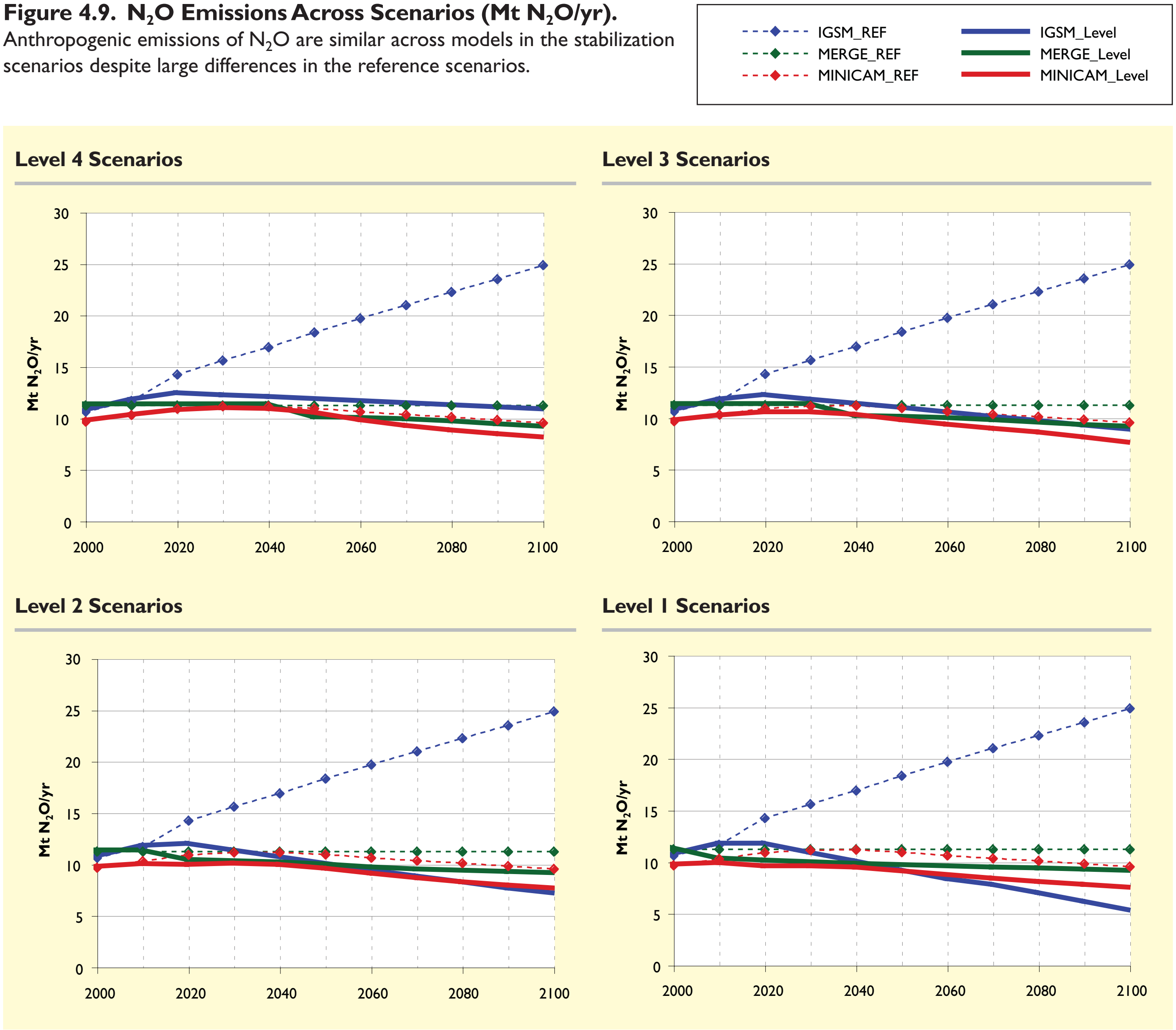
Level 2 Scenarios

Level 1 Scenarios

IMPLICATIONS FOR ENERGY USE, INDUSTRY, AND TECHNOLOGY

In these scenarios, stabilizing radiative forcing requires a transformation of the global energy system, including reductions in the demand for energy 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. CO_2 emissions from electricity production 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 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.

Figure 4.9. N_2O Emissions Across Scenarios (Mt N_2O/yr). Anthropogenic emissions of N_2O are similar across models in the stabilization scenarios despite large differences in the reference scenarios.



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. Although differences in the reference scenarios developed by each of the three modeling groups led to different patterns of response, some important similarities emerge. The more stringent the radiative forcing stabilization level, the larger the change in the global energy system relative to the reference scenario; moreover, the scale of this change is increasing over time. Also, significant fossil fuel use continues at all four stabilization levels. This pattern can be seen in Figure 4.10, which shows the global primary energy consumption across the scenarios, and Figure 4.11, which shows the reference scenario from Chapter 3 with an additional plot of the net changes in the various sources of primary energy for each stabilization level.

Although atmospheric stabilization would take away much of the growth potential of coal over the century, its usage expands 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 in the scenarios from all three modeling groups. Figure 4.10 shows that as the carbon price rises, 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 other assumptions that shaped the reference scenarios. For example, the MERGE reference scenario assumes 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 leads to reductions in coal use and end-use energy consumption. As the carbon price rises, nuclear and non-biomass renewable energy forms and CCS augment the response.

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

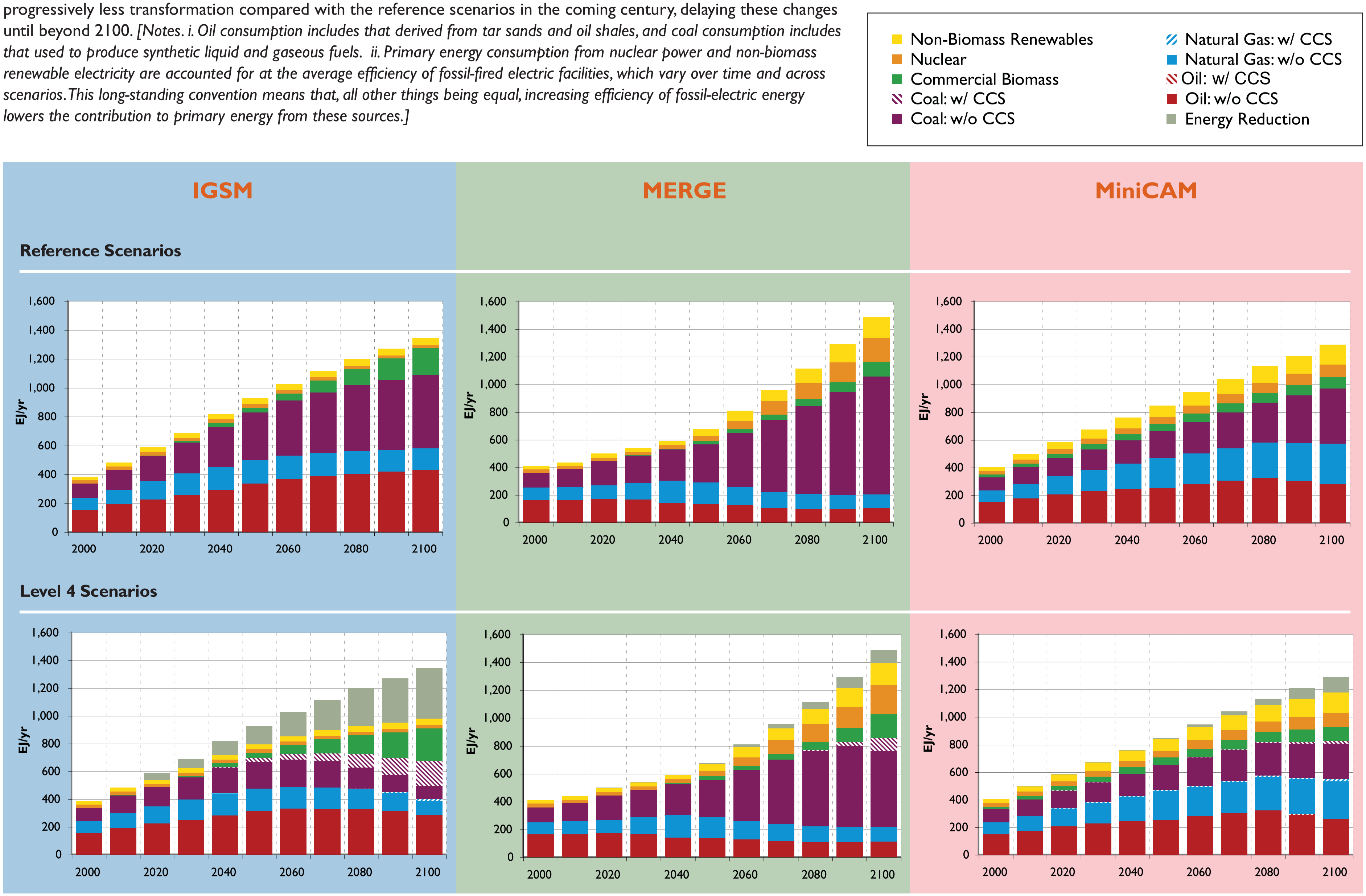
The MiniCAM stabilization scenarios include the smallest reductions in energy consumption among the models. The imposition of constraints on radiative forcing leads to reductions in oil, gas, and coal, as is the case with the IGSM and MERGE stabilization scenarios, but also leads to considerable expansion of nuclear power and renewable energy supplies. The largest supply response is in commercial bio-derived fuels. These fuels are largely limited to bio-waste recycling in the MiniCAM reference scenario. As the price of CO_2 rises, commercial bioenergy becomes increasingly attractive. As will be discussed in Section 4.5, the expansion of the commercial biomass industry to produce hundreds of EJ/yr of energy has implications for crop prices, land use, land-use emissions, and unmanaged ecosystems.

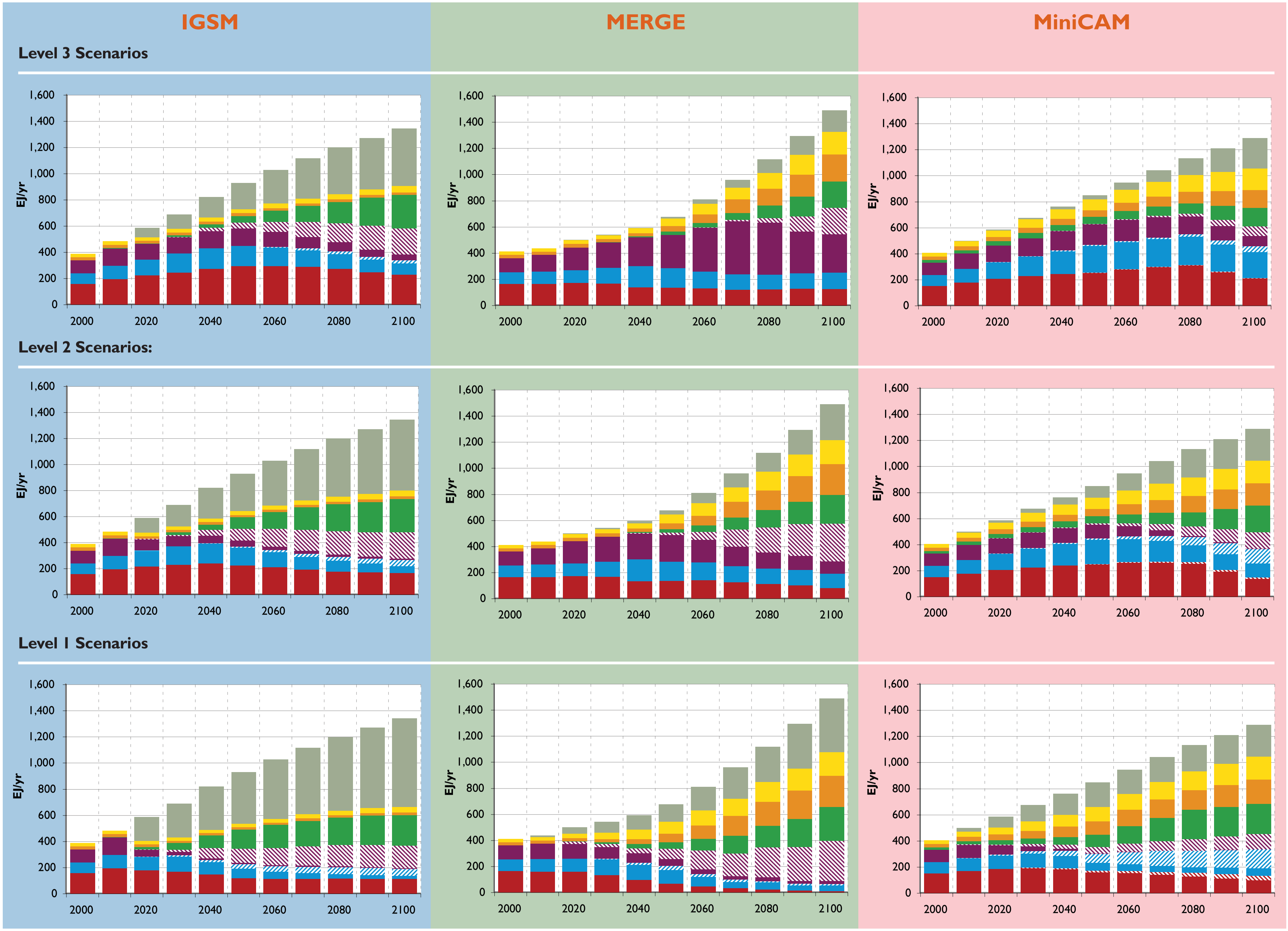
The relative role of nuclear energy differs among the scenarios from the three modeling groups. The MERGE reference scenario deploys the largest amount of nuclear power, contributing 170 EJ/yr of primary energy in the year 2100. In the Level 1 stabilization scenario, deployment expands to 240 EJ/yr of primary energy in 2100. Nuclear power in the MiniCAM reference scenario produces 90 EJ/yr in the year 2100, which in the Level 1 stabilization scenario expands to more than 180 EJ/yr of primary energy in the year 2100. The IGSM stabilization 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 safety, waste, and proliferation that are unaffected by climate policy.

Reductions in total primary energy consumption 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, the MERGE and MiniCAM stabilization scenarios also exhibit reductions in energy demand. As will be discussed in Section 4.6, differences in primary energy reductions among the models reflect differences in the carbon prices required for stabilization, which are substantially higher in the IGSM stabilization scenarios than in the MERGE and MiniCAM stabilization scenarios. In all the stabilization scenarios, 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 GHG 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 na-

Figure 4.10. Global Primary Energy Consumption by Fuel Across Scenarios (EJ/yr). The transition to stabilization, reflected most fully in the Level 1 stabilization scenarios, means an eventual phase-out of fossil fuel use unless CCS is employed. Consumption of non-fossil energy sources increases 6-fold to 14-fold over the century in the Level 1 stabilization scenarios. In the IGSM stabilization scenarios, more of the emissions reductions are met through demand reductions than in the scenarios from the other two modeling groups, with 2100 energy use cut by up to one-half relative to the reference scenario in 2100. In the MiniCAM Level 1 scenario, in contrast, total energy is reduced by less than 20%. Levels 2, 3, and 4 require progressively less transformation compared with the reference scenarios in the coming century, delaying these changes until beyond 2100. *[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
EJ/yr
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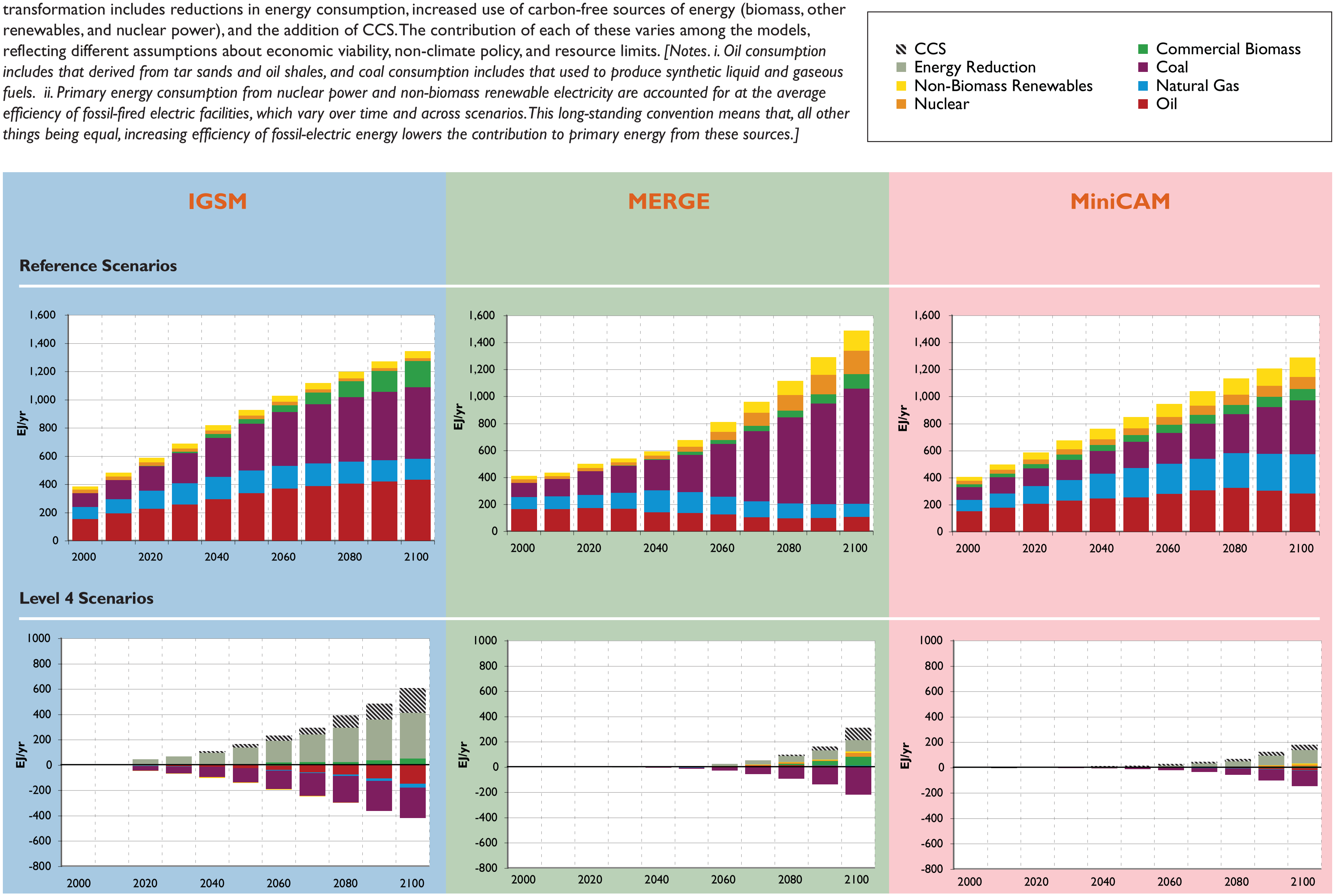
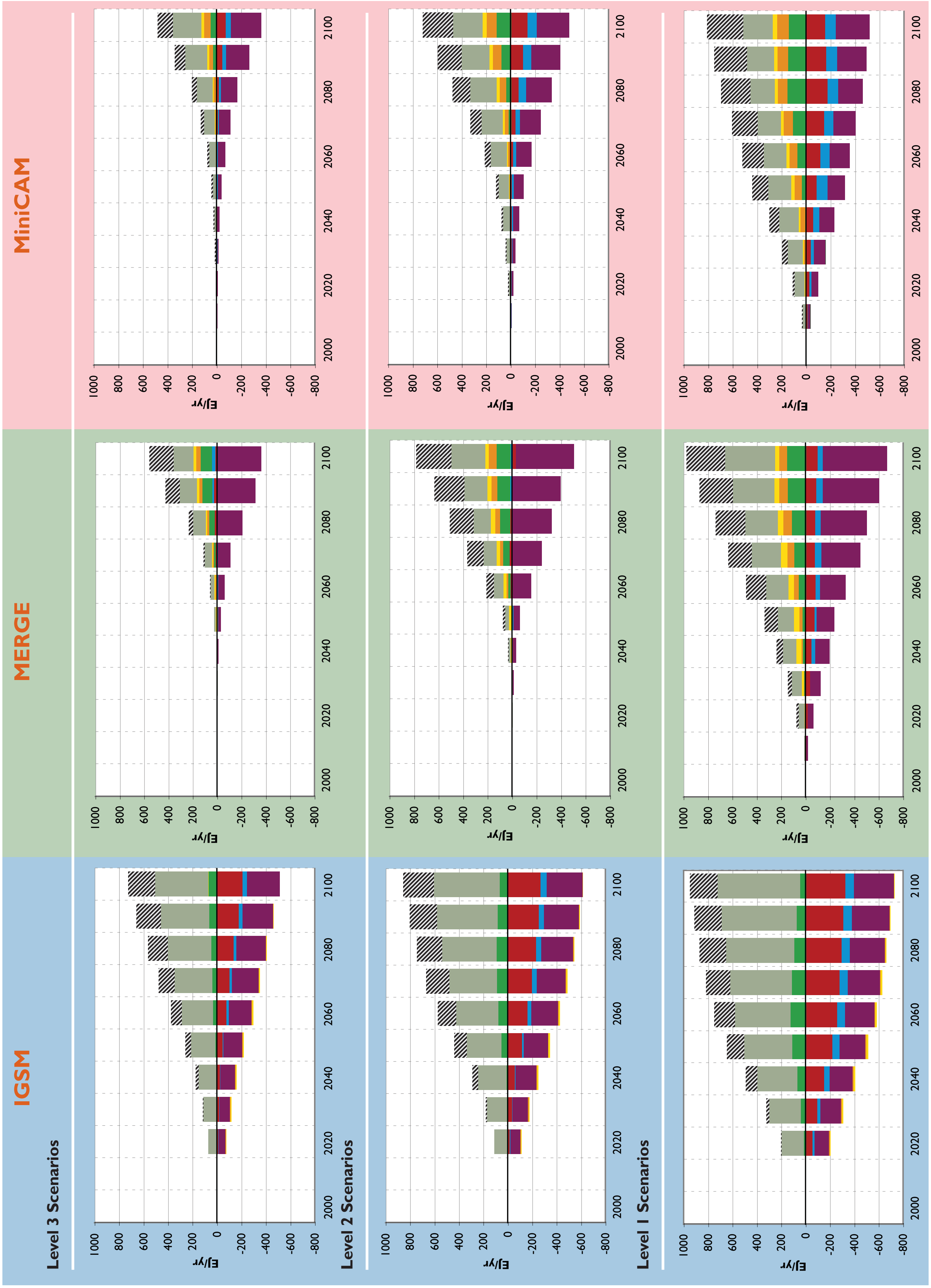
Figure 4.11. Change in Global Primary Energy Consumption by Fuel Across Stabilization Scenarios, Relative to Reference Scenarios (EJ/yr). The energy system is significantly transformed from the reference scenarios in the stabilization scenarios from all three modeling groups. The transformation begins later in the Level 3 and 4 stabilization scenarios, 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, and nuclear power), and the addition of CCS. The contribution of each of these varies among the models, reflecting different assumptions about economic viability, non-climate 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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MiniCAM
Level 3 Scenarios
Level 2 Scenarios
Level 1 Scenarios
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ture 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. For example, the prices of oil and carbon set the price at which bio-fuels compete. It is therefore possible to infer the marginal costs of bio-fuels when they first enter the market and how the marginal cost changes as the market expands.

It is worth reemphasizing that reductions in energy consumption are an important component of response at all stabilization levels. 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
- 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.

Changes in Global Electric Power Generation

Across the scenarios, stabilization leads to substantial changes in electricity-production technologies, although the MERGE and MiniCAM stabilization scenarios exhibit relatively little change in electricity production. Indeed, across the models, the relative reductions in electricity production under stabilization are lower than relative reductions in total primary energy consumption. One reason for this 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 consumer cost of electricity. 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 electricity production across the three reference scenarios, as shown in Chapter 3 and repeated at the top of Figure 4.12. Electricity production increases from about 50 EJ/yr in the year 2000 to between 230 EJ/yr (IGSM) to 310 EJ/yr (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/yr in 2000 to between 150 EJ/yr and 190 EJ/yr in 2100. Thus, the difference in total reference scenario electricity production among the models largely reflects differences in the deployment of non-fossil energy forms: bio-fuels, nuclear power, fuel cells, and other renewables such as wind, geothermal, and solar power.

The imposition of radiative forcing limits dramatically changes the electricity sector. Common characteristics of the stabilization scenarios across models are that CCS (with coal, gas, and, where present, oil-generated power) is deployed at a large scale by the end of the century and that use of coal without CCS declines and eventually is not viable. The IGSM scenarios, as has been noted, assume restrictions on the expansion of nuclear power, and other renewables are either resource limited (hydro power and electricity from bio-fuels) or become more costly to integrate into the grid as their share of electricity production rises because they are intermittent (wind and/or solar). Partly as a result, natural gas use in electricity production increases in the IGSM stabilization scenarios, especially in the nearer term before CCS becomes economically viable. In the MERGE stabilization scenarios, carbon-free technologies, including non-biomass renewables and nuclear, are viable and, thus, are favored over natural gas, the use of which falls relative to the reference scenario. In the MiniCAM stabilization scenarios, nuclear and non-biomass renewable energy technologies capture a larger share of the market. At the less stringent levels of stabilization, Level 3 and Level 4, additional bio-fuels are deployed in electricity production, and total electricity production declines. Under the most stringent stabilization level, commercial bio-fuels used in electricity production in the

Table 4.3. Global Annual CO_2 Capture and Storage in 2030, 2050, and 2100 for Four Stabilization Levels.

		Annual Global Carbon Capture and Storage (GtC/yr)		
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 4.4. Global Cumulative CO_2 Capture and Storage in 2050 and 2100 for Four Stabilization Levels.

		Cumulative Global Carbon Capture and Storage (GtC)		
Stabilization Level	**Year**	**IGSM**	**MERGE**	**MiniCAM**
Level 4	2030	0.0	0.0	1.1
	2050	3.6	0.0	3.4
	2100	91.7	21.1	20.7
Level 3	2030	0.2	0.0	1.2
	2050	8.5	0.0	4.0
	2100	152.8	64.2	51.8
Level 2	2030	0.5	0.0	1.5
	2050	19.5	3.2	6.4
	2100	208.0	187.7	144.2
Level 1	2030	1.8	7.4	6.9
	2050	36.7	32.4	43.0
	2100	230.6	272.5	278.0

MiniCAM stabilization scenarios are diverted to the transportation sector, and use in electricity production actually declines relative to the reference toward the end of the century. In all of the IGSM scenarios, bio-fuels are used preferentially for transportation rather than for electricity generation. The difference between MiniCAM and IGSM scenarios in this regard is in part a reflection of the higher fuel prices in the IGSM scenarios 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 scenarios CCS becomes a large-scale activity. Annual capture quantities are shown in Table 4.3. CCS is always one of the largest single changes in the electricity production system in response to stabilization, as can be seen in Figure 4.13. As with mitigation in general, CCS starts relatively modestly in all the scenarios, but grows to large levels. The total

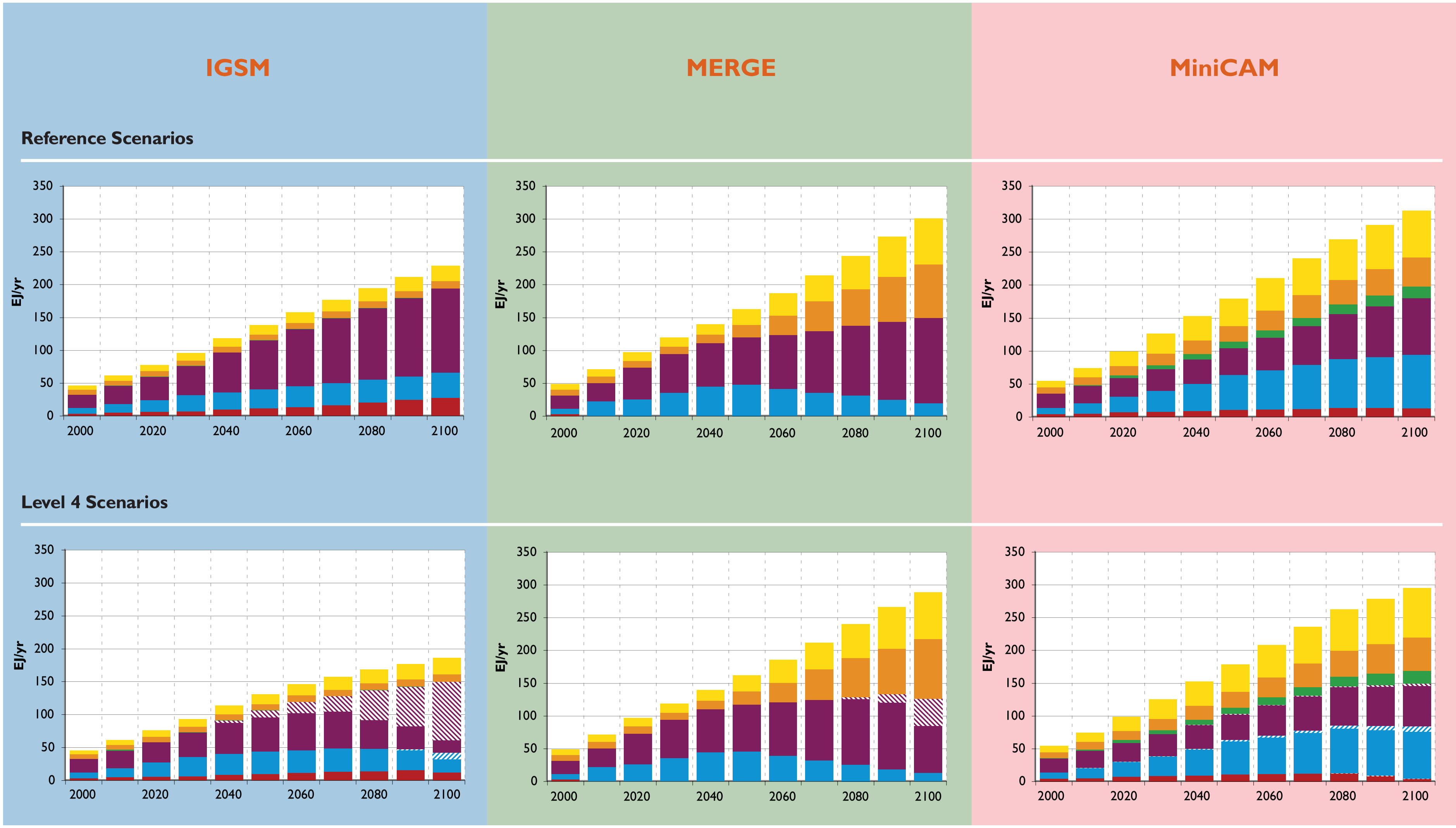

Figure 4.12. Global Electricity Production by Fuel Across Scenarios (EJ/yr). Global electricity production would need to be transformed to meet the four stabilization levels. CCS is important in the scenarios from all three modeling groups; thus, while coal use is reduced in all the stabilization scenarios relative to the reference scenarios, it remains an important fuel for electricity production. Use of CCS is the main supply response in the IGSM stabilization scenarios, in part because nuclear power is limited by assumption to reflect non-climate policy concerns. Nuclear power and renewable electricity sources play a larger role in the MERGE and MiniCAM stabilization scenarios.

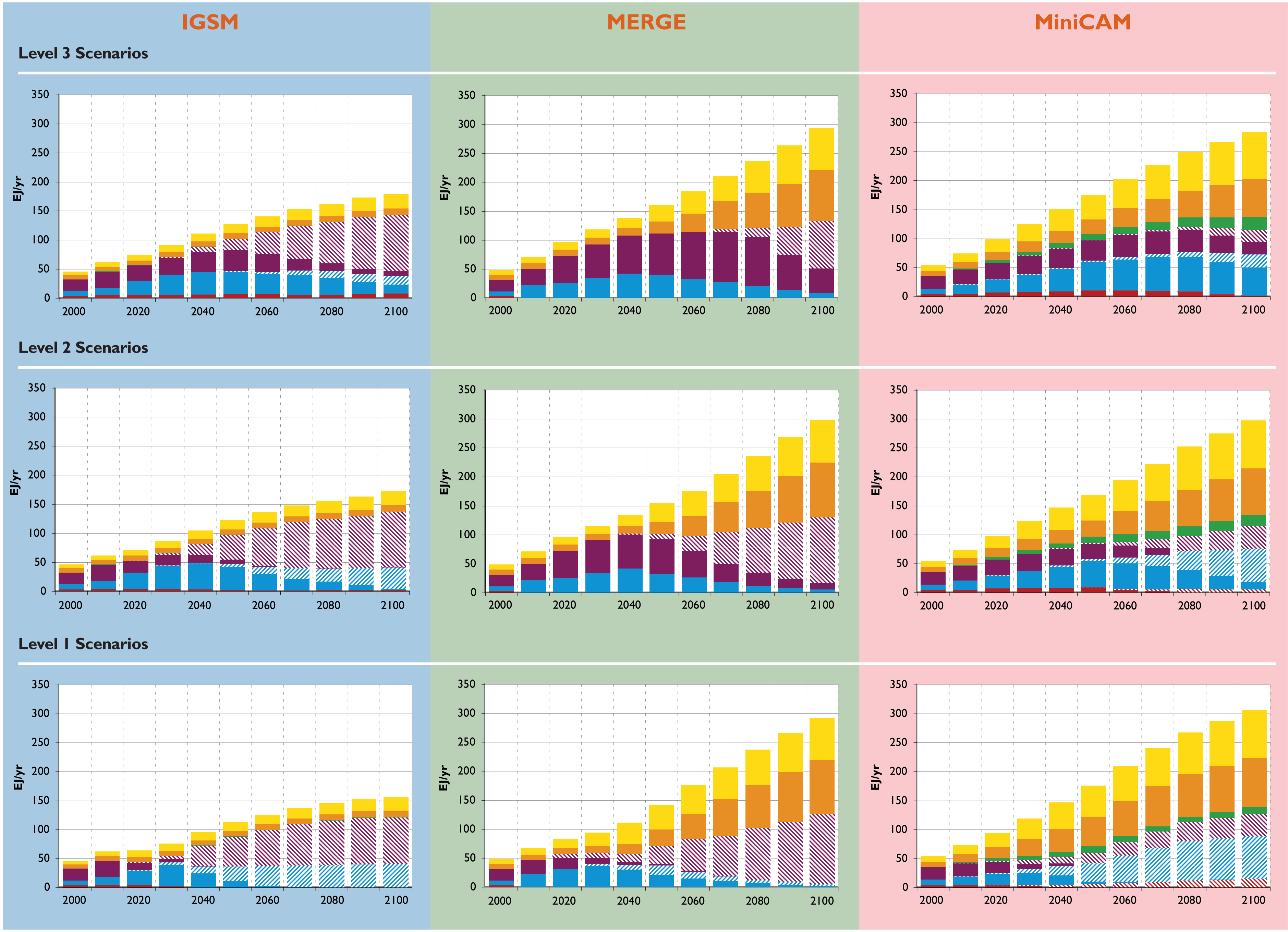
IGSM
MERGE
MiniCAM
Level 3 Scenarios
Level 2 Scenarios
Level 1 Scenarios
EJ/yr
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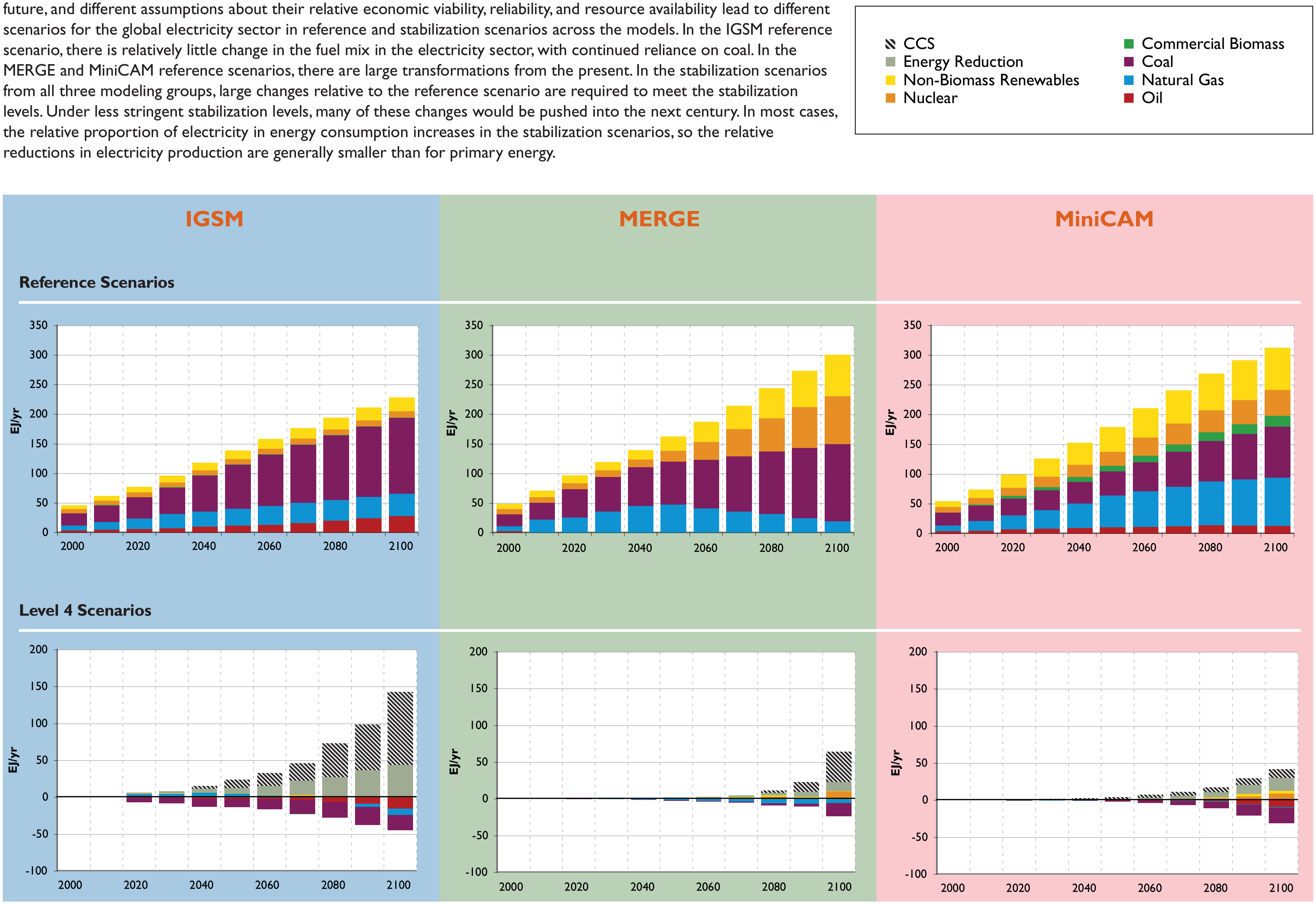
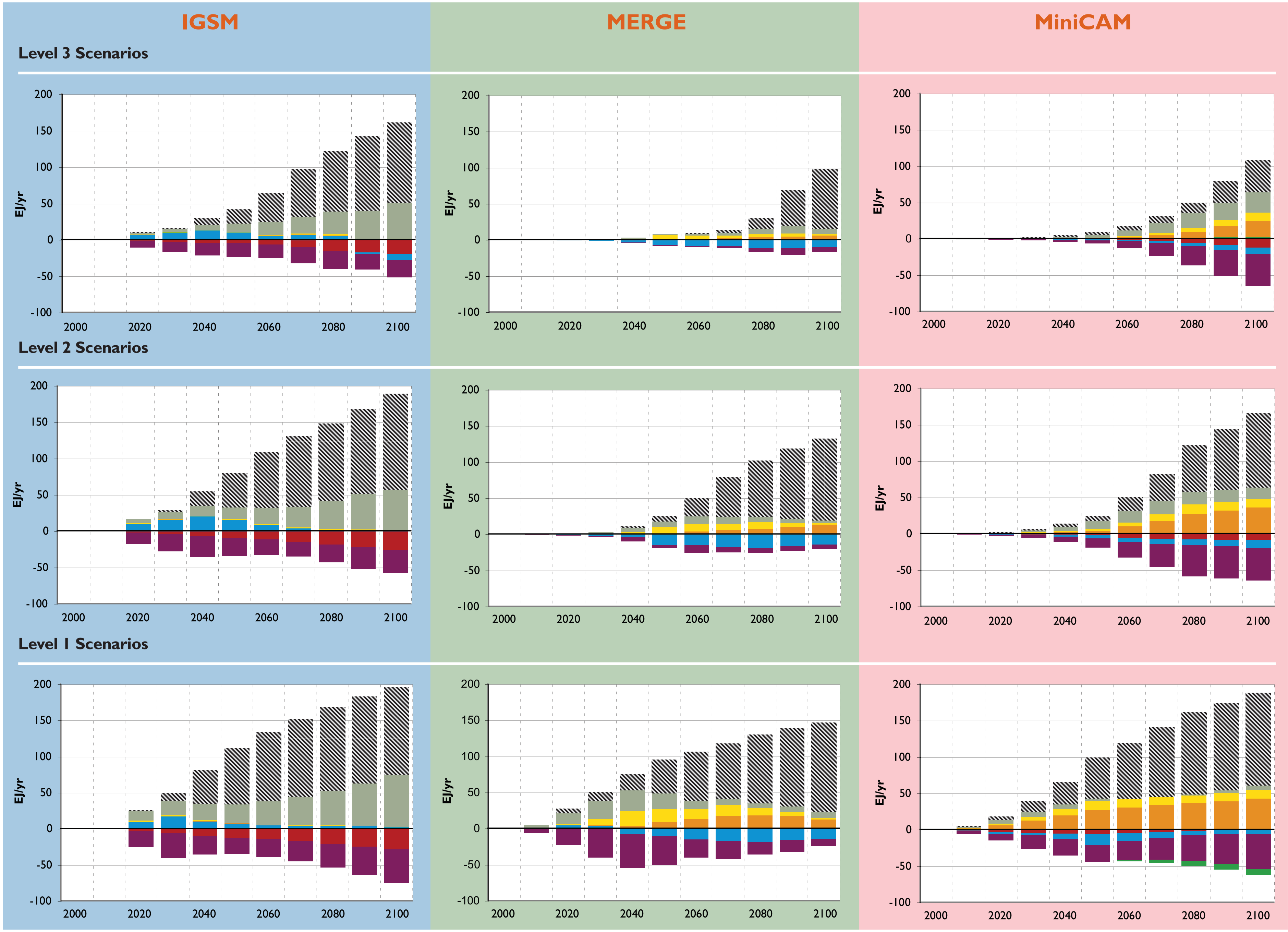
Figure 4.13. Changes in Global Electricity Production by Fuel Across Stabilization Scenarios, Relative to Reference Scenarios (EJ/yr). There are multiple electricity technology options that could be competitive in the future, and different assumptions about their relative economic viability, reliability, and resource availability lead to different scenarios for the global electricity sector in reference and stabilization scenarios across the models. In the IGSM reference scenario, there is relatively little change in the fuel mix in the electricity sector, with continued reliance on coal. In the MERGE and MiniCAM reference scenarios, there are large transformations from the present. In the stabilization scenarios from all three modeling groups, large changes relative to the reference scenario are required to meet the stabilization levels. Under less stringent stabilization levels, many of these changes would be pushed into the next century. 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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Level 3 Scenarios
Level 2 Scenarios
Level 1 Scenarios
EJ/yr
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storage over the century is recorded in Table 4.4, spanning a range from 20 GtC to 90 GtC for Level 4 and 230 GtC to 280 GtC for Level 1. The modeling groups did not 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 (Edmonds et al. 2001, Dooley et al. 2004).

Deployment rates for CCS 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, and that it successfully navigates other potential obstacles to widespread deployment, it could be a crucial component of future power generation.

Yet CCS 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 stabilization in all of the scenarios. These scenarios tend to favor CCS, but that tendency could easily change with different assumptions about technologies such as nuclear power that are well within the range of uncertainty about future costs and the policy environment. Nuclear power carries with it issues of safety, waste, and proliferation. Thus, the viability of both CCS and nuclear power depends on regulatory and public acceptance issues. For example, global nuclear power in the reference scenarios ranges from about 1½ times current levels (if non-climate concerns such as safety, waste, and proliferation constrain its growth as is the case in one reference scenario), to an expansion of almost an order of magnitude assuming relative economics as the only constraint.

Absent CCS and nuclear power, these models would need to deploy other emissions reduction options that could potentially be more costly, or would need to assume large breakthroughs in cost, performance, and reliability. 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.

Changes in Energy Patterns in the United States

Changes in U.S. energy patterns are similar to those observed for the world in general. This 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. primary energy consumption in 2000 represented roughly a quarter of the world total.

Changes in the U.S. energy system are modest for stabilization Level 4, but even with this loose constraint, significant changes begin upon implementation of the stabilization policy (the first period shown is 2020) in the IGSM Level 4 scenario (Figure 4.14 and Figure 4.15). Near-term changes are more modest in the MERGE and MiniCAM Level 4 scenarios. At more stringent stabilization levels, the changes are more substantial in the scenarios from all three modeling groups. In the Level 1 scenarios, the reduction is in U.S. primary energy consumption ranges from 8 EJ/yr to over 25 EJ/yr in 2020.

Near-term changes in the U.S. energy system vary more among models than the long-term adjustments. While oil consumption declines at higher carbon prices for all the models and all stabilization levels, near-term changes in oil consumption do not follow a consistent pattern. However, there is no ambiguity regarding the effect on coal consumption, which declines relative to the reference scenario in all stabilization scenarios for all models in all time periods. Similarly, total primary energy consumption declines in all the stabilization 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 across models.

The stabilization scenarios from the three modeling groups exhibit different energy sector responses reflecting differences in underlying reference scenarios and technology assumptions. The largest change in the U.S. energy system in the IGSM stabilization scenarios is the reduction in total primary energy consumption augmented by an expansion in the use of commercial biomass fuels and deployment of CCS. Similarly, the largest change in the MERGE scenarios is the reduction in total primary energy consumption augmented by deployment of CCS and bioenergy. The MiniCAM stabilization scenarios also exhibit reductions in primary energy consumption and increases in nuclear power, along with smaller additions of commercial biomass and other renewable energy forms. The adjustment of the U.S. electric sector to the various stabilization levels is similar to that for the world electricity sector. (Figure 4.16 and Figure 4.17).

IMPLICATIONS FOR AGRICULTURE, LAND-USE, AND TERRESTRIAL CARBON

In the stabilization scenarios, increased use is made of biomass energy crops, the contribution of which is ultimately limited by competition with agriculture and forestry. Two of the modeling groups employed explicit agriculture-land-use models to represent this competition and represent land constraints on the use of bio-energy. In the scenarios from one modeling group, increased use of bio-energy at more stringent stabilization levels leads to substantial land use change emissions as previously unmanaged lands are shifted to biomass production.

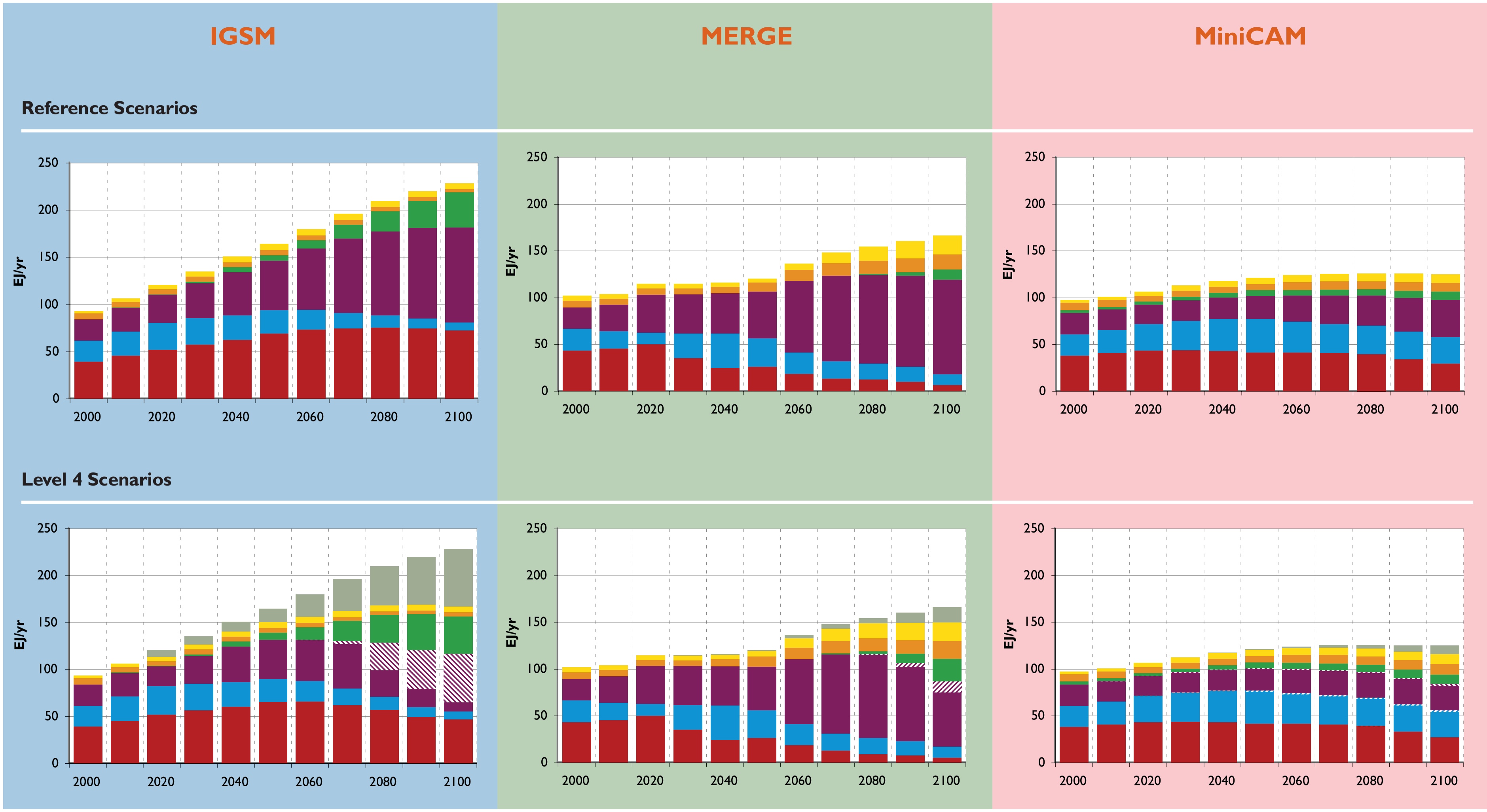
The three modeling groups employed different approaches to the treatment of the terrestrial carbon cycle, ranging from a simple neutral biosphere model to a state-of-the-art terrestrial carbon-cycle model. In two of the models, a CO_2 fertilization effect plays a significant role. As stabilization levels 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 groups' treatments of the terrestrial carbon cycle, the aggregate behavior of the carbon cycles across models is similar.

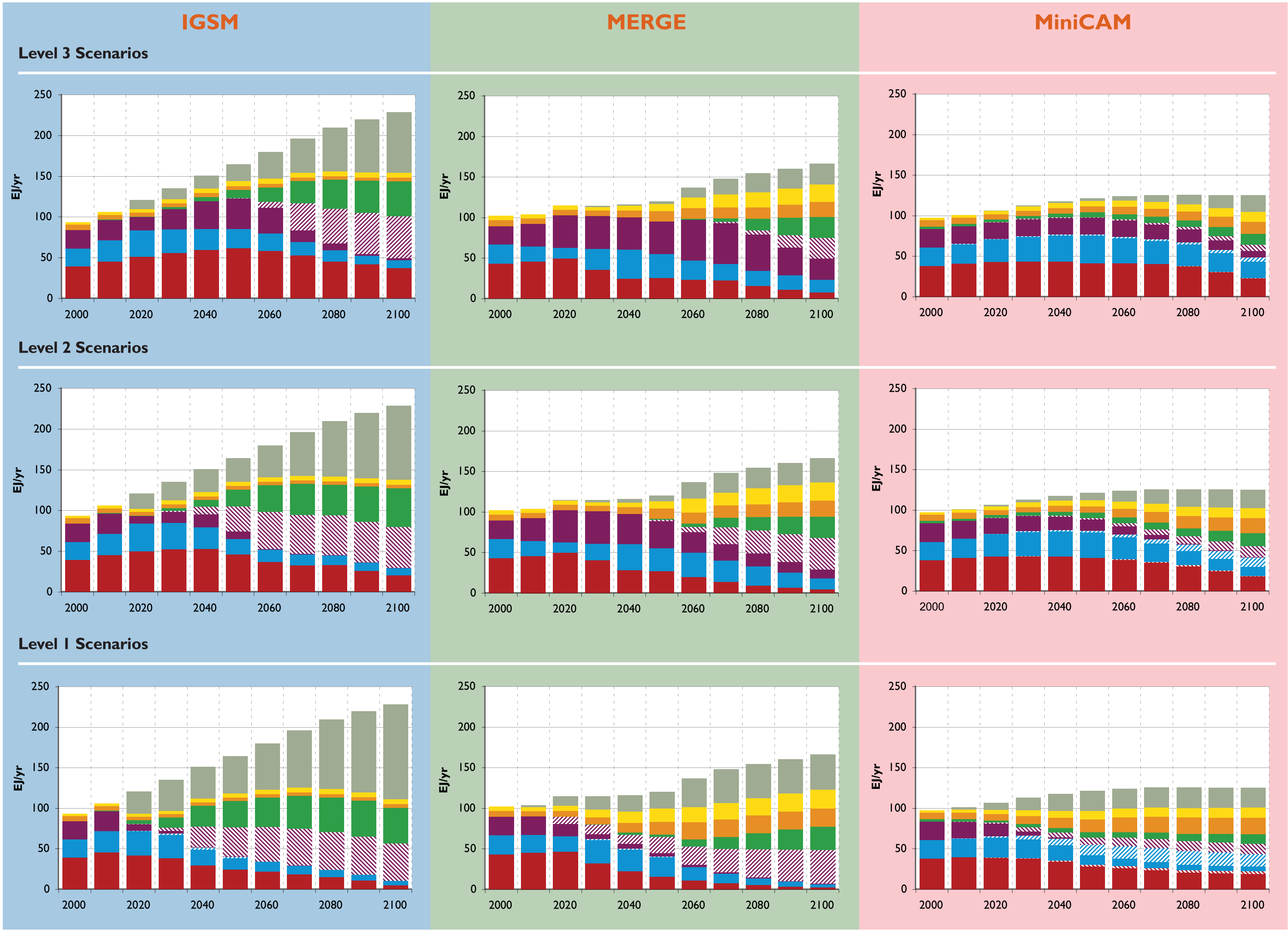
In the stabilization scenarios, the cost of using fossil fuels and emitting CO_2 rises, providing an increasing motivation for the production and transformation of bioenergy, as shown in Figure 4.18. In all of the stabilization scenarios, production begins earlier and produces a larger share of global energy as the stabilization level becomes more stringent. Under less stringent stabilization levels, production of bio-crops is lower in the second half of the century in the MERGE and MiniCAM scenarios than in the IGSM scenarios. 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 areas 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 the MiniCAM and IGSM scenarios – MiniCAM and IGSM are the two models with agriculture and land-use submodels – demands on land for bio-fuels cause land prices to increase substantially as compared with the reference scenarios because of competition with other agricultural demands.

Stabilization scenarios limit the rise in CO_2 concentrations and reduce the CO_2 fertilization effect below that in the reference scenarios, which in turn leads to smaller CO_2 uptake by the ter-

Figure 4.14. U.S. Primary Energy Consumption by Fuel Across Scenarios (EJ/yr). U.S. primary energy consumption under the four stabilization levels differs considerably among the three models. All the scenarios 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 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.]*




IGSM
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Level 3 Scenarios
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Level 1 Scenarios
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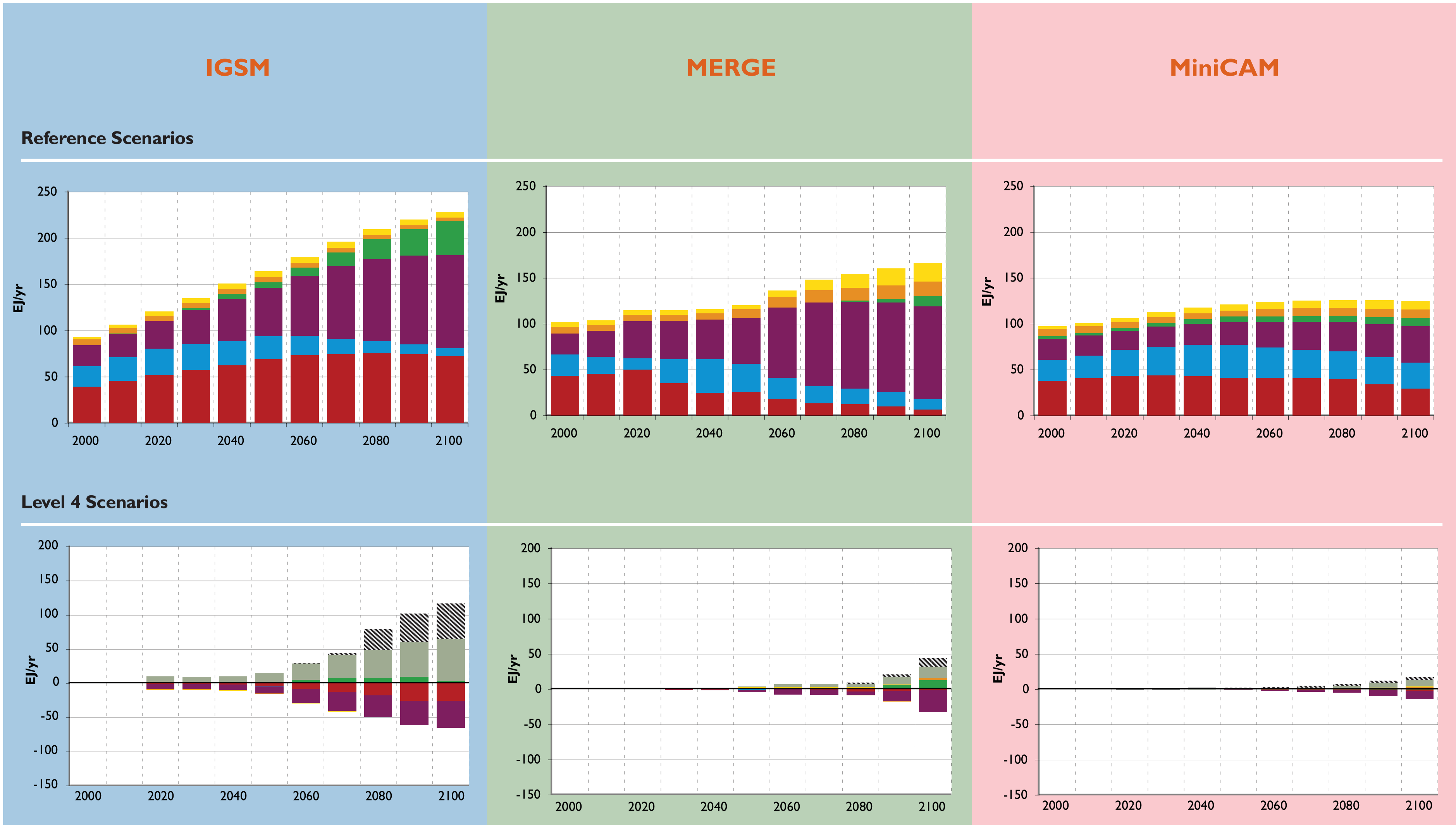
Figure 4.15. Changes in U.S. Primary Energy Consumption by Fuel Across Stabilization Scenarios, Relative to Reference Scenarios (EJ/yr). The transformations in the U.S. energy system in the stabilization scenarios are similar to those for the global energy system. Although it is not illustrated in this figure, one difference is the transformation from conventional oil and gas to synthetic fuel production derived from shale oil or coal. The IGSM reference scenario includes heavy use of shale oil with some coal gasification, whereas the MERGE reference scenario is based more heavily on synthetic liquid and gaseous fuels derived from coal. The MiniCAM reference scenario includes moderate levels 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.]*

▨ CCS
🟫 Energy Reduction
🟨 Non-Biomass Renewables
🟧 Nuclear
🟩 Commercial Biomass
🟪 Coal
🟦 Natural Gas
🟥 Oil



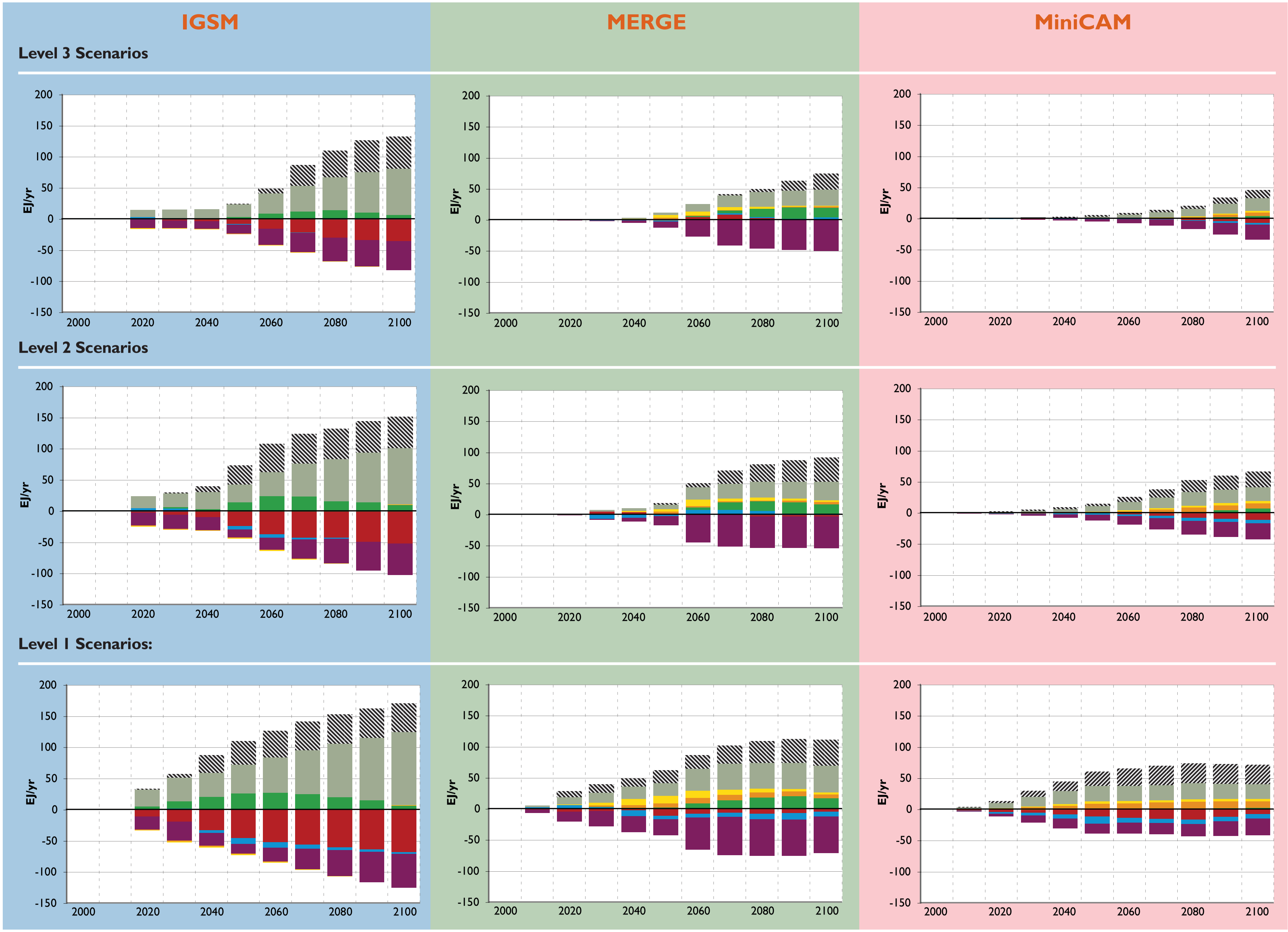

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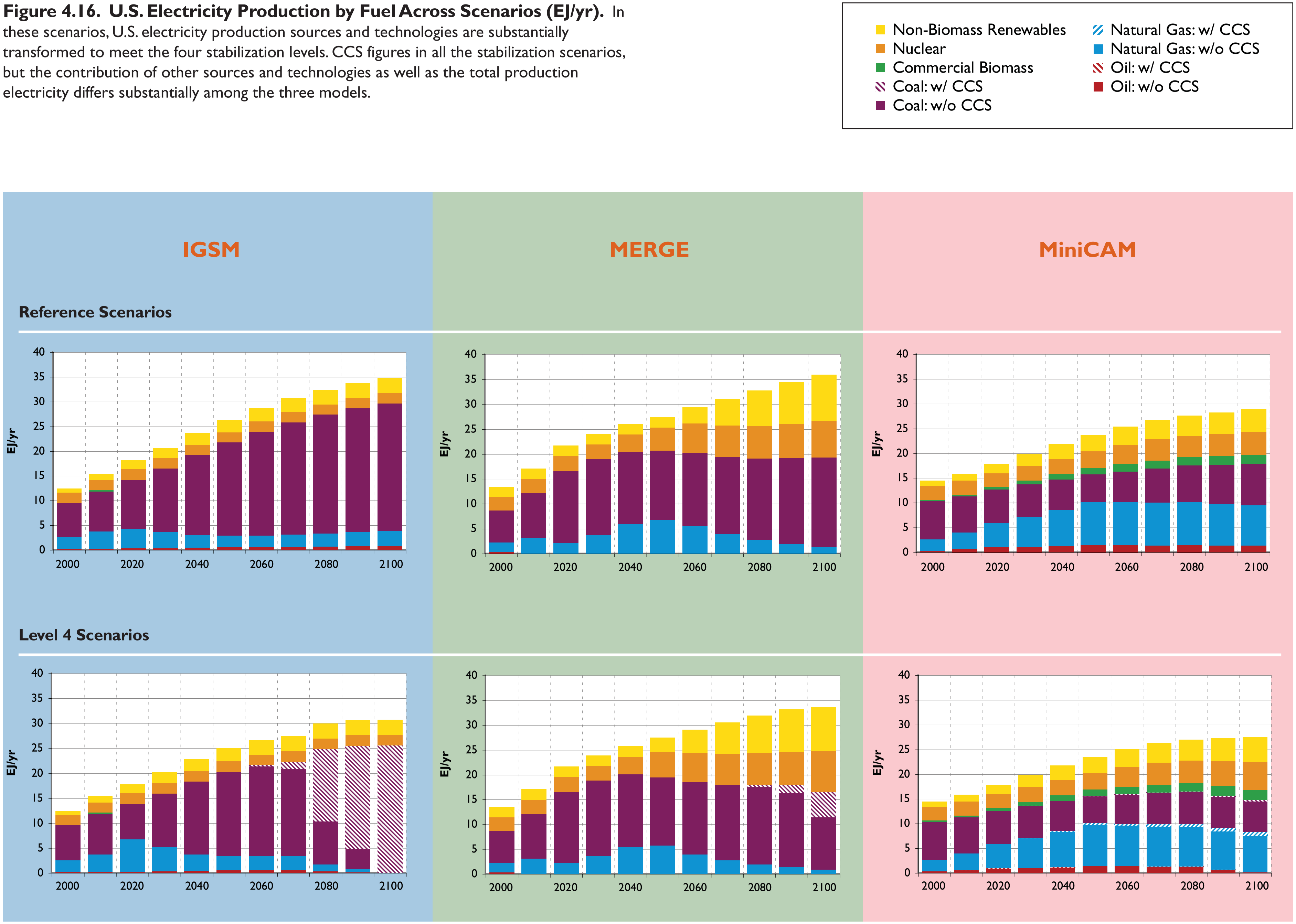
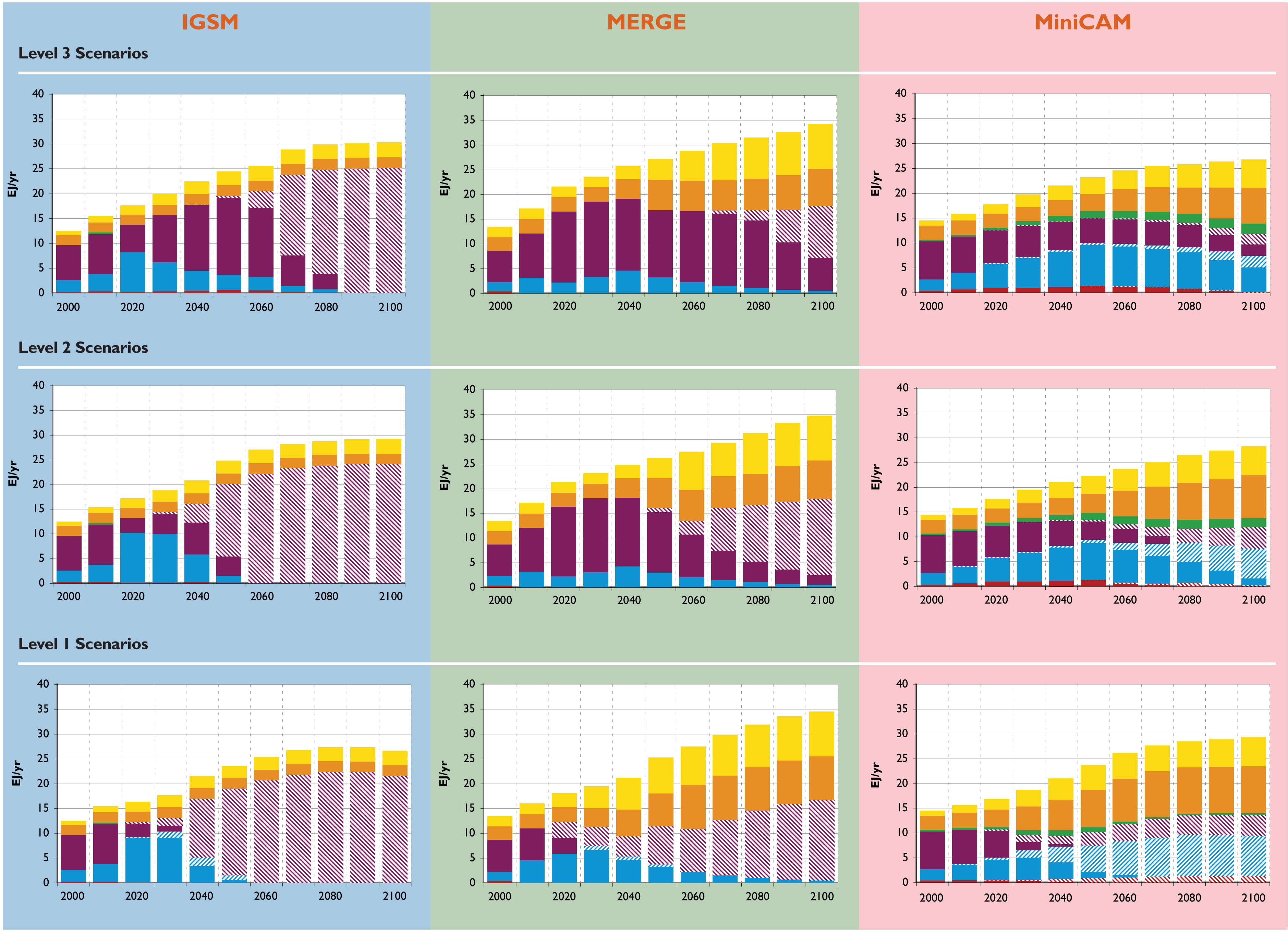
Figure 4.16. U.S. Electricity Production by Fuel Across Scenarios (EJ/yr). In these scenarios, U.S. electricity production sources and technologies are substantially transformed to meet the four stabilization levels. CCS figures in all the stabilization scenarios, but the contribution of other sources and technologies as well as the total production electricity differs substantially among the three models.

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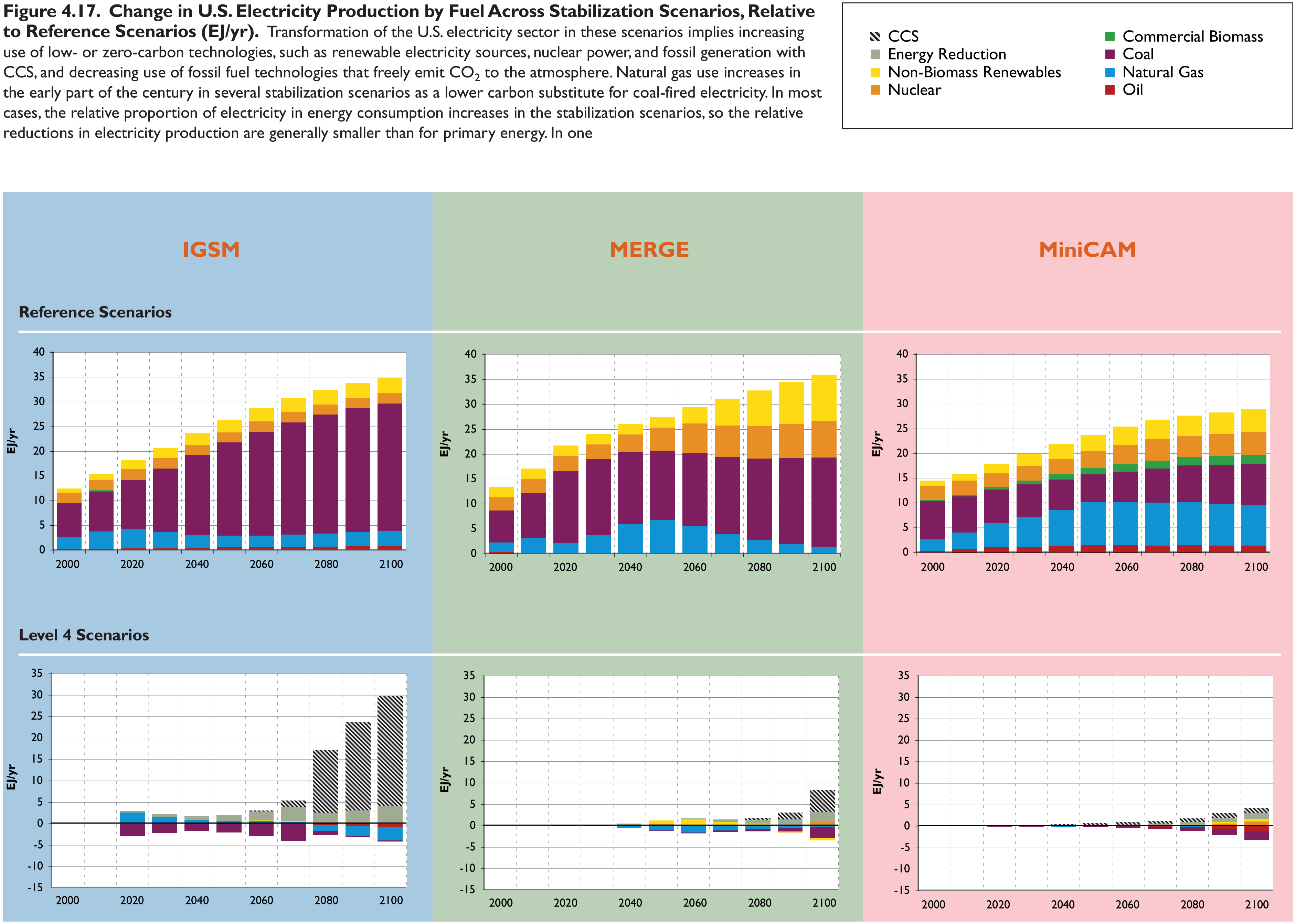
2100

Figure 4.17. Change in U.S. Electricity Production by Fuel Across Stabilization Scenarios, Relative to Reference Scenarios (EJ/yr). Transformation of the U.S. electricity sector in these scenarios implies increasing use of low- or zero-carbon technologies, such as renewable electricity sources, nuclear power, and fossil generation with CCS, and decreasing use of fossil fuel technologies that freely emit CO_2 to the atmosphere. Natural gas use increases in the early part of the century in several stabilization scenarios as a lower carbon substitute for coal-fired electricity. 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




IGSM
MERGE
MiniCAM
Level 3 Scenarios
Level 2 Scenarios
Level 1 Scenarios
EJ/yr
35
30
25
20
15
10
5
0
-5
-10
-15
2000
2020
2040
2060
2080
2100

Figure 4.18. 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 scenarios. Dramatic growth in bioenergy crop production raises important issues about 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 other resource and environmental impacts.

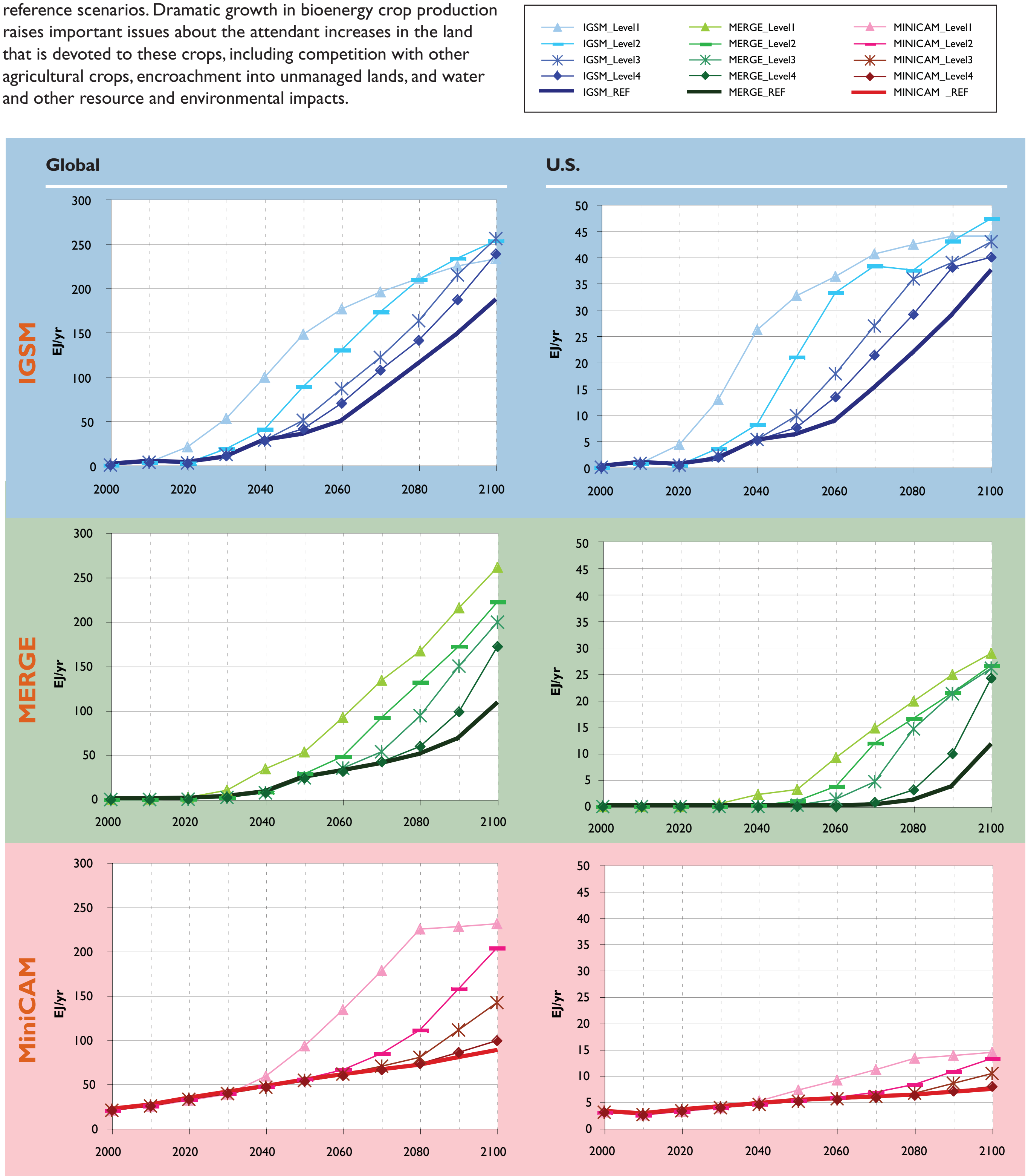
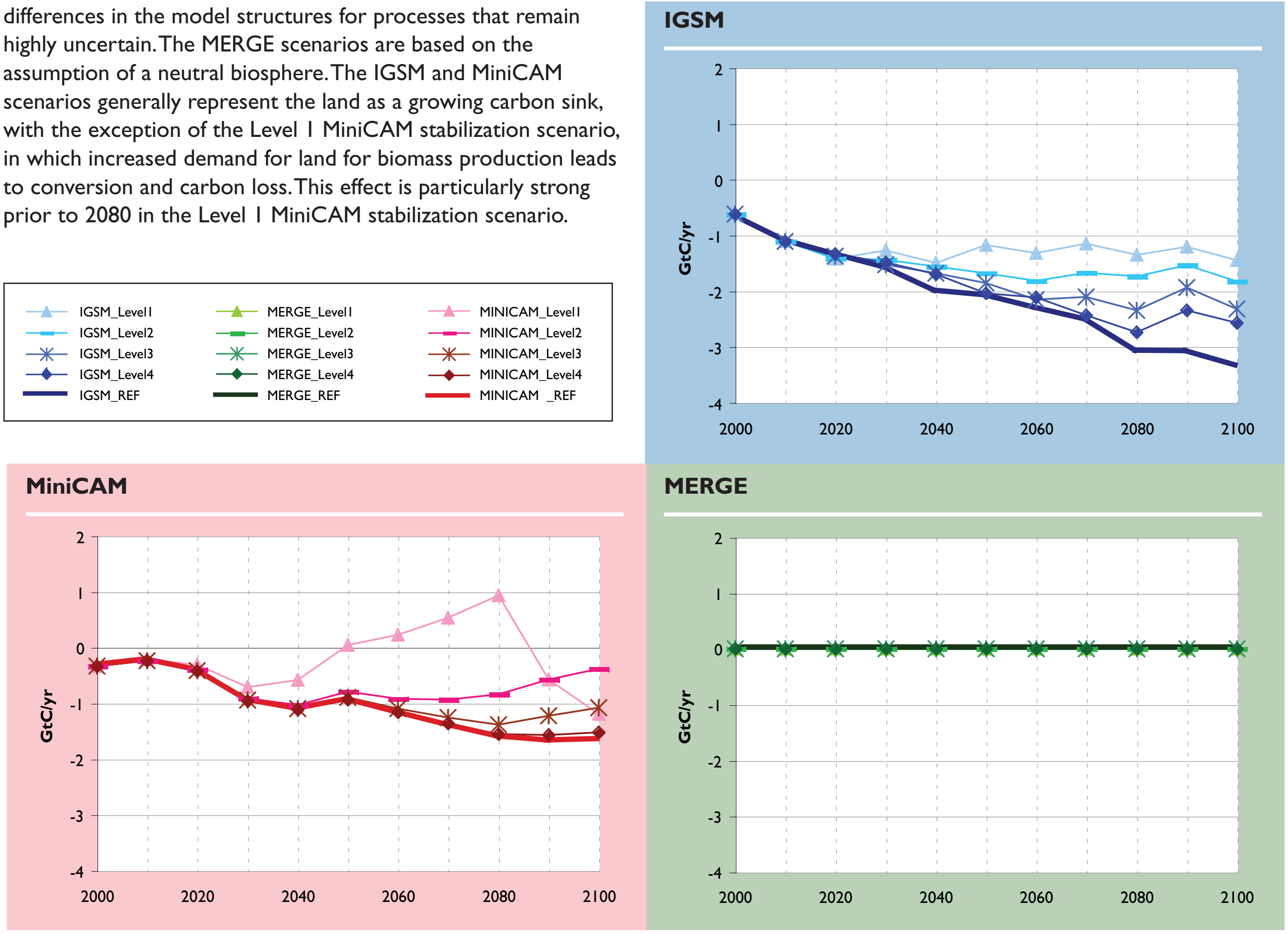


Figure 4.19. Net Terrestrial Carbon Emissions Across Scenarios (GtC/yr). Net terrestrial carbon emissions to the atmosphere, under reference and stabilization levels, reflect differences in the model structures for processes that remain highly uncertain. The MERGE scenarios are based on the assumption of a neutral biosphere. The IGSM and MiniCAM scenarios generally represent the land as a growing carbon sink, with the exception of the Level 1 MiniCAM stabilization scenario, 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 stabilization scenario.



restrial biosphere in the IGSM and MiniCAM stabilization scenarios (Figure 4.19). The effect is larger and begins earlier the more stringent the stabilization level. For example, in the IGSM Level 4 scenario, the effect becomes substantial after 2070 and amounts to about 0.8 GtC/yr 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/yr 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. The MiniCAM stabilization scenarios exhibit similar carbon cycle behavior. The MERGE stabilization scenarios maintain the assumption of a neutral terrestrial biosphere as in the MERGE reference scenario.

The MiniCAM scenarios also include a second effect that results from the interaction between the energy system and emissions from changes in land use, such as converting previously unmanaged lands to bioenergy crop production. As in the IGSM scenarios, economic competition among alternative human activities, crops, pasture, managed forests, bioenergy crops, and unmanaged ecosystems determine land use. In the MiniCAM scenarios, this competition also determines land-use change emissions. One implication is increasing pressure to deforest under stabilization in order to clear space for biomass crops (Sands and Leimbach 2003). 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. Thus, terrestrial uptake in the MiniCAM scenarios is

Figure 4.20. Carbon Prices Across Stabilization Scenarios ($/tonne C, 2000$). In all the stabilization scenarios, the carbon 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 stabilization scenarios, on the one hand, and the IGSM stabilization scenarios on the other. Differences between the models reflect differences in the emissions reductions necessary for stabilization and differences in the technologies that might facilitate carbon emissions reductions, particularly in the second half of the century.

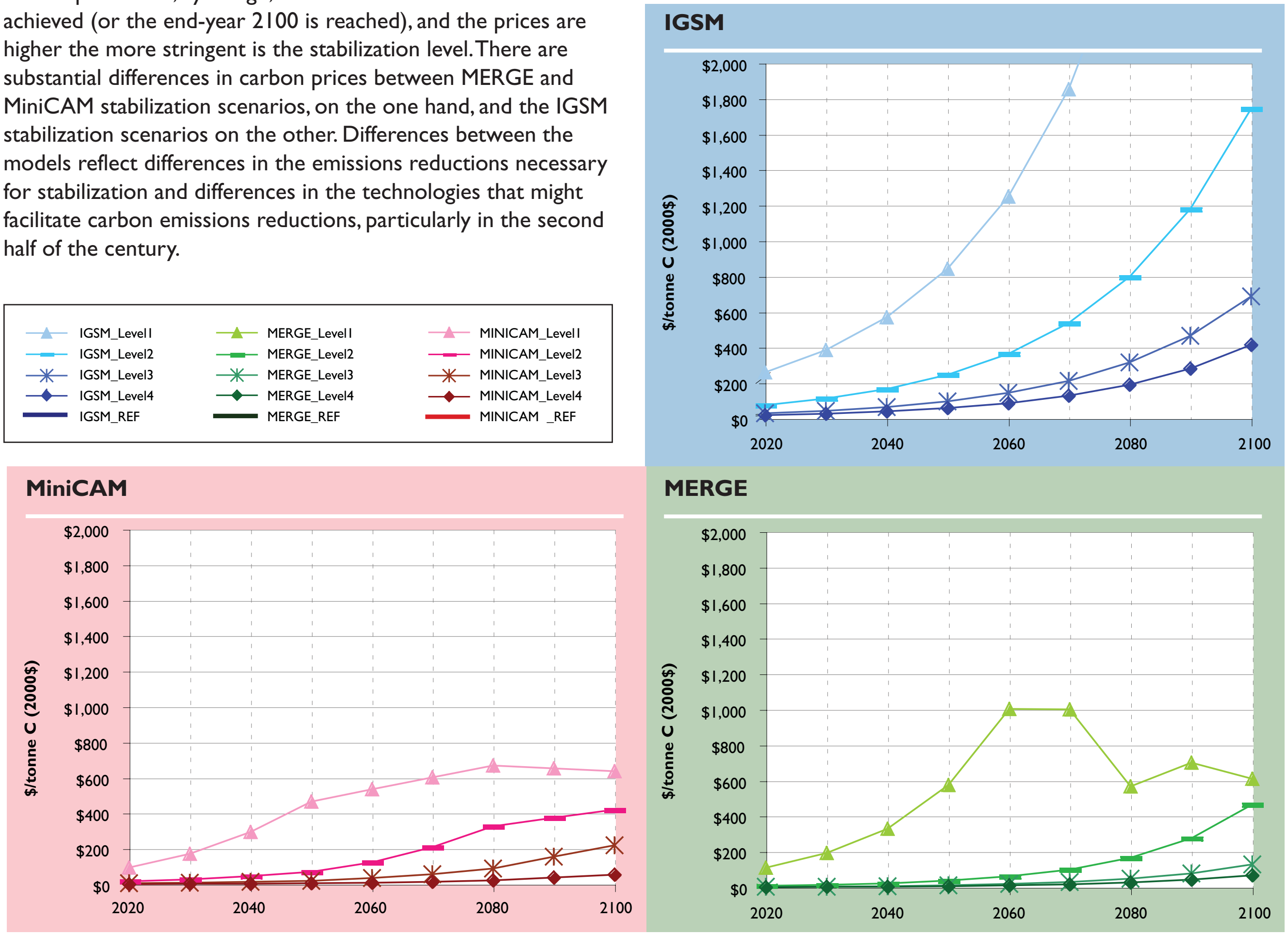


Table 4.5. Carbon Prices in 2020, 2030, 2050, and 2100 for Each Stabilization Scenario and Model.

	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

reduced because of the lower CO_2 fertilization effects as in the IGSM scenarios, and it is also reduced by any land use change emissions that derive from the increasing demand for bioenergy crops.

The terrestrial emissions reported in Figure 4.19 for the MiniCAM scenarios assume a policy architecture that places a value on energy and industrial emissions as well as carbon in terrestrial systems. 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. Pricing terrestrial carbon exerts an important counter-pressure to deforestation and other land-use changes that generate increased emissions. To illustrate this effect, sensitivity cases were run by the MiniCAM modeling group in which no price was applied to terrestrial carbon emissions. These sensitivity analyses showed increased levels of land-use change emissions when terrestrial carbon was not valued, particularly at the more stringent stabilization levels, and the potential for a vicious cycle to emerge. Efforts to reduce emissions in the energy sector create an incentive to expand bioenergy production without a counter incentive to maintain carbon in terrestrial stocks. The resultant deforestation increases terrestrial CO_2 emissions, requiring even greater reductions in fossil fuel CO_2 emissions, even higher prices on fossil fuel carbon, and further increases in the demand for bioenergy, leading, in turn, to additional deforestation. The net terrestrial emissions for the MiniCAM scenarios reported here avoid this vicious cycle because they include a policy architecture that places a value on terrestrial carbon.

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.

ECONOMIC IMPLICATIONS OF STABILIZATION

The economic implications of stabilization include increases in the prices of fossil fuels and electricity, along with reductions in economic output. Substantial differences in GHG emissions prices and associated economic costs arise among the modeling groups for each stabilization level. Among the most important factors influencing the variation in economic costs are: (1) differences in assumptions – such as those regarding economic growth over the century, the behavior of the oceans and terrestrial biosphere in taking up CO_2, and opportunities for reduction in non-CO_2 GHG emissions – that determine the amount that CO_2 emissions that must be reduced to meet the radiative forcing stabilization levels; and (2) differences in assumptions about technologies, particularly in the second half of the century, to shift final demand to low-CO_2 sources such as biofuels and low-carbon electricity or hydrogen in transportation, industrial, and buildings end uses. Although differences in technology do not strongly emerge until the second half of the century, they cast a shadow over the full century because of the manner in which all three the modeling groups allocated carbon emissions reductions over time.

In most scenarios, carbon prices depress demand for fossil fuels and therefore their producer prices. Electricity producer prices generally increase because of increasing demand for electricity along with substitution to higher cost, lower emitting electricity production technologies. Consumer prices for all fuels (fuel price plus the carbon price for emitted carbon plus any added cost of capturing and storing carbon) are generally higher under the stabilization scenarios due to carbon price. The approaches to Non-CO_2 GHG prices differs among the modeling groups, reflecting differing approaches to the tradeoffs between reductions in the emissions of these GHGs and reductions in CO_2 emissions.

Stabilization and Carbon Prices

As discussed earlier, all of the modeling groups implemented prices or constraints that provide economic incentives to reduce GHG emissions. The instruments used to reduce CO_2 emissions in the models can be interpreted as the carbon price that would be consistent with either a universal cap-and-trade system or a harmonized carbon tax.

Across models, the more stringent stabilization levels require higher carbon prices because they require larger emissions reductions (Figure 4.20 and Table 4.5). Stabilization becomes increasingly difficult at the more stringent stabilization levels as can be seen in the difference in carbon prices between Level 2 and Level 1 as compared to that between Level 3 and Level 4. (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 $CO_{ç}$.)

Table 4.6. Cumulative Emissions Reductions Across 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

Across models, the carbon prices rise exponentially throughout the century (in the IGSM scenarios) or until stabilization is reached (in the MERGE and MiniCAM scenarios). This similarity in the qualitative structure of the carbon price paths reflects the similarity in the approach that the modeling groups took to allocate emissions reductions over time, or *when* flexibility, as discussed in Section 4.2. This approach to *when* flexibility, with a carbon price that rises over time, tends to minimize the present discounted cost of emissions mitigation over the whole century. It also has the effect of linking future carbon prices to near-term carbon prices in a predictable way. Thus, when there are differences in technology assumptions that mostly appear in the second half of the century or in reference emissions that occur mostly in the middle of the century, the assumption imposed on the price path means that the burden of emissions reduction is spread over the entire century. In this way, forces that do not emerge until mid-century or beyond cast a shadow onto the present.

At every stabilization level, there is variation in the carbon prices among the models. For example, the carbon price in 2100 exceeds $1700/tonne C in the IGSM Level 2 scenario while the carbon prices in the MERGE and MiniCAM Level 2 scenarios are $420 to $460/tonne C. The ratio among the models of carbon prices for other stabilization levels follows the same pattern. The range of carbon prices shown in these scenarios is consistent with other studies in the literature (IPCC 2001).

The carbon prices in the scenarios in this study are the result of a complex interplay of differing structural characteristics of the participating models and variation in key parameter values. Nonetheless major differences among carbon prices can be attributed to two influences: (1) the amount that emissions must be reduced to

Figure 4.21. Relationship Between Carbon Price and Percentage Emissions Reductions in 2050 and 2100. The relationship between carbon price and percentage reductions in carbon emissions is similar among the models in 2050. In 2100, a given percentage emissions reduction is generally more expensive in the IGSM stabilization scenarios than in the MERGE and MiniCAM stabilization scenarios. The difference in 2100 is due, in large part, to different assumptions regarding the technologies available to facilitate emissions reductions in the second half of the century, with IGSM scenarios assuming relatively fewer or more costly options than the scenarios from the other two modeling groups.

[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.]

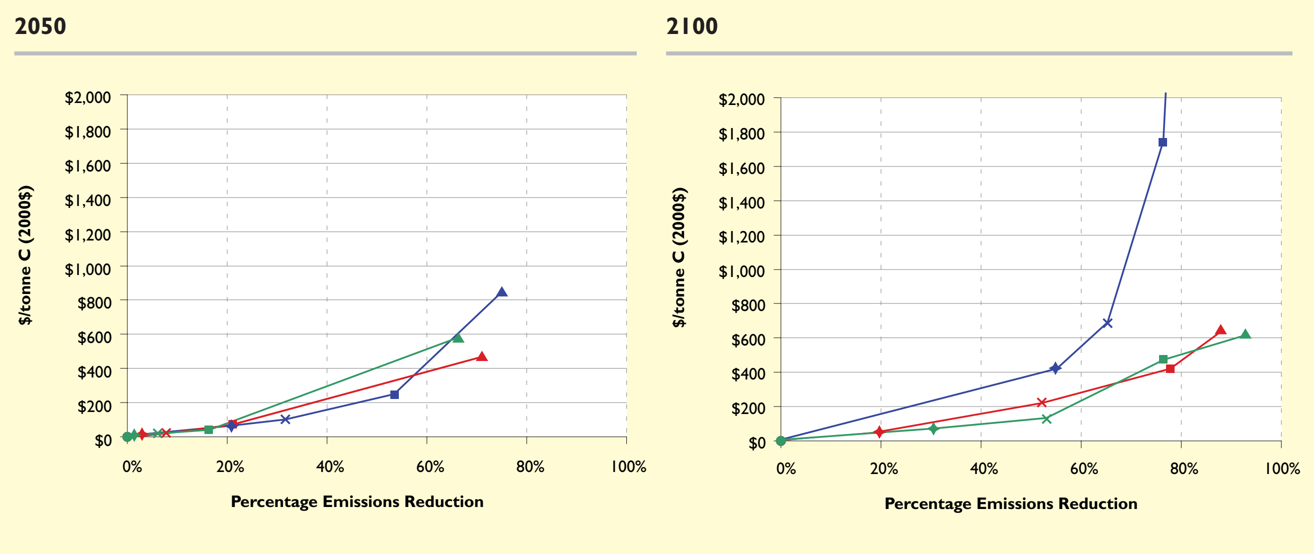
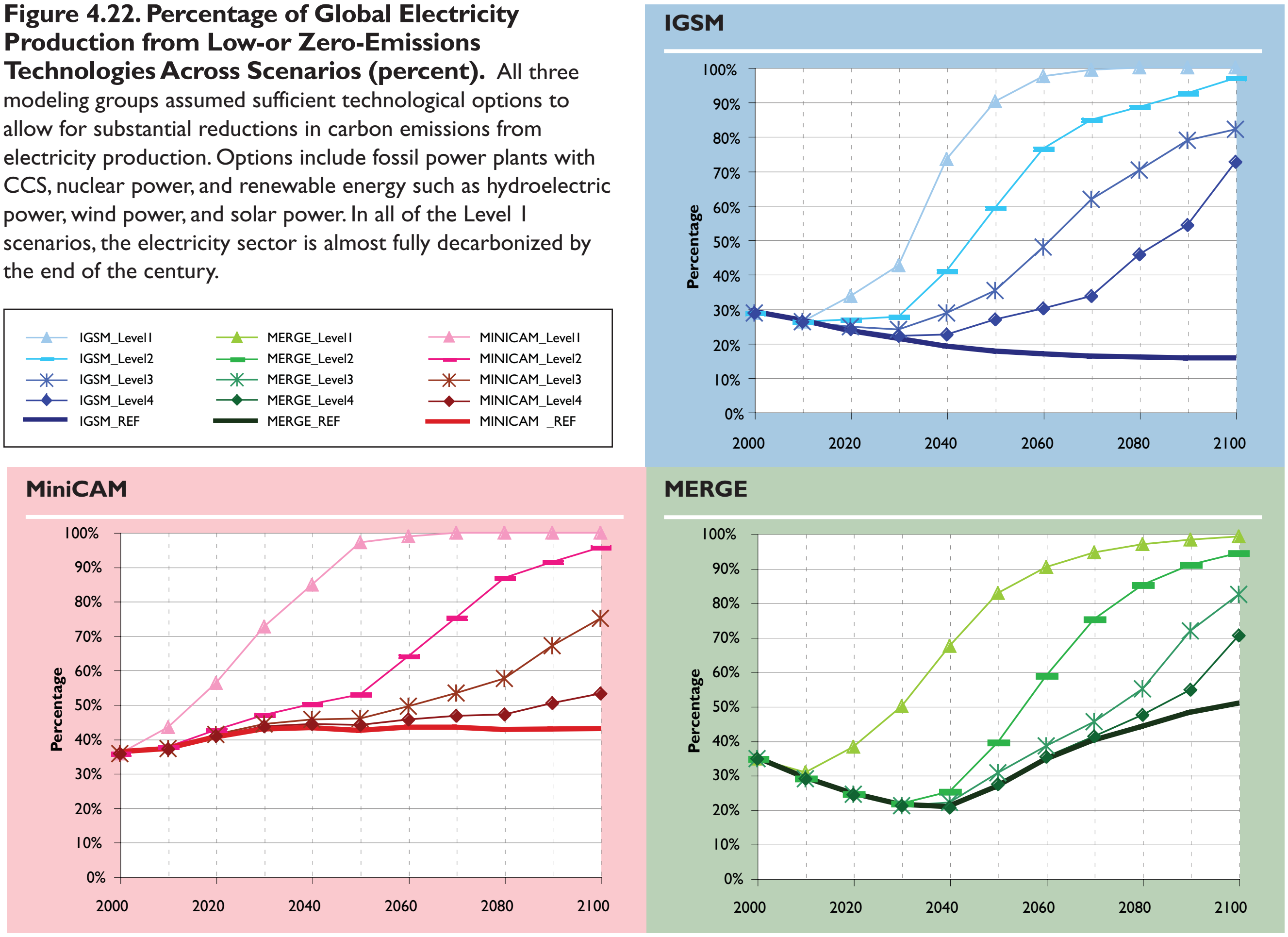


Figure 4.22. Percentage of Global Electricity Production from Low-or Zero-Emissions Technologies Across Scenarios (percent). All three modeling groups assumed sufficient technological options to allow for substantial reductions in carbon emissions from electricity production. Options include fossil power 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.

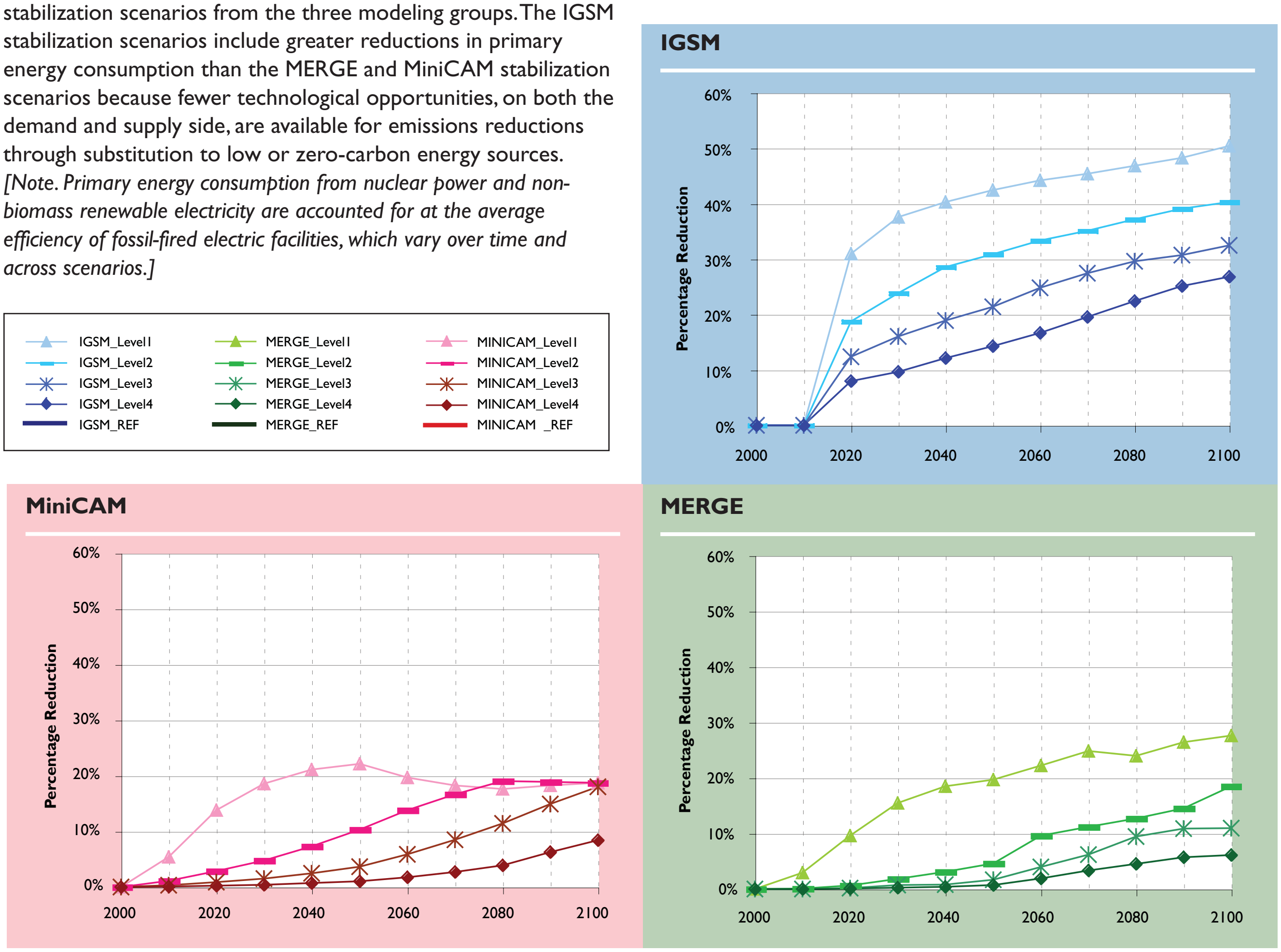


achieve an emissions path to stabilization, and (2) the technologies that are available to facilitate these changes in the economy.

On the first point, Table 4.6 shows the cumulative CO_2 emissions reductions required over the century across all four stabilization scenarios from each modeling group. Differences in total reductions come principally from three aspects of model behavior and assumptions: differences in forces, such as economic growth, that determine emissions in the reference scenario (Tables 3.2 and 3.3, and Figure 3.2); the behavior of the ocean and terrestrial systems in taking up carbon (Figure 4.6 and Figure 4.19); and the technological options available for constraining the emissions of non-CO_2 GHGs (Figure 4.8 and Figure 4.9). At all stabilization levels, the IGSM stabilization scenarios require greater CO_2 emissions reductions than the MERGE or MiniCAM stabilization scenarios. Indeed, the emissions reductions in the IGSM Level 2 scenario are commensurate with those of the MERGE and MiniCAM Level 1 scenarios. All other things being equal, the greater the required emissions reductions the higher will be the emissions prices required to meet each target.

The second factor, the modeling of technology, also contributes to the differences among costs. The aggregate effect of differing technological assumptions is illustrated in Figure 4.21, which shows the relationship between the carbon price and percentage emissions reductions in 2050 and 2100 across all four stabilization scenarios from each modeling group. Roughly speaking, these figures represent what economists refer to as the marginal abatement cost functions for these periods. They broadly capture the technological opportunities for emissions reductions represented in the models. The similarity between the marginal abatement cost functions in 2050 implies that the technological opportunities represented by the three modeling groups are similar in 2050. The implication is that if the three modeling groups were to determine the carbon price associated with, for example, a 50% reduction in emissions in 2050, the results would be similar.

Figure 4.23. Percentage Reduction in World Primary Energy Consumption Across Scenarios (percent). Differences in assumptions about technological opportunities result in different aggregate approaches to emissions reductions in the stabilization scenarios from the three modeling groups. The IGSM stabilization scenarios include greater reductions in primary energy consumption than the MERGE and MiniCAM stabilization scenarios because fewer technological opportunities, on both the demand and supply side, are available for emissions reductions through substitution to low or zero-carbon energy sources. *[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.]*



It is in the second half of the century that substantial differences in the marginal abatement cost functions emerge, particularly when the required abatement pushes towards and beyond 60% below the reference level as is the case in the Level 1 and Level 2 scenarios. There is no small set of technology assumptions used by the modeling groups that determines these differences. Among the modeling groups, assumptions about technology vary along a range of dimensions such as the rate of growth in labor productivity, the cost and performance of particular energy supply technologies, the productivity of agriculture and the associated costs of bioenergy, and the ability to substitute among various fuels and electricity in key demand sectors such as transportation. These assumptions are embodied not just in model parameters, but also, as discussed in Chapter 2, in the underlying mathematical structures of the models. As can be seen in Table 2.1, end-use technologies, are, in general, not represented explicitly. None of the participating models, for example, identify multiple steel production technologies or a wide range of vehicle options each with different energy using characteristics. Instead, energy demand responses are represented in relatively aggregate economic sectors (e.g., energy intensive industry or transportation). Other technologies, particularly in energy supply (e.g., CCS) are more likely to be identified specifically.

Three general characteristics of technology bear note with respect to the variation in carbon prices: (1) the availability of low- or zero-carbon electricity production technologies, (2) the supply of non-electric energy substitutes such as biofuels and hydrogen, and (3) the availability of technologies to facilitate substitution toward the use of electricity.

All three modeling groups assumed a variety of cost-effective technology options would be available to limit CO_2 emissions from electricity production. For example, the electric sector is almost fully de-carbonized by the end of the century in all three Level 1 scenarios (Figure 4.22). Electricity is produced with non-fossil technologies (nuclear or renewables) or fossil-fired power plants with CCS. Thus, although low carbon technologies in the electric sector do influence the carbon prices, it is forces outside of electricity production that drive costs at higher levels of abatement because options available to the electric sector can support its almost complete de-carbonization.

The second technology factor is the set of options available to substitute alternative, non-electric fuels for fossil energy in end-use sectors, most importantly in transportation. All three modeling groups assumed biofuels as a substitute for fossil fuels in non-electric applications. As discussed in Section 2 and Section 3, production of bioenergy crops must compete with other uses of agricultural lands in the IGSM and MiniCAM scenarios, which constrains total production of these substitutes. MERGE uses an aggregate parameterization to represent these same constraints. Even with these differing approaches, bioenergy production is similar across the stabilization scenarios. However, because of higher oil prices (Figure 3.7), the IGSM reference scenario includes substantial biofuels (Figure 4.10) so that expansion of biofuels is more limited in the IGSM stabilization scenarios.

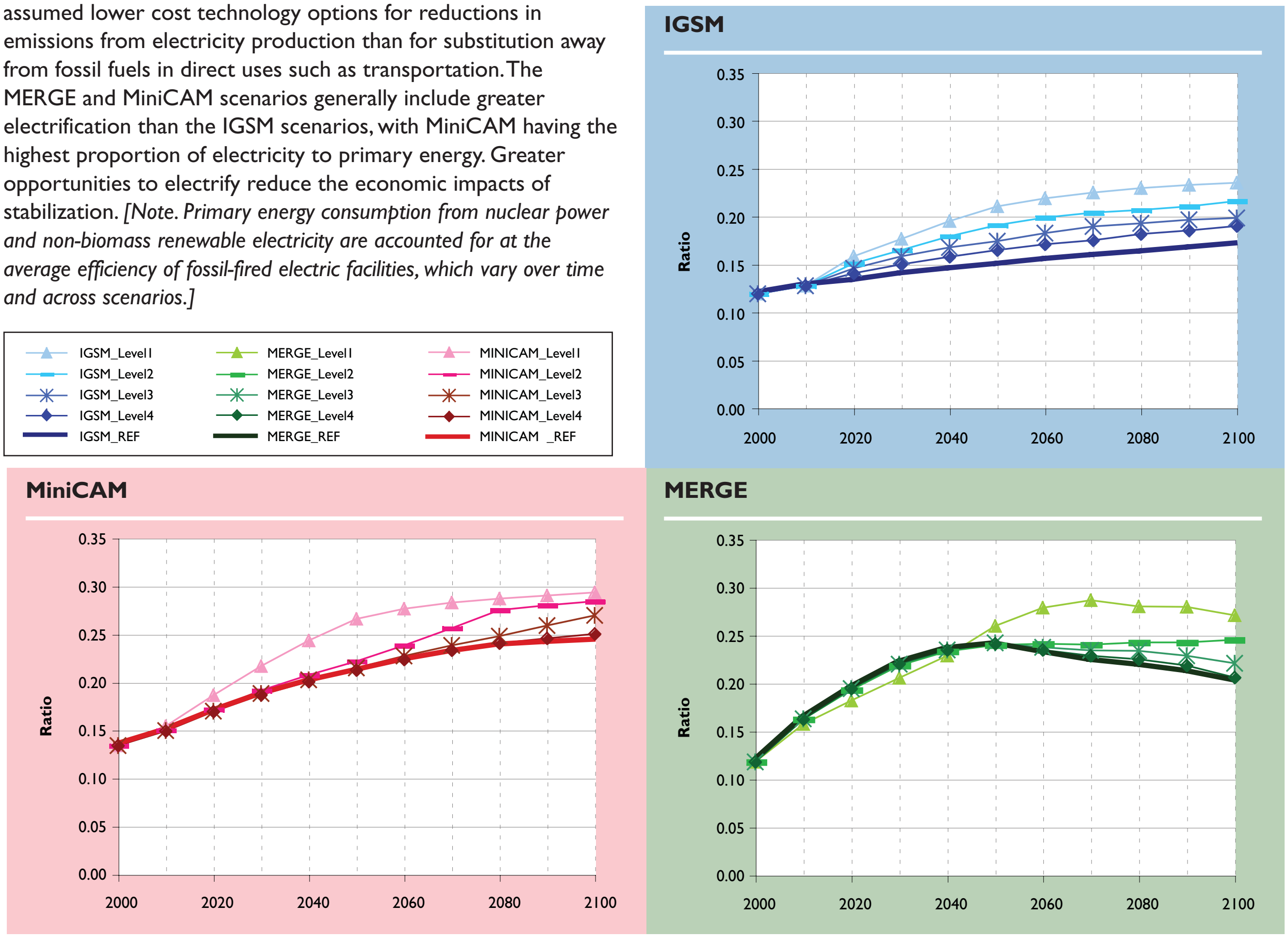
In addition to biofuels, the MiniCAM and MERGE scenarios include other non-electric alternatives, and these become important for more stringent emissions reductions. The MERGE scenarios include a generic alternative fuel generated from renewable sources; which could be, for example, hydrogen from solar or wind power. In the MERGE Level 1 scenario, this alternative fuel provides roughly 80% as much non-electric energy as biofuels by 2100. The MiniCAM scenarios include hydrogen production using electricity, nuclear thermal dissociation, and fossil fuels with and without CCS. Though smaller than biofuels, the contribution of hydrogen rises to a little over 15% of global non-electric energy consumption in the Level 1 MiniCAM scenario. Without these additional options included in the MERGE and MiniCAM scenarios, the marginal cost of emissions reductions is higher in the IGSM scenarios, and more of the abatement is met through reductions in energy use (Figure 4.23).

Another factor influencing carbon prices at higher levels of emissions reduction is the ability to substitute to electricity in end-use sectors, through technologies such as heat pumps, electrically-generated process heat, or electric cars. Were all end uses to easily switch to electricity, then the availability of nearly carbon-free electricity production options in these scenarios would allow complete CO_2 emissions reduction at no more than the cost of these generation options. However, assumptions about technologies for electrification differ substantially among the modeling groups. The MERGE and MiniCAM modeling groups assumed greater opportunities for substitution to electricity than did the IGSM modeling group in the second half of the 21st century. As a result the electricity fraction of primary energy consumption is higher in the MERGE and MiniCAM scenarios in both the reference scenario and the stabilization scenarios, as shown in Figure 4.24. This means that low- or zero-carbon electricity production technologies can serve more effectively as a low-cost option for emissions reduction, reducing costs. In the IGSM scenarios, fuel demand for transportation, where electricity is not an option and for which biofuels supply is insufficient, continues to be a substantial source of emissions.

Although the main technological influences discussed above do not emerge for many decades, they influence carbon prices and economic costs from the outset because of the approach the modeling groups took to *when* flexibility, as discussed above. This dynamic view of the stabilization challenge reinforces the fact that actions taken today both influence and are influenced by the possible ways that the world might evolve in the future.

Finally, there are other structural differences among the approaches taken by the modeling groups that likely play a role in the variation in carbon prices. For example, MERGE is a forward-looking model and that behavior allows it to more fully optimize investments over time than the other two models, including investments in emissions reductions. Another difference is that the MiniCAM scenarios include CCS in cement production, which allows for cement emissions to be reduced to almost zero at more stringent stabilization levels. The IGSM scenarios include cement production within an aggregate sector so that mitigation options that

Figure 4.24. 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 MERGE and MiniCAM scenarios generally include greater electrification than the IGSM scenarios, with MiniCAM having the highest proportion of electricity to primary energy. 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.]*



may be specific to this industry are not explicitly modeled. The MERGE scenarios explicitly include emissions from cement production, but do not include options for reducing these emissions. This omission puts more pressure on emissions reductions elsewhere in the IGSM and MERGE stabilization scenarios and would tend to raise carbon prices relative to the MiniCAM scenarios. Finally, IGSM and MERGE explicitly track savings and investment, whereas MiniCAM does not. In IGSM and MERGE, investments in emissions reductions lower savings and investment in other sectors, affecting the scale of economic output in future periods, and this effect accumulates over time. The most direct effect of this dynamic is felt on economic output, and therefore stabilization costs (addressed later in this chapter), but it may also affect carbon prices through reductions in the scale of economic activity.

Stabilization and Non-CO_2 Greenhouse Gas Prices

Each of the three modeling groups employed a different approach to reductions in the emissions the non-CO_2 GHGs. After CO_2, CH_4 is the next largest component of radiative forcing in all three reference scenarios. Emissions of CH_4 vary among the reference scenarios. The IGSM reference scenario starts in the year 2000 at about 350 Mt/yr and rises to more than 700 Mt/yr (Figure 4.8), while the MERGE and MiniCAM scenarios begin with 300 Mt/yr in the year 2000. These are anthropogenic CH_4 emissions, and the differences reflect existing uncertainties in how much of total CH_4 emissions are from anthropogenic and natural sources. CH_4 emissions grow to almost 600 Mt/yr in the MERGE reference scenario. The MiniCAM reference scenario is characterized by a peak in CH_4 emission at less than 400 Mt/yr, followed by a decline to about 300 Mt/yr.

Each of the modeling groups took a different approach to setting a stabilization constraint on CH_4. The MiniCAM stabilization scenarios are based on constant GWP coefficients, so the price of CH_4 is simply the price of CO_2 multiplied by the GWP. This means that the price of CH_4 relative to the carbon price (the relative CH_4 price) is constant over time, as shown in Figure 4.25.

In contrast, MERGE determines the price of CH_4 to carbon through inter-temporal optimization. The relative price of CH_4 begins very low, although it is higher the more stringent the stabilization level. The relative price then rises at a roughly constant exponential rate of between 8% and 9% per year until stabilization is reached, at which point, the relative price remains approximately constant at around 10 times the carbon price. These characteristics of the CH_4 price and its relationship to the carbon price are the product of the inter-temporal optimization in which the long-term limit on 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.

The IGSM stabilization scenarios are based on a third approach. CH_4 emissions are limited to a maximum value in each stabilization scenario: 425 Mt/yr at Level 4, 385 Mt/yr at Level 3, 350 Mt/yr at Level 2, and 305 Mt/yr at Level 1. As a consequence, the relative price of CH_4 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 time path of relative GHG prices cannot be determined.

As with CH_4, emissions of N_2O in the reference scenarios vary across the three modeling groups (Figure 4.9). The IGSM reference trajectory roughly doubles from approximately 11 Mt/yr to approximately 25 Mt/yr. In contrast, the MERGE and MiniCAM reference scenarios are roughly constant over time.

MERGE also sets the price of N_2O as part of the inter-temporal optimization process. The relative price trajectory for N_2O begins at roughly the level of the GWP-based relative price used in the MiniCAM stabilization scenarios and then rises, roughly linearly with time (Figure 4.25). The relative N_2O price approximately doubles in the MERGE Level 4 scenario, but is almost constant in the MERGE Level 1 scenario. Thus, in the Level 1 scenarios, the relative N_2O price path is virtually the same in the MERGE and MiniCAM scenarios.

In contrast, in the IGSM stabilization scenarios, stabilization sets a path to a predetermined N_2O concentration for each stabilization level, and the complexity of the price paths in Figure 4.25 shows the difficulty of stabilizing the atmospheric level of this GHG. 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.

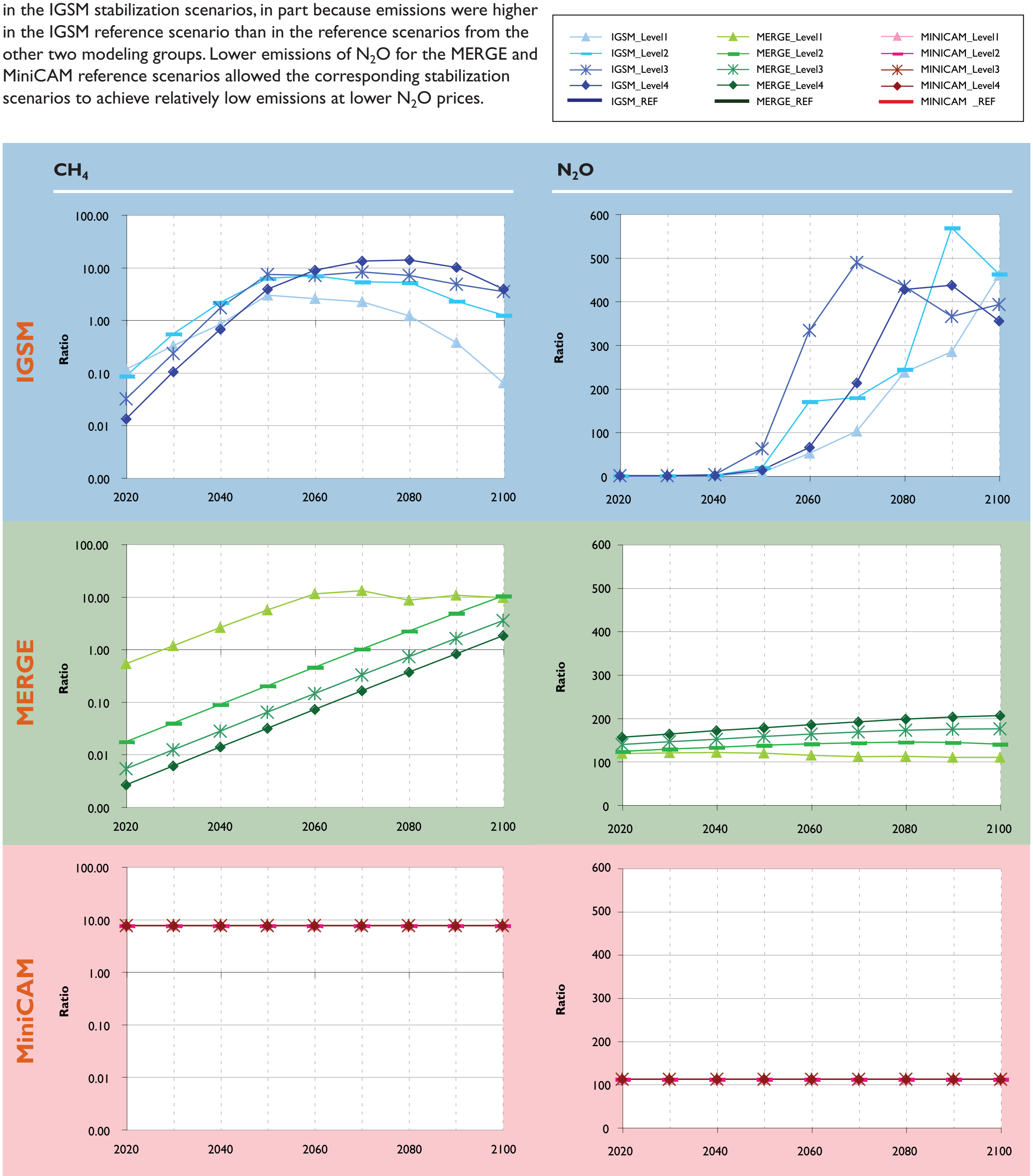
The approaches employed by the three modeling groups do not necessarily lead to the stabilization of the concentrations of the non-CO_2 GHGs before the end of the twenty-first century, as concentrations are still rising slowly in some scenarios but below a long-term stabilized level (Figure 4.4 and Figure 4.5). How long-term stabilization was approached was independently developed by each modeling group.

Stabilization and Energy Prices

The carbon price drives a wedge between the producer prices of fuels and the costs to consumers. Table 4.7 provides an approximation of that of the relationship. A given carbon price has the largest impact on consumer 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 lower than oil or coal. This means that the carbon price has a relatively smaller effect in comparison to the fuel price.

Stabilization scenarios tend to result in a lower producer price for oil (Figure 4.26). Stabilization

Figure 4.25. Relative Prices of CH_4 and N_2O to Carbon Price Across Scenarios (CH_4 in log scale). Differences in the prices of CH_4 and N_2O relative to the carbon price reflect different treatments of this tradeoff among the modeling groups, often referred to as *what* flexibility. In the MiniCAM stabilization scenarios, the tradeoff is based on the GWPs of the non-CO_2 GHGs, which are constants, leading to constant relative prices of the non-CO_2 GHGs. In the MERGE stabilization scenarios, relative prices are optimized with respect to meeting the long-run stabilization levels. In the IGSM stabilization scenarios, stabilization was forced for each GHG independently. Emissions were set so that concentrations of CH_4 would stabilize and allowed the CH_4 price path to be determined by changing opportunities for reducing emissions. Given N_2O emissions from agriculture, the relative price of N_2O is higher in the IGSM stabilization scenarios, in part because emissions were higher in the IGSM reference scenario than in the reference scenarios from the other two modeling groups. Lower emissions of N_2O for the MERGE and MiniCAM reference scenarios allowed the corresponding stabilization scenarios to achieve relatively low emissions at lower N_2O 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 U.S. average prices for the 4th quarter of 2005 as reported by DOE (2006).

Table 4.7. Relationship Between a $100/tonne Carbon Price and Energy 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.)

at Level 4 has a relatively modest effect on the oil producer price, particularly prior to 2040; the effect is stronger the more stringent the stabilization level. Oil producer price reductions vary across the three models, ranging from the IGSM stabilization scenarios, which show the most pronounced effects, to the MERGE stabilization scenarios, which show a substantial effect only in the Level 1 scenario. The effect on world oil producer 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 bio-fuels or hydrogen.

Coal producer prices are similarly depressed in the IGSM and MiniCAM stabilization scenarios (Figure 4.27). The effect is mitigated by two features: (1) the assumed availability of CCS technology, which allows the continued large-scale use of coal in electricity production in the presence of a positive carbon price and (2) a coal supply schedule that is highly elastic. That is, demand for coal can exhibit large increases

Figure 4.26. World Oil Price Across Scenarios (Index, yr 2000 = 1). World oil prices (producer price) vary considerably across the reference scenarios. In all three models, stabilization tends to depress the producer prices of oil relative to the reference scenarios. *[Note. Producer prices as defined here do not include additional costs associated with carbon emissions to the atmosphere through the combustion of fossil fuels, as shown in Table 4.7.]*

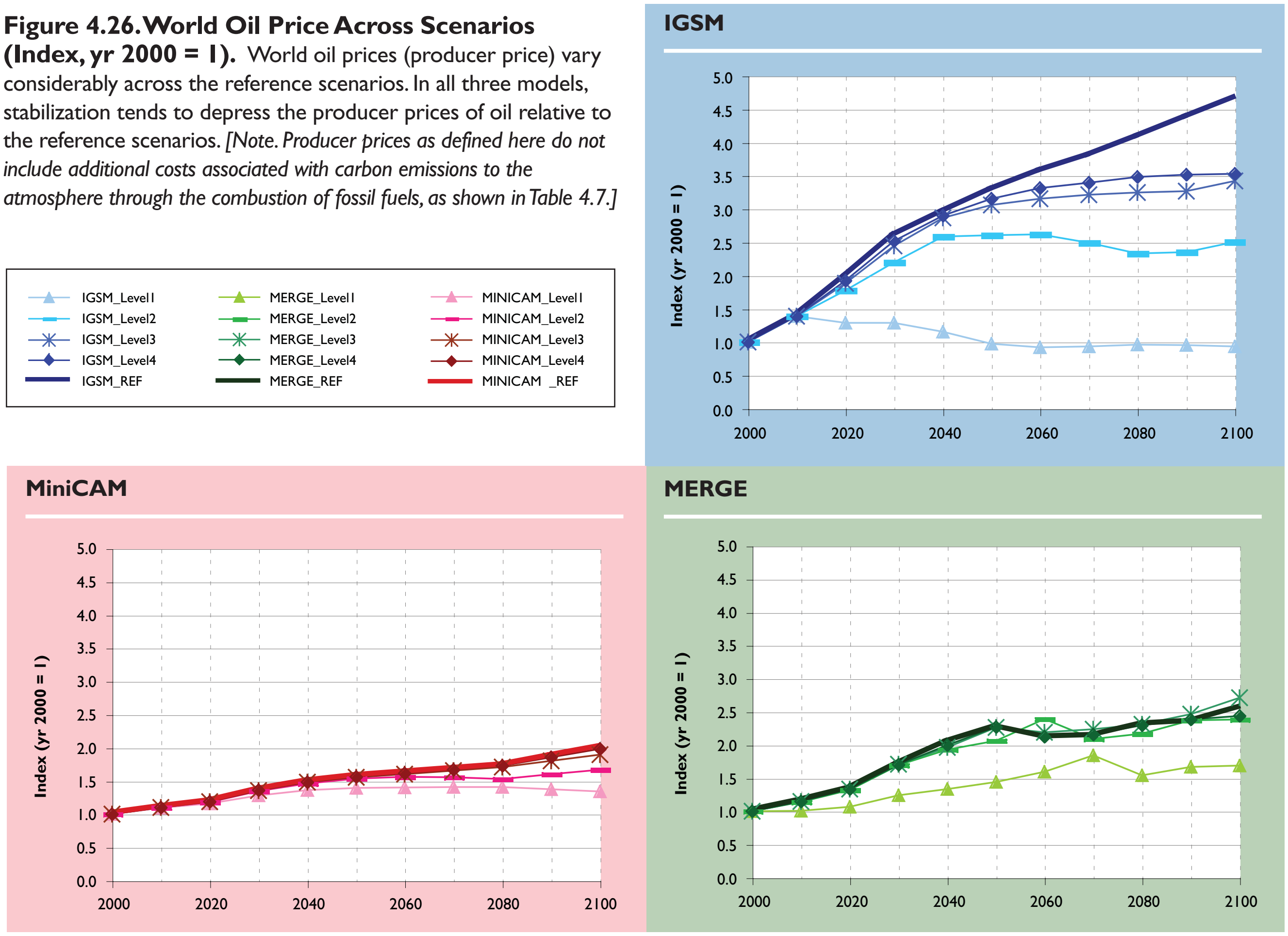
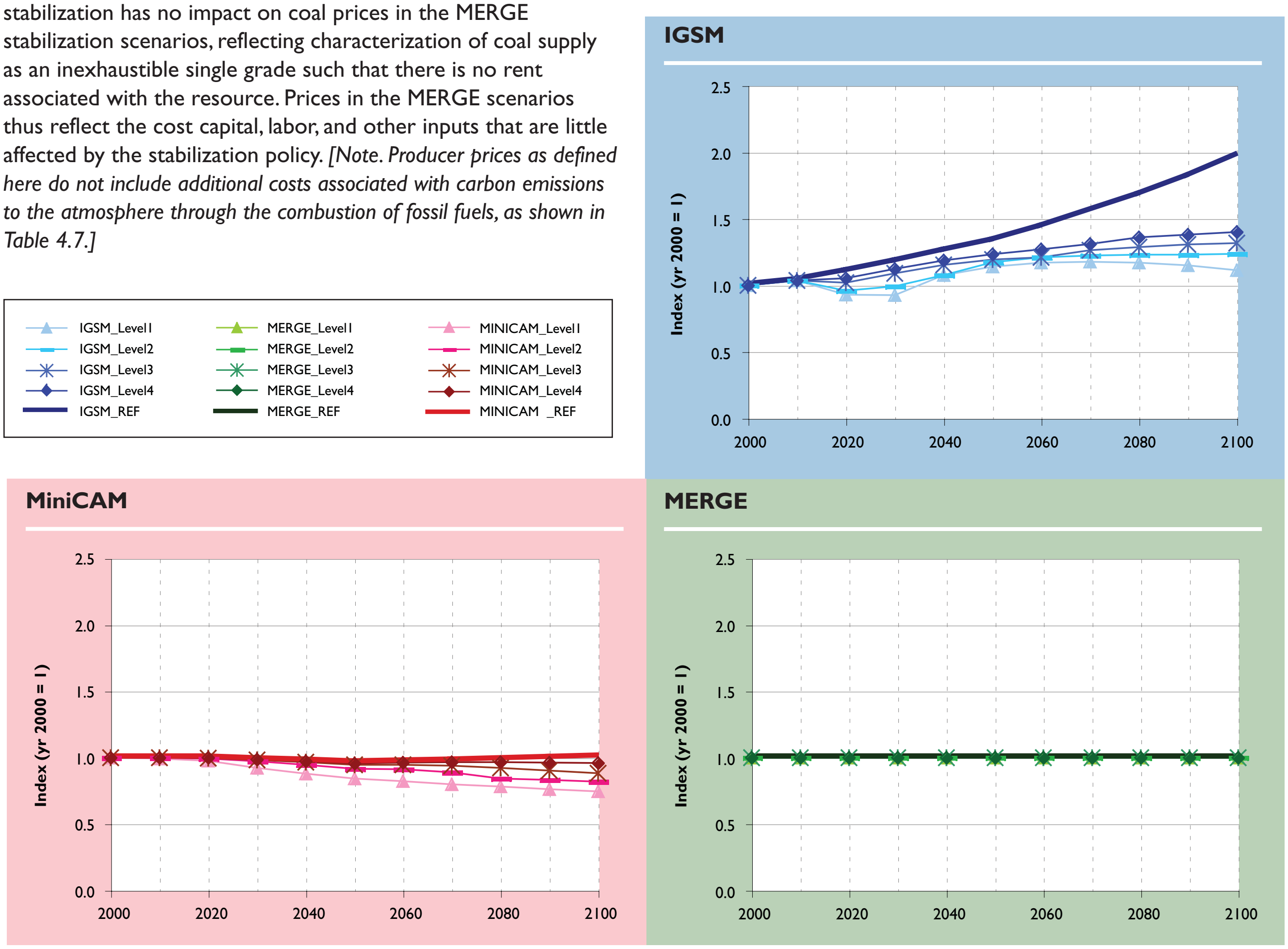


Figure 4.27. U.S. Mine-Mouth Coal Price Across Scenarios (Index, yr 2000 = 1). U.S. mine-mouth coal price varies acrosss the reference scenarios. In the IGSM and MiniCAM stabilization scenarios, stabilization depresses coal prices, whereas stabilization has no impact on coal prices in the MERGE stabilization scenarios, reflecting characterization of coal supply as an inexhaustible single grade such that there is no rent associated with the resource. Prices in the MERGE scenarios thus reflect the cost capital, labor, and other inputs that are little affected by the stabilization policy. *[Note. Producer prices as defined here do not include additional costs associated with carbon emissions to the atmosphere through the combustion of fossil fuels, as shown in Table 4.7.]*



or decreases without much change in price. The high elasticity of supply in the MERGE scenarios leaves coal producer prices unchanged across the stabilization scenarios, whereas the MiniCAM and IGSM scenarios have lower supply price elasticities and, hence, greater producer price responses.

The impact on the natural gas producer price is more complex (Figure 4.28). 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. With a postive carbon price, natural gas tends to substitute for other fossil fuels, increasing its demand. But a positive carbon price also means that a low- or zero-carbon substitutes, such as electricity, bioenergy, or energy-efficiency technologies, will tend to displace natural gas from markets, as happens for the more carbon-intensive fuels. Thus, depending on the strength of these two effects, the producer price of natural gas can either rise or fall.

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

Although the price that oil and coal producers receive tends to be either stable or depressed, that is not the full cost of using the fuel. Users, such as households or industrial fuel users, pay the market price plus the value of the carbon emissions associated with the fuel, which is the carbon price times the fuel's carbon-to-energy

Figure 4.28. U.S. Natural Gas Producers' Price Across Scenarios (Index, yr 2000 = 1). U.S. natural gas producers' prices vary among the reference scenarios. In the MiniCAM and MERGE stabilization scenarios, stabilization has little effect on the natural gas price. Stabilization at Levels 2, 3, and 4 increases the price of natural gas in the IGSM stabilization scenarios because of substitution toward natural gas and away from coal and oil. Natural gas prices fall relative to reference scenario in the IGSM Level 1 stabilization scenario because natural gas demand is depressed from the tight carbon constraint. *[Note. Producer prices as defined here do not include additional costs associated with carbon emissions to the atmosphere through the combustion of fossil fuels, as shown in Table 4.7.]*

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 users' 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 consumed. In this case, users would be able to buy fuel relatively inexpensively, but would pay a separate large price for necessary carbon charges associated with emissions.

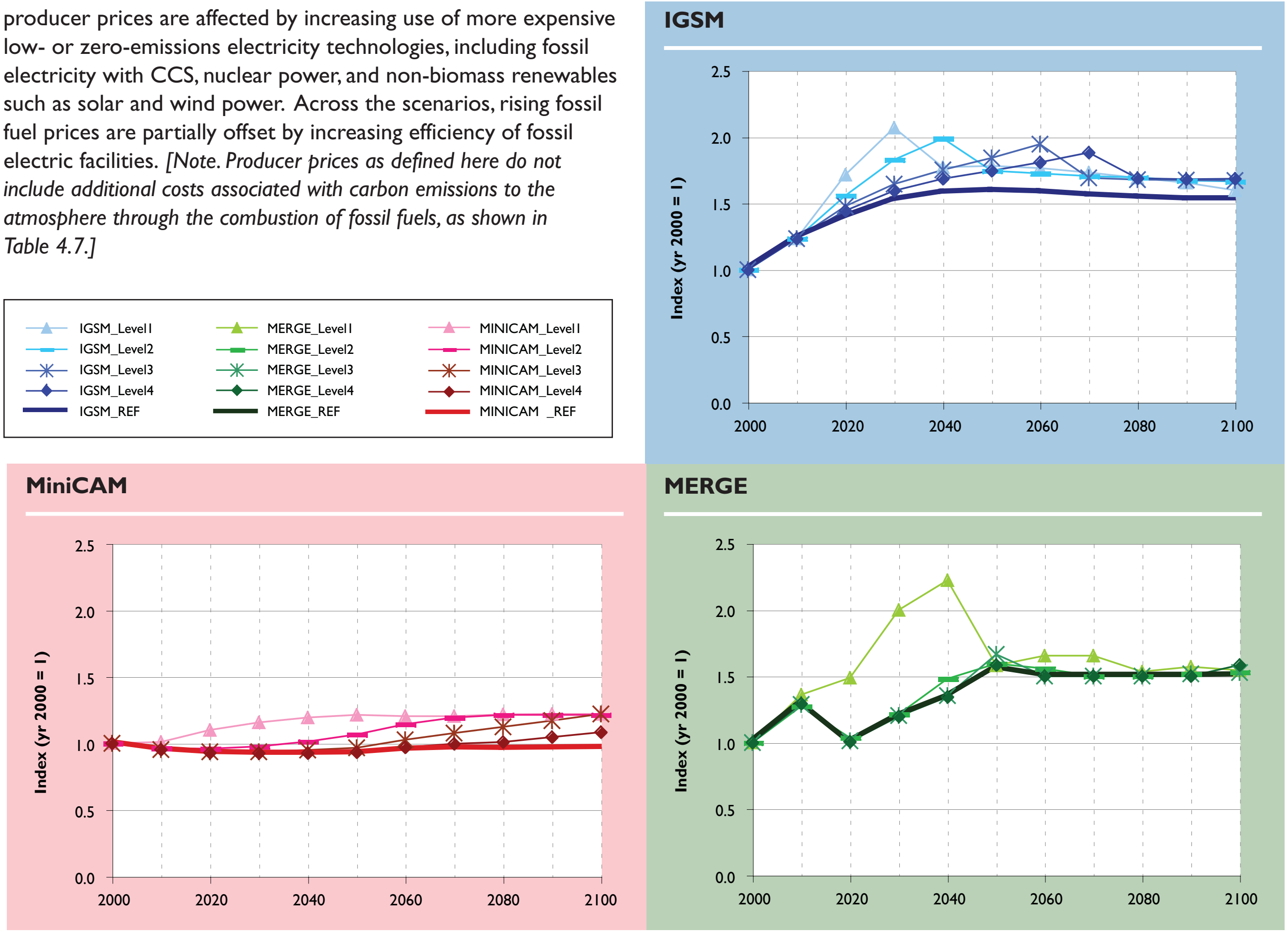
The effect on the price of electricity is another unambiguous result (Figure 4.29). Because electricity producers are fossil fuel consumers, the price of electricity contains the implicit carbon price in the fuels used for generation. All of the scenarios exhibit upward pressure on electricity prices, 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.

The Total Cost of Stabilization

Assessing 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 pursuing stabilization or equivalently, the value of activities that society will not be able to undertake as a consequence of pursuing stabilization. Although the concept is easy enough to articulate, defining an unambiguous measure is problematic. Any measure of cost is a more or less satisfactory compromise.

The task is further complicated by the need to aggregate the welfare of individuals who have

Figure 4.29. U.S. Electricity Producer Price Across Scenarios (Index, yr 2000 = 1). U.S. electricity prices in the reference scenarios range from little change over the century in the MiniCAM reference scenario to about a 50% increase from present levels in the IGSM reference scenario. Under stabilization, producer prices are affected by increasing use of more expensive low- or zero-emissions electricity technologies, including fossil electricity with CCS, nuclear power, 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 facilities. *[Note. Producer prices as defined here do not include additional costs associated with carbon emissions to the atmosphere through the combustion of fossil fuels, as shown in Table 4.7.]*

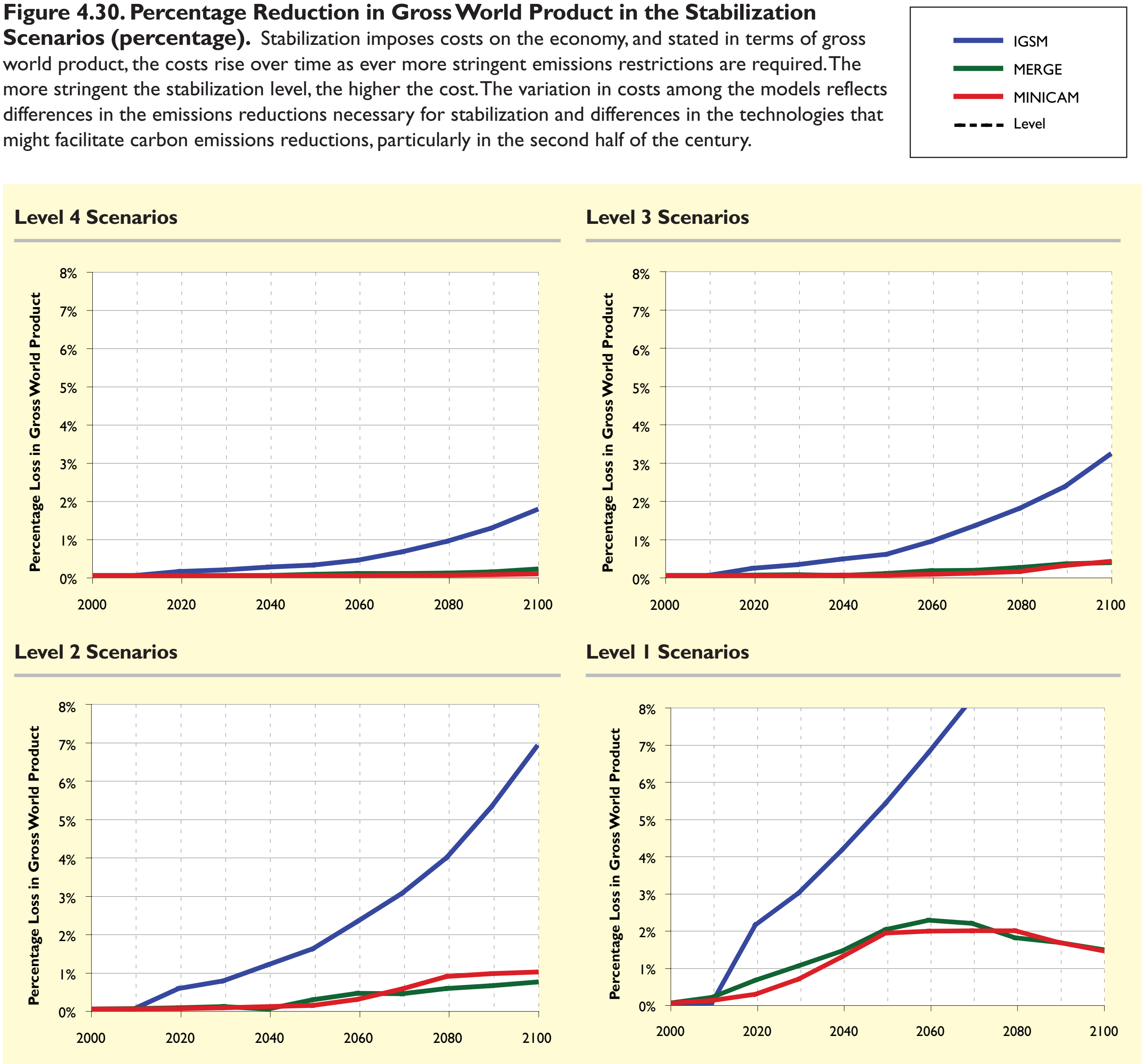


not yet been born and who may or may not share present preferences. Even if these problems were not difficult enough, economies can hardly be thought to currently be at a maximum of potential welfare. Preexisting market distortions impose costs on the economy, and mitigation actions may interact with them so as to reduce or exacerbate their effects. Any measure of global cost also runs into the 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. To create a metric that is consistent and comparable across the three modeling platforms used in this study, all of these issues would have to be addressed in some way.

Beyond conceptual measurement issues, any metric including gross domestic product, depends 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 GHG 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 in this research employ more or less idealized representations of economic structure, political decision, and policy implementation (i.e., conditions that likely do not accurately reflect the real world, and these simplifications tend to lead to lower mitigation costs).

Finally, assessing welfare effects would require explicit consideration of how the burden of emissions reduction is 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

Figure 4.30. Percentage Reduction in Gross World Product in the Stabilization Scenarios (percentage). Stabilization imposes costs on the economy, and stated in terms of gross world product, the costs rise over time as ever more stringent emissions restrictions are required. The more stringent the stabilization level, the higher the cost. The variation in costs among the models reflects differences in the emissions reductions necessary for stabilization and differences in the technologies that might facilitate carbon emissions reductions, particularly in the second half of the century.



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 have 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, Babiker et al. 2003b, Babiker et al. 2004, Paltsev et al. 2005).

Figure 4.30 reports the change of gross world product in the stabilization scenarios during the twenty-first century in the year in which it oc-

Table 4.8. Percentage Reduction in Gross World Product in the Stabilization Scenarios.

Level 1

	2020	2040	2060	2080	2100
IGSM	2.1%	4.1%	6.7%	10.1%	16.1%
MERGE	0.6%	1.4%	2.2%	1.8%	1.4%
MiniCAM	0.2%	1.2%	1.9%	1.9%	1.4%

Level 2

	2020	2040	2060	2080	2100
IGSM	0.5%	1.2%	2.3%	3.9%	6.8%
MERGE	0.0%	0.0%	0.4%	0.5%	0.7%
MiniCAM	0.0%	0.1%	0.2%	0.8%	1.0%

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%	0.4%

Level 4

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

curs aggregated using 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). Though change in gross world product is not the most intellectually satisfying measure, it serves as a common reference point.

The effects on gross world product are tightly linked to the carbon prices. Therefore effects on gross world product in the stabilization scenarios follow the same patterns and logic as the carbon prices, which are discussed in substantially greater detail in Section 4.6.1. As with the carbon price, costs rise with increasing stringency of the stabilization level. And, as with the carbon price, there is variation in costs of stabilization among the modeling groups. For example, gross world product in 2100 is reduced by 6.8% in the IGSM Level 2 scenario, while the reduction is less than 1% in the MERGE and MiniCAM Level 2 scenarios. The ratio of stabilization costs among the models at other radiative forcing stabilization levels follows the same pattern.

The differences in stabilization costs among the models can largely be attributed the same influences discussed in Section 4.6.1: (1) the amount that emissions must be reduced to achieve an emissions path to stabilization, and (2) the technologies that are available to facilitate these changes in the economy. A number of additional, structural differences, such as treatment of capital investment, intertemporal model structure, and emissions reductions opportunities in cement production also lead to differences in prices and costs. As with emissions prices, although technology differences emerge primarily in the second half of the century, their influence felt throughout the century because of the common implementation of *when* flexibility in the policy design.

Expressed throughout the report is the view that the development of independent sets of scenarios using three different models helps to inform common understanding of the forces that shape opportunities to stabilize greenhouse gas concentrations. The differences discussed here demonstrate the fundamental importance of technology in facilitating stabilization – particularly the importance of future technology, even developments more than half a century in the future. The scenarios also suggest the particular importance of options that facilitate the production of alternative non-electric fuels and demand-side technologies that will allow the substitution of electricity for current applications of fossil fuels.