4. STABILIZATION SCENARIOS

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

4.1. Introduction

In Chapter 3, each modeling team developed scenarios of long-term greenhouse gas (GHG) emissions associated with changes in key economic characteristics, such as demographics and technology. This chapter describes how such developments might be modified in response to limits to changes in radiative forcing. It illustrates that society's response to a stabilization goal can take many paths, reflecting factors shaping the reference scenario and the availability and performance of emission-reducing technologies. It should be emphasized that there has been no international agreement on a desired stabilization target; the four levels analyzed below and detailed in Table 4.1

were chosen for illustrative purposes only. They reflect neither a preference nor a recommendation. However, they correspond roughly to four of the frequently analyzed levels of CO_2 concentrations.

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

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

4.2. Stabilizing Radiative Forcing: Model Implementations

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

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

In two areas the teams employed different approaches:

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

4.2.1. Reference Scenario Climate Policies

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

4.2.2. Timing of Participation in Stabilization Scenarios

There has been no international agreement on the desired level at which to stabilize radiative forcing or the path to such a goal, nor is there any consensus about the relative sharing of burdens other than a general call for “common but differentiated responsibilities” by the United Nations Framework Convention on Climate Change (United Nations, 1992). For the stabilization scenarios, it was assumed that policies to limit the change in radiative forcing would be applied globally, as directed by the Prospectus. Although it seems unlikely that all countries would simultaneously join such a global agreement, and the economic implications of stabilization would be greater with less-than-universal participation, the assumption that all countries participate provides a useful benchmark. Indeed, analyses using alternative burden sharing schemes suggest that the costs can be an order of magnitude higher without the involvement of non-Annex B emitters.

4.2.3. Policy Instrument Assumptions in Stabilization Scenarios

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

4.2.4. Timing of CO_2 Emissions Mitigation

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

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

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

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

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

As with MERGE, the exponential increase in the price of CO_2 continues until such time as radiative forcing is stabilized. Thereafter the price is set by the carbon cycle. That is, once radiative forcing has risen to its stabilization level, additional CO_2 can only enter the atmosphere to the extent that natural processes remove it, otherwise CO_2 radiative forcing would be increasing. This is relevant in the Level 1 stabilization scenario and, to a lesser extent, in the Level 2 stabilization scenario. However, it is not present in the Level 3 or Level 4 scenarios because stabilization is not reached until after the end of the twenty-first century.

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

4.2.5. Non-CO_2 Emissions Mitigation

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

The MiniCAM team tied non-CO_2 GHG prices to the price of CO_2 using the GWPs of the gases. This procedure has been adopted by parties to the Kyoto Protocol and applied in the definition of the U.S. emissions intensity goal. IGSM used the same approach as MiniCAM to determine the prices for HFCs, PFCs, and SF_6, pegging the prices to that of CO_2 using GWP coefficients. For CH_4 and N_2O, however, independent emission stabilization levels were set for each gas in the IGSM because GWPs poorly represent the full effects of CH_4 and emissions trading at GWP rates leads to problems in defining what stabilization means when CH_4 and N_2O are involved (Sarofim et al. 2005). The relatively near-term stabilization for CH_4 specified in the IGSM analysis implies that near-term reductions in climate change result in economic benefit. This approach is consistent with a view that there are risks associated with lesser amounts of radiative forcing. This is quite different than the MERGE approach, where any value of abatement derives only from the extent to which it contributes to avoiding the long-term stabilization level. In that approach, early abatement of short-lived species like CH_4 have very little consequence for a target that will not be reached for many decades, and the optimized result places little value on abating short-lived species until the target is approached. Without a full analysis of the economic effects of climate change that occurs along these different stabilization paths, these two approaches provide some bounds on possible reasonable paths for non-CO_2 GHG stabilization, with the MiniCAM result representing an intermediate approach.

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

> *Despite significantly different levels of radiative forcing in their reference scenarios the modeling teams reported very similar levels of radiative forcing relative to pre-industrial levels for the year 2100 in all four stabilization scenarios. Nevertheless, the teams produced stabilization scenarios with different combinations of GHG concentrations. Differences in year 2100* CO_2 *concentrations could be as much as 75 ppmv, and year 2100 fossil fuel* CO_2 *emissions could vary by up to 8 GtC/year. Of necessity, models that had high* CO_2 *concentrations for a given stabilization level had lower concentrations and emissions of non-*CO_2 *greenhouse gases. These differences in stabilization results highlight the fact that there are many different pathways to stabilizing radiative forcing..*

As a result of the economic assumptions imposed in the solutions, all of the modeling teams produced results in which the reduction in emissions below reference levels was much smaller in the period between 2000 and 2050 than between 2050 and 2100. All of the stabilization scenarios were characterized by a peak and decline in global CO_2 emissions in the twenty-first century.

4.3.1. Implications for Radiative Forcing

Given that all were constrained by the same atmospheric targets, the modeling teams reported very similar levels of radiative forcing relative to pre-industrial levels for the year 2100 although the time-scale for stabilization exceeds the 2100 horizon of the analysis. Table 4.2 shows the long-term target level and the level of radiative forcing reported by each of the three modeling teams in the year 2100. All the teams successfully constrained radiative forcing not to exceed target levels. A minor exception is that for Level 1 for which the IGSM team's approximation reports a slightly higher radiative forcing level than the long-term target. The implication of this slightly higher radiative forcing is that the IGSM Level 1 scenario has less non-emitting technology and lower economic costs than would be the case if the constraint were met precisely. In general, the differences between the long-term target and the modeled radiative forcing levels are smaller for Levels 1 and 2 than for Levels 3 and 4 because the latter allow a greater accumulation of GHGs in the atmosphere than do Levels 1 and 2. For Levels 3 and 4 each modeling team required radiative forcing to be below the long-term limits in

2100 to allow for subsequent emissions to fall gradually toward levels required for stabilization.

Table 4.2. Radiative Forcing in the Year 2100 across Scenarios

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

Figure 4.1. Total Radiative Forcing by Year across Scenarios

Although their totals are similar, the GHG composition of radiative forcing is different among the three modeling teams. Figure 4.2 plots the breakdown among gases in 2100 for the reference scenario along with all four stabilization levels. Forcing is dominated by CO_2 for all modeling teams at all target levels, but there are variations among models. For example, the MiniCAM scenario has larger contributions from CO_2 and lower contributions from CH_4 than the other modeling teams. Conversely, the MERGE scenarios have higher contributions from CH_4 and lower contributions from CO_2 relative to the other modeling teams. In the case of the latter, the tighter the target, the greater the reduction in CH_4. This is because the price of CH_4 relative to CO_2 increases with the proximity to the goal.

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

4.3.2. Implications for Greenhouse Gas Concentrations

The relative GHG composition of radiative forcing across models in any scenario reflects differences in concentrations of the GHGs. Thus, consistent with the higher CO_2 role in Figure 4.1 and Figure 4.2, the CO_2 concentrations projected by MiniCAM are systematically higher than for the other modeling teams, as plotted in Figure 4.3, and its methane and N_2O concentrations are systematically lower in Figure 4.4 (see also Figure 4.21). Differences in the gas concentrations among the three models reflect differences in the way the models make tradeoffs among gases, differences in assumed mitigation opportunities for non-CO_2 GHGs compared to CO_2. MiniCAM assumes that methane abatement technologies are available that lead to abatement even when the value of emissions is zero, thus leading to a lower methane emissions trajectory than either MERGE or IGSM. Further methane emissions mitigation is induced in MiniCAM as the price on methane emissions rises.

Figure 4.3. CO_2 Concentrations across Scenarios

Figure 4.4. CH_4 Concentrations across Scenarios

Tradeoffs among GHG emissions mitigation opportunities lead to differences in year 2100 CO_2 concentrations associated with the four target levels (see Table 4.3). All three models yield CO_2 concentrations that are close to the reference value for the Level 4 scenario. While the MiniCAM value slightly exceeds the reference CO_2 concentration in 2100, the CO_2 concentration is falling, as can be seen in Figure 4.3.

Table 4.3. CO_2 Concentrations in the Year 2100 across Scenarios

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

Natural removal processes are uncertain, and this uncertainty is reflected in differences in results from three modeling teams, as shown in Figure 4.5. The IGSM model projects that the rate of uptake will reach a limit at very high concentrations under the reference scenario (Figure 3.20), and all models show ocean uptake to be reduced at the more stringent stabilization levels because the rate of uptake is strongly influenced by the CO_2 concentration in the atmosphere. The IGSM uptake is systematically smaller than shown in the MERGE and MiniCAM models. As a consequence, the IGSM control scenarios must achieve lower anthropogenic emissions for a comparable CO_2 concentration. All three ocean-uptake regimes are within the present range of carbon-cycle uncertainty, which points up the importance of improved understanding of carbon-cycle processes for future stabilization investigations.

Figure 4.5. Ocean CO_2 Uptake across Scenarios

4.3.3. Implications for Greenhouse Gas Emissions

4.3.3.1. Implications for Global CO_2 Emissions

For the Level 1 target, global CO_2 emissions begin declining nearly immediately in all three modeling efforts (see Figure 4.6). The constraint is so tight that there is relatively little latitude for variation. Only in the second half of the century do some modest differences emerge among the scenarios.

Figure 4.6. Fossil Fuel and Industrial CO_2 Emissions across Scenarios

All three modeling teams show continued emissions growth throughout the first half of the twenty-first century for Level 4, the loosest constraint. Near-term variation in emissions largely reflects differences in the reference scenarios. Importantly, global emissions peak before the end of the twenty-first century and begin a long-term decline for all three groups.

The scenarios of all three teams exhibit more emissions reduction in the second half of the twenty-first century than in the first half, as noted earlier, so the mitigation challenge grows with time. The precise timing and degree of departure from the reference scenario depend on many aspects of the scenarios and on each model's representation of Earth system properties, including the radiative forcing limit, the carbon cycle, atmospheric chemistry, the character of technology options over time, the reference scenario CO_2 emissions path, the non-climate policy environment, the rate of discount, and the climate policy environment. For Level 4, more than 85% of emissions mitigation occurs in the second half of the twenty-first century in the scenarios developed here. For Level 1, where the limit is the tightest and near-term mitigation most urgent, more than 75% of the emissions mitigation occurs in the second half of the century.

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

4.3.3.2. Implications for Non-CO_2 Greenhouse Gas Emissions

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

Emissions under stabilization are systematically lower the more stringent the target, as can be seen in Figure 4.7. The MiniCAM modeling team, with its relatively lower reference scenario, has the lowest CH_4 emissions in stabilization scenarios. The assumed policy environment for CH_4 control is also important. Despite the fact that the IGSM modeling team has higher reference CH_4 emissions than MERGE, the latter group's scenarios have the higher emissions under stabilization. The reason is that the MERGE inter-temporal optimization leads to a low relative price for CH_4 emissions in the near-term, which grows rapidly relative to CO_2, whereas IGSM controls CH_4 emissions through quantitative limits.

Figure 4.7. CH_4 Emissions across Scenarios

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

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

Figure 4.8. N_2O Emissions across Scenarios

4.4. Implications for Energy Use, Industry, and Technology

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

4.4.1. Changes in Global Energy Use

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

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

Figure 4.10. Global Primary Energy by Fuel across Scenarios

Although atmospheric stabilization would take away much of the growth potential of coal over the century, all three models project coal usage to expand under stabilization Levels

2, 3, and 4. However, under the most stringent target, Level 1, 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 at the tighter limits on radiative forcing, they are progressively squeezed out of the mix. One reason that fossil fuels continue to be utilized despite constraints on GHG emissions is that CCS technologies are available. Figure 4.10 shows that as the carbon values rise, CCS technology takes on an increasing market share. Section 4.4.2 addresses this pattern, as well as the contribution of non-biomass renewable energy forms in greater detail.

Changes in the global energy system in response to constraints on radiative forcing reflect an interplay between technology options and the assumptions that shaped the reference scenarios. For example, the MERGE reference assumes a relatively limited ability to access unconventional oil and gas resources and the evolution of a system that increasingly employs coal as a feedstock for the production of liquids, gases, and electricity. Because there is little oil and gas in the system, fossil CO_2 emissions come predominantly from coal. Against this background, a constraint on radiative forcing results in reductions in coal use and end-use energy consumption. As the price of carbon rises, nuclear and non-biomass renewable energy forms and CCS augment the response.

The IGSM reference scenario assumes greater availability of unconventional oil and gas than in the MERGE scenarios. Thus, the stabilization scenarios involve less reduction in coal use but a larger decline in oil and gas than in the MERGE scenarios. To produce liquid fuels for the transportation sector, the IGSM model responds to a constraint on radiative forcing by growing biomass energy crops both earlier and more extensively than in the reference scenario. Also, the IGSM model projects larger reductions in energy demand than either of the other two models. The MiniCAM model produces the smallest reductions in energy consumption of any of the modeling groups. The imposition of constraints on radiative forcing leads to reductions in oil, gas, and coal, as do the other models, but also involves considerable expansion of nuclear and renewable supplies. The largest supply response is in commercial bio-derived fuels. Commercial bio-derived fuels are largely limited to traditional and bio-waste recycling in the reference scenario, leaving a level of bio-derived energy in the year 2100 similar to those of the other two modeling teams. As the price on CO_2 rises, bio-energy becomes increasingly attractive. As will be discussed in Section 4.5, the expansion of the commercial biomass industry to produce hundreds of EJ of energy per year has implications for crop prices, land-use, land-use emissions, and unmanaged ecosystems that are of concern.

The relative role of nuclear differs in each of the three analyses. The MERGE reference scenario deploys the largest amount of nuclear power, contributing 231 EJ/y of primary energy in the year 2100. In the Level 1 stabilization scenario, deployment expands to 306 EJ/y of primary energy in 2100. Nuclear power in the MiniCAM reference scenario produces 129 EJ/y in the year 2100, which in the Level 1 stabilization scenario expands to more than 234 EJ/y of primary energy in the year 2100. The IGSM scenarios show little change in nuclear power generation among the stabilization scenarios or compared with the reference, reflecting the assumption that nuclear levels reflected policy decisions regarding nuclear siting, safety, and proliferation that are unaffected by climate policy. None of the scenarios report a detailed technology characterization, implications for uranium and thorium resources, or information on reprocessing and disposal that would accompany continued expansion of the nuclear industry. However, some models, such as MiniCAM, include explicit descriptions of the nuclear fuel cycle.

Reductions in total energy demand play an important role in all of the stabilization scenarios. In the IGSM stabilization scenarios, this is the largest single change in the global energy system. While not as dramatic as in the case of the IGSM stabilization scenarios, MERGE and MiniCAM stabilization scenarios also exhibit changes in energy demand under stabilization. As will be discussed in Section 4.6, the difference in the change in energy use among the models in response to stabilization policies reflects differences in the resulting carbon prices which are substantially higher for the IGSM. In all three models, carbon price differences are reflected in the user prices of energy. Carbon prices, in turn, reflect technological assumptions about both supply of alternative energy and the responsiveness of users to changing prices.

4.4.2. Changes in Global Electric Power Generation

The three models project substantial changes in electricity-generation technologies as a result of stabilization but relatively little change in electricity demand. Electricity price increases as a result of climate policy are smaller relative to those for direct fuel use because the fuel input, while important, is only part of the cost of electricity supply to the consumer. Also, the long-term cost of transitioning to low and non-carbon-emitting sources in electricity production is relatively smaller than in the remaining sectors taken as an average.

There are substantial differences in the scale of global power generation across the three reference scenarios, as shown in Chapter 3 and repeated at the top of Figure 4.11. Power generation increases from about 50 EJ/y in the year 2000 to between 229 EJ/y (IGSM) to 458 EJ/y (MiniCAM) by 2100. In all three reference scenarios, electricity becomes an increasingly important component of the global energy system, fueled by growing quantities of fossil fuels. Despite differences in the relative contribution of different fuel modes across the three reference scenarios, total fossil fuel use rises from about 30 EJ/y in 2000 to between 170 EJ/y and 270 EJ/y in 2100. Thus, the larger difference in total power generation reflects large differences in the deployment of non-fossil energy forms: biofuels, nuclear power, fuel cells, and other renewables such as wind, geothermal, and solar power.

Figure 4.11. Global Electricity Generation by Fuel across Scenarios

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

The imposition of radiative forcing limits dramatically changes the electricity sector. The IGSM model responds to the stabilization scenario by reducing the use of coal and oil relative to the reference scenario, expanding the deployment of gas and coal with CCS, and reducing demand. However, at low carbon prices, substitution of natural gas for coal occurs in the IGSM scenarios. MERGE reduces the use of coal in power generation, while expanding the use of non-biomass renewables and coal with CCS. The MiniCAM model reduces the use of coal without CCS, and expands deployment of oil, gas, and coal with CCS technology. In addition, nuclear and non-biomass renewable energy technologies capture a larger share of the market. At the less-stringent levels of stabilization, i.e., Levels 3 and 4, additional biofuels are deployed in power generation, and total power generation declines. At the more-stringent stabilization levels, commercial bio-fuels are diverted to the transportation sector, and use actually declines relative to the reference.

All modeling groups assumed that CO_2 could be captured and stored in secure repositories, and in all cases CCS becomes a large-scale activity. Annual capture quantities are shown in Table 4.4. It is always one of the largest single changes in the power-generation system in response to stabilization in radiative forcing, as can be seen in Figure 4.12. As with mitigation in general, CCS starts relatively modestly in all the scenarios, but grows to large levels. The total storage over the century is recorded in Table 4.5, spanning a range from 27 GtC to 92 GtC for Level 4 and 160 GtC to 328 GtC for Level 1. The modeling groups made no attempt to report either location of storage sites for CO_2 or the nature of the storage reservoirs, but these scenarios are within the range of the estimates of global geologic reservoir capacity.

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

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

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

Yet capture technology is hardly ordinary. 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 on cost would be adverse. These scenarios tend to favor CCS but that tendency could easily change with different assumptions about nuclear power that are well within the range of uncertainty about future costs. Nuclear power carries with it issues of long term storage or disposal of nuclear materials and proliferation concerns. Thus, either are viable options but both involve regulatory and public acceptance issues. Absent CCS and nuclear fission, these models would need to deploy other emissions abatement options that would potentially be more costly, or would need to envision large breakthroughs in the cost, performance, and reliability of other technologies. This study has not attempted to quantify the increase in costs or the reorganization of the energy system in stabilization scenarios without CCS. This sensitivity is an important item in the agenda of future research.

CCS is not the only technology that is advantaged in stabilization scenarios. Renewable energy technologies clearly benefit, and their deployment expands in both the MERGE and MiniCAM scenarios. Nuclear power also obtains a cost advantage in stabilization scenarios and experiences increased deployment, particularly in the MiniCAM stabilization scenarios. The fact that no clear winner emerges from among the suite of non-fossil power-generating technologies reflects the differences among the modeling teams regarding expectations for future technology performance, market and non-market factors affecting deployment, and the ultimate severity of future emissions mitigation regimes.

4.4.3. Changes in Energy Patterns in the United States

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

Energy-system changes are modest for stabilization Level 4, as shown in Figure 4.13, but even with this loose constraint, significant changes begin upon implementation of the stabilization policy (the first period shown is 2020) in the IGSM. At more stringent stabilization levels, the changes are more substantial and begin with initiation of the policy in all three models. With Level 1 stabilization, the U.S. energy system net changes range from 11 to almost 26 EJ per year in 2020. These changes are net reductions and do not reflect other changes in the composition of the energy system.

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

Near-term changes in the U.S. energy system are more complex than in the long term. While oil consumption always declines at higher carbon tax rates for all the modeling teams and all stabilization regimes, near-term changes in oil consumption can be ambiguous at lower tax rates. 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 energy consumption declines along all scenarios. While nuclear power, commercial biomass, and other renewable energy forms are advantaged, and at least one of them always deploys to a greater extent in stabilization scenarios than in the reference scenario, the particular form and timing of expanded development varies from model to model.

The three models exhibit different responses reflecting differences in underlying reference scenarios and technology assumptions. The largest change in the U.S. energy system for the IGSM modeling team is always the reduction in total energy consumption augmented by an expansion in the use of commercial biomass fuels and deployment of CCS at higher carbon tax rates. Similarly, the largest change in the MERGE model is the reduction in total energy consumption augmented by deployment of CCS. Unlike the IGSM stabilization scenarios, however, it augments those changes with increased deployment of nuclear power and renewable energy forms rather than commercial biofuels. The MiniCAM model also exhibits reductions in total energy consumption and increasingly deploys nuclear power, commercial biomass, and other renewable energy forms.

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

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

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

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

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

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

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

The three modeling teams employ three different approaches to the production of biofuels from land. Two of the modeling teams employed explicit agriculture-land-use models to determine production of bioenergy crops. They found that *stabilization scenarios lead to expanded deployment of biofuels relative to the reference scenarios, with attendant implications for land use and land cover.*

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

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

In stabilization regimes, the cost of fossil fuels rises, providing an increasing motivation for the production and transformation of bio-energy, as shown in Figure 4.16. In the IGSM modeling system, production begins earlier and produces a larger share of global energy as the stabilization limit becomes more stringent. Similarly, in the MiniCAM scenarios, deployment begins earlier and production grows larger the more stringent the stabilization target. In the presence of less-stringent stabilization limits, production of bio-crops is lower in the MiniCAM scenarios than in IGSM. Production reaches higher levels when stabilization limits are more stringent in Levels 1 and 2. These differences between the models are not simply due to different treatments of agriculture and land use but also reflect the full suite of technology and behavior assumptions.

Although total land-areas allocated to bioenergy crops are not reported in these scenarios, the extent of land area engaged in the production of energy becomes substantial. For example, in the Level 1 stabilization scenario, bioenergy corps are the largest activity conducted on the land in the MiniCAM scenario. 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 the IGSM, demands on land for biofuels cause land prices to increase substantially as compared with the reference because of competition with other agricultural demands.

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

Stabilization scenarios limit the rise in CO_2 concentrations and reduce the CO_2 fertilization effect below that in the reference scenario, which in turn leads to smaller CO_2 uptake by the terrestrial biosphere. The effect is larger and begins earlier the more stringent the stabilization level. For example, Figure 4.17 shows that in the IGSM Level 4 scenario, the effect is largest in the post-2050 period and amounts to about 0.8 GtC/y in 2100. The IGSM Level 1 scenario begins to depart markedly from the reference before

2050, and the difference grows to approximately 3.0 GtC/y by 2100. The effect of the diminished CO_2 fertilization effect is to require emissions mitigation in the energy-economy system to be larger by the amount of the difference between the reference aggregate net terrestrial CO_2 uptake and the uptake in the stabilization scenario.

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

The MiniCAM model uses the terrestrial carbon-cycle model of MAGICC as one component to determine the aggregate net carbon flux to the atmosphere. However, unlike either the IGSM or the MERGE models, MiniCAM determines land-use change emissions (e.g., deforestation) from an interaction between the choice of land use and associated carbon stocks and flows. Thus, economic competition among alternative human activities, crops, pasture, managed forests, bioenergy crops, and unmanaged ecosystems determine land use, which in turn (along with its associated changes) determines land-use change emissions. Thus, not only does MiniCAM exhibit the same types of CO_2 fertilization effects as IGSM, but also there are significant interactions between the agriculture sector and the unmanaged terrestrial carbon stocks in both the reference and stabilization scenarios. MERGE maintains its neutral biosphere in the stabilization scenarios.

One implication of the MiniCAM approach is that unless a value is placed on terrestrial carbon emissions as well as on fossil fuel emissions, stabilization scenarios can lead to increased pressure to deforest. MiniCAM results reported in Figure **4.17** assume that both fossil fuel and terrestrial carbon are priced. Thus, there is an economic incentive to maintain and/or expand stocks of terrestrial carbon as well as an incentive to bring more land under cultivation to grow bioenergy crops. Carbon value exerts an important counter-pressure to deforestation and other land-use changes that generate increased emissions.

To illustrate the importance of valuing terrestrial carbon, especially in more stringent stabilization scenarios, sensitivity cases were run using MiniCAM in which no price was applied to terrestrial carbon emissions. These sensitivity results showed dramatically increased levels of land-use change emissions when terrestrial carbon was not valued. The reason was that the value of carbon in the energy system created an incentive to expand bioenergy production. In turn, that expansion led to increased demand for land for biomass energy crops. But the resultant deforestation increased terrestrial CO_2 emissions, requiring even greater reductions in fossil fuel CO_2 emissions and even higher prices on fossil fuel carbon. This increased the demand for bioenergy and led to even more deforestation. Thus, without a value on terrestrial carbon, a vicious cycle can emerge in which accelerated deforestation (which occurs when terrestrial carbon is not valued) leads to a higher emissions mitigation requirement in the energy sector, which in turn leads to higher carbon prices, and then to an increased demand for biomass fuels. and thus, is a positive feedback to land-use change emissions. The MiniCAM results reported here assume a policy architecture that places a value on terrestrial carbon, avoiding the vicious cycle described above. Most proposed policy architectures have not envisioned such complete incentives for land use and land use change (Reilly and

Asadoorian, 2006). This sensitivity study illustrates the potential importance of this aspect of effective policy design related to land use.

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

4.6. Economic Consequences of Stabilization

> *The price paths for CO_2 and the other GHGs that are needed to achieve the stabilization targets are of similar patterns across the three models. However there are substantial differences in the estimate of the magnitude of the effort needed. Many factors contribute to the differences, but the largest factors are differences among reference scenarios (which determine the size of the needed reductions) and variation in assumptions about technology developments that may be achieved by the latter half of the century. For the most stringent Level 1, for example, carbon prices in 2050 range from \$500 to \$1200 per ton, and in 2100 range from \$550 to several thousand dollars, with the IGSM results producing the higher end costs in all scenarios.*
>
> *The penalties on CO_2 emissions have an influence on the producer prices of fossil fuels. For oil and coal the main effect is a fall in the producer price, with the oil price most affected. Effects on natural gas prices are influenced as well, particularly in the EPPA scenarios, where with less stringent targets gas prices increase due to substitution toward gas. Electricity prices generally increase because they reflect the carbon allowance price but the increase is moderated because of the possibilities substituting non-carbon, and lower carbon emitting fuels, and the fact that fuel cost (inclusive of carbon price) is only one component of cost. These effects are, of course, on the producer price; the consumer prices for all fuels (inclusive of the carbon price) are higher under the stabilization scenarios.*
>
> *The models estimated macroeconomic cost of the stabilization, measured as change in Global World Product (GWP), mirror the results for carbon prices, rising over time and with the stringency of the constraint but with substantial differences among the models with the ISGM producing considerably higher costs than the other models. For example, the estimated reduction in GWP for stabilization at Level 1 at mid-century is about 1% for MiniCAM and MERGE to approximately 5% for EPPA, a difference mainly arising from the higher EPPA reference emissions. In 2100 on the other hand the range is from 16% for EPPA to between 1% and 2% for the other two models. This difference is principally a function of divergent assumptions about technology development, and the range is an indication of the limits to our knowledge of technology advance a half-century and more into the future.*

4.6.1. Variation in Carbon Prices across Models

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

Figure 4.18. Carbon Prices across Stabilization Scenarios

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

The IGSM shows the highest marginal costs in all four stabilization scenarios. Yet the marginal abatement curves of the IGSM, MERGE, and MiniCAM models are very similar for the 2050 period when plotted in terms of percentage reduction from reference, seen in Figure 4.19. The models' behaviors diverge in the post-2050 period, reflecting differences in long-term technology expectations among the three reference scenarios, and this has repercussions for earlier periods. The approximated forward-looking behavior created by the carbon price path means that the IGSM results anticipate less significant technological breakthroughs and overall price incentives for abatement must be higher throughout the century to achieve target reductions. With relatively low cost abatement options after 2050, the MiniCAM carbon prices are lower throughout the century. The MERGE results are based on an explicit forward-looking response, featuring technology assumptions more similar to MiniCAM and showing similar lower carbon prices throughout the century than in the IGSM.

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

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

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

Prior to 2050, absolute differences in carbon prices across the scenarios are smaller than in 2100 (see Table 4.6**)**, while relative differences are far larger. Of note, the carbon price levels out in the most stringent case at $1000/tC in MERGE. This result is a function of an assumption in MERGE that at this price, actors in the economy can purchase emissions rights in lieu of reducing their emissions further. This assumption limits the level of emissions reduction in MERGE to that which is economically efficient at $1000/tC. Note that MERGE still reaches the Level 1 radiative forcing target even with this assumption.

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

4.6.2. Stabilization and Non-CO_2 Greenhouse Gases

Each of the three models employs a different approach to the non-CO_2 GHGs. After CO_2, CH_4 is the next largest component of reference scenario radiative forcing. The three models project different reference scenario emissions (Figure 3.18). The IGSM reference scenario starts in the year 2000 at about 350 MtC/y and rises to more than 700 MtC/y (Figure 4.7), while the MERGE and MiniCAM models begin in the year 2000 with 300 MtC/y in the year 2000. These are anthropogenic methane emissions and the differences reflect existing uncertainties in how much of total methane emissions are from anthropogenic and natural sources. MERGE CH_4 emissions grow to almost 600 MtC/y in the reference scenario. Like the MERGE reference, the MiniCAM scenario begins with emissions in the year 2000 at approximately 300 MtC/y, but the MiniCAM reference scenario is characterized by a peak in CH_4 emission at less than 400 MtC/y, followed by a decline to about 250 MtC/y.

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

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

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

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

IGSM employs a third approach. Methane emissions are limited to a maximum value in each stabilization scenario: Level 4 at 425 MtC/y; Level 3 at 385 MtC/y; Level 2 at 350 MtC/y; and Level 1 at 305 MtC/y. As a consequence, the ratio of the price of CH_4 to carbon initially grows from one-tenth to a maximum of between 3 and 14 between the years 2050 and 2080 and then declines thereafter. As previously discussed, this reflects an implicit assumption that places higher value on near term reductions in climate change, and a long run requirement of stabilization that eventually each substance must be (approximately) independently stabilized.

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

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

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

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

Figure 4.21. N_2O Concentrations across Scenarios

4.6.3. Stabilization and Energy Markets

The carbon price drives a wedge between the producer price of fuels and the cost to the user. Table 4.7 provides an approximation of that of the relationship.

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

One of the clearest results to emerge from the stabilization scenarios is their depressive effect on the world price of oil (Figure 4.22). Level 4 stabilization scenarios have a relatively modest effect on the oil price but this effect is stronger with the more stringent the level of stabilization. The three models give different degrees of oil price reduction, which in turn depends on many factors, including how the supply of oil is characterized, the carbon price, and the availability of substitute technologies for providing transportation liquids, such as biofuels or hydrogen.

Figure 4.22. World Oil Price, Reference and Stabilization Scenarios

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

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

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

Coal prices are similarly depressed in stabilization scenarios (see Figure 4.23). The effect is mitigated by two features: the assumed availability of CCS technology, which allows the continued large-scale use of coal in power generation in the presence of a positive price of carbon, and a coal supply schedule that is highly elastic. That is, demand for coal can exhibit large increases or decreases without much change in price.

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

The natural gas price is most affected in the IGSM stabilization scenarios, reflecting the greater substitution of natural gas for coal in IGSM stabilization Levels 2, 3, and 4, particularly in the pre-2050 period. At Level 1 stabilization, natural gas use is reduced over the entire period. On balance, the natural gas price is less affected by stabilization in the MERGE and MiniCAM models when the substitution and conservation effects are roughly offsetting. The different impacts on the coal price reflect the different characterization of supply. MERGE models coal supply as a constant marginal cost supply technology; with no resource rents or different resource grades, so the price is equal to the marginal cost in any period regardless of the production level. The IGSM and MiniCAM include a resource characterization of coal that is graded and/or includes resource rents and thus reduced demand leads to lower prices. Thus, while the models agree that stabilization will tend to depress oil prices, they show different pictures of the effect on natural gas and coal prices.

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

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

4.6.4. Total Cost of Stabilization

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

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

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

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

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

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

Figure 4.26. Global GWP Impacts of Stabilization across Stabilization Levels

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

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

Up to mid-century differences in the model results are mainly attributable mainly to their different reference case emissions. The IGSM reference scenario reaches 18 GtC/y in 2050 compared with 12 GtC/y for MERGE and 14 GtC/y for MiniCAM (Figure 4.6). With its higher reference emissions the IGSM must undertake more stringent mitigation than in either the corresponding MERGE or MiniCAM scenarios. This influence is particularly important for the more ambitious stabilization Levels, 1 and 2. Returning to Figure 4.19, note that the relationship between the price of carbon and the percentage abatement relative to the reference scenario in 2050 is very similar between the three modeling teams. Given this result, it is likely that if the required mitigation was of the same relative magnitude, then the GWP costs would be more similar as well. But, the degree of emissions mitigation is not the same and costs rise non-linearly with the required reduction. The IGSM with its higher reference emissions must reduce by 75% while MERGE mitigates only 70% and MiniCAM by 66%.

In the post-2050 period, the relationship between emissions mitigation and the price of carbon, shown in Figure 4.19, is less similar across the three models. For the year 2100 the relationship between carbon prices and percentage emissions mitigation in MiniCAM and MERGE has shifted to the right relative to its 2050 positions while the IGSM mapping has shifted to the left. Yet, the degree of emissions mitigation required by the three modeling teams is more similar in 2100 than it was in 2050. In fact, in 2100 the percentage rate of emissions mitigation required by the IGSM Level 1 case is smaller than the percentage rate of emissions mitigation required by either the MiniCAM or MERGE models.

In the post-2050 period, therefore, assumptions about available technology and the rate of technological change are the major causes for the difference in outlook. This variation is most important in end-use sectors, buildings, industry and transport. In power generation all three models have essentially decarbonized by the year 2100 (Figure 4.11), but not in the end-use sectors where fossil fuels remain important. As a second factor causing the difference, electricity also plays a more important role in the MERGE and MiniCAM scenarios than in the IGSM stabilization scenarios. Thus, the relative ease that all three models display in removing carbon from power generation is especially helpful to the MERGE and MiniCAM stabilization scenarios as end-use applications rely more heavily on electricity to deliver energy services in these models. The variation in estimated cost serves to underscore the importance of the rate and character of technological change over long periods of time, and the fundamental uncertainty regarding technology developments more than half a century into the future.

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

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

Table 4.2. Radiative Forcing in the Year 2100 across Scenarios

		Radiative Forcing in 2100 (Wm^{-2} relative to pre-industrial)		
Stabilization Level	Long-Term Radiative Forcing Limit (Wm^{-2} relative to pre-industrial)	IGSM	MERGE	MiniCAM
Ref	No Constraint	8.6	6.7	6.5
Level 4	6.7	6.1	6.1	6.0
Level 3	5.8	5.4	5.5	5.5
Level 2	4.7	4.4	4.6	4.5
Level 1	3.4	3.5	3.4	3.4

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

		CO_2 Concentration in 2100 (ppmv)		
Level	Approximate Long-term CO_2 Concentration Limit (ppmv)	IGSM	MERGE	MiniCAM
Ref	--	875	717	762
Level 4	750	677	649	725
Level 3	650	614	590	673
Level 2	550	526	520	565
Level 1	450	451	426	463

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

		Annual Global Carbon Capture and Storage (PgC/y)		
Stabilization Level	Year	IGSM	MERGE	MiniCAM
Level 4	2030	0.01	0.03	0.09
	2050	0.44	0.22	0.18
	2100	4.12	2.48	0.95
Level 3	2030	0.05	0.03	0.10
	2050	0.83	0.38	0.22
	2100	4.52	3.66	3.03
Level 2	2030	0.12	0.10	0.13
	2050	1.96	1.37	0.62
	2100	4.97	4.40	6.47
Level 1	2030	0.37	0.18	0.72
	2050	2.76	1.60	3.12
	2100	4.44	3.38	7.77

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

		Cumulative Global Carbon Capture and Storage (PgC)		
Stabilization Level	Year	IGSM	MERGE	MiniCAM
Level 4	2050	4	3	4
	2100	92	50	27
Level 3	2050	8	5	4
	2100	153	118	58
Level 2	2050	19	13	8
	2100	208	199	179
Level 1	2050	37	17	42
	2100	231	160	328

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

	2020 ($/tonne C)			2030 ($/tonne C)		
Stabilization Level	IGSM	MERGE	MiniCAM	IGSM	MERGE	MiniCAM
Level 4	$18	$1	$1	$26	$2	$2
Level 3	$30	$3	$4	$44	$5	$7
Level 2	$75	$8	$17	$112	$13	$29
Level 1	$259	$112	$94	$384	$196	$166

	2050 ($/tonne C)			2100 ($/tonne C)		
Stabilization Level	IGSM	MERGE	MiniCAM	IGSM	MERGE	MiniCAM
Level 4	$58	$7	$6	$415	$72	$72
Level 3	$97	$14	$18	$686	$160	$217
Level 2	$245	$37	$99	$1,743	$440	$330
Level 1	$842	$589	$435	$6,053	$1,000	$676

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

Fuel	**Base Cost ($1990)**	**Added Cost ($)**	**Added Cost (%)**
Crude Oil ($/bbl)	$16.0	$12.2	76%
Gasoline ($/gal)	$0.98	$0.26	27%
Heating Oil ($/gal)	$0.89	$0.29	33%
Wellhead Natural Gas ($/tcf)	$1.81	$1.49	82%
Residential Natural Gas ($/tcf)	$5.87	$1.50	26%
Mine-mouth Coal ($/short ton)	$23.0	$55.3	240%
Utility Coal ($/short ton)	$33.5	$55.3	165%
Electricity (c/kWh)	6.5	1.76	27%

Source: Bradley et al. (1991). [Good table. Referring to 1990 prices, seems however, to be awfully dated. Couldn’t we just replace Base cost with EIA data for e.g 2005, and then recomputed the percentage—the added cost should not change because $100 remains $100.

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

Level 1

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

Level 2

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

Level 3

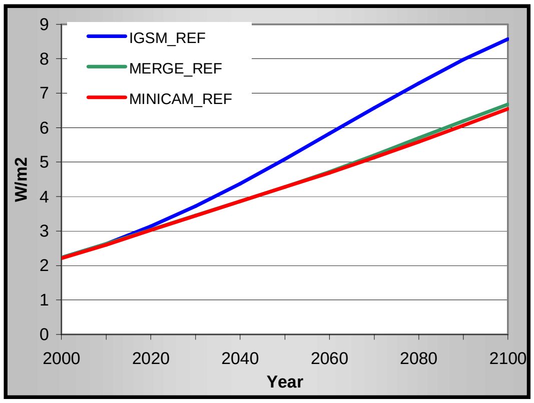
	2020	2040	2060	2080	2100
IGSM	0.2%	0.4%	0.9%	1.8%	3.1%
MERGE	0.0%	0.0%	0.1%	0.2%	0.3%
MiniCAM	0.0%	0.0%	0.0%	0.1%	0.3%

Level 4

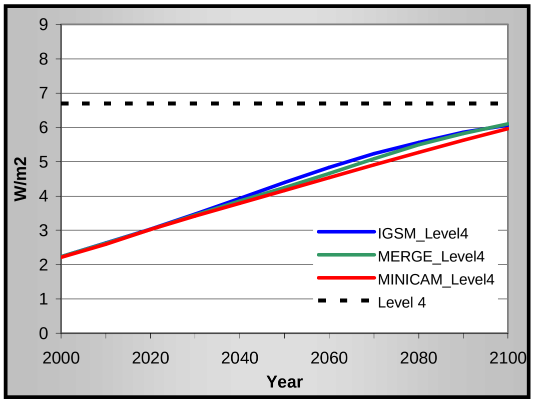
	2020	2040	2060	2080	2100
IGSM	0.1%	0.2%	0.4%	0.9%	1.7%
MERGE	0.0%	0.0%	0.0%	0.1%	0.2%
MiniCAM	0.0%	0.0%	0.0%	0.0%	0.0%

Figure 4.1. Total Radiative Forcing by Year across Scenarios (W/m^2). Results for radiative forcing (W/m^2; increase from preindustrial) for the reference and four stabilization levels show differences among the models for the reference case but essentially identical results for all three models in each of the stabilization scenarios reflecting their design. Models remain below the Levels 3 and 4 targets in 2100, allowing for a gradual approach to the target levels in the following century.

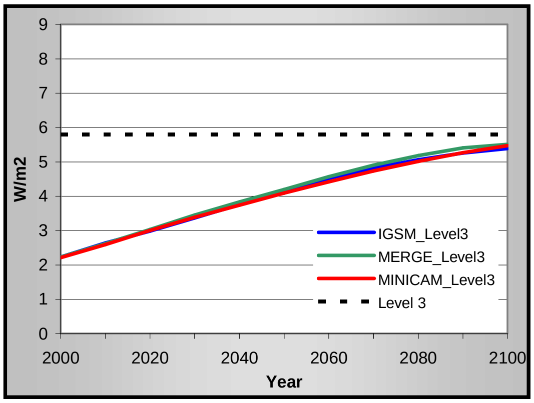
Reference Scenarios



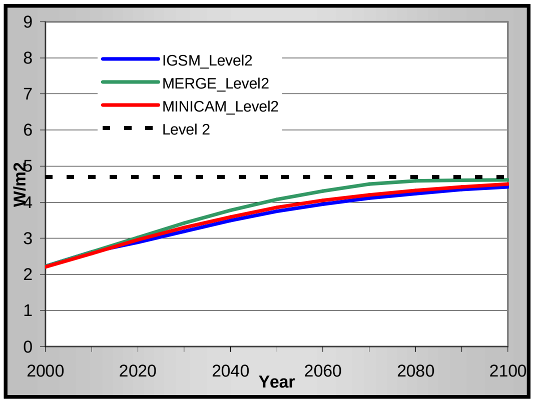
Level 4 Scenarios



Level 3 Scenarios



Level 2 Scenarios



Level 1 Scenarios

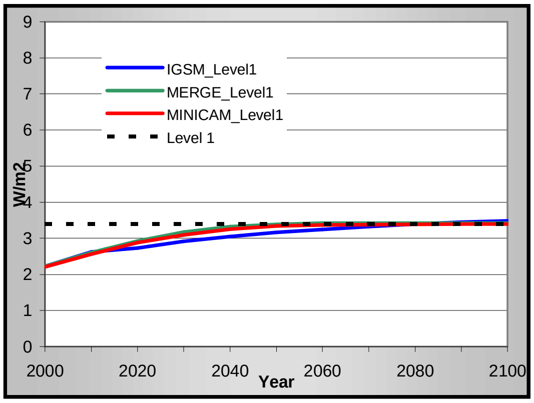
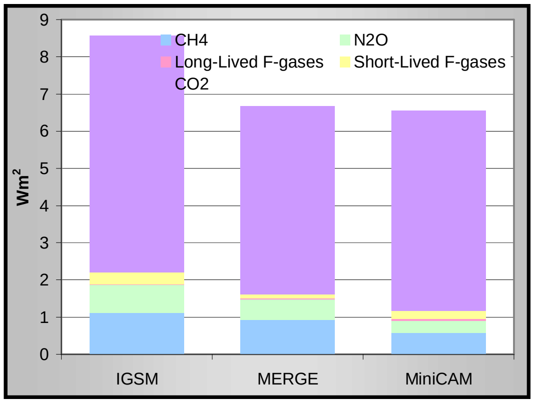


Figure 4.2. Total Radiative Forcing by Gas in 2100 across Scenarios (W/m^2 relative to preindustrial). Results for radiative forcing in the year 2100 by GHG show CO_2 to be the main contributor. Contributions from non-CO_2 gases are relatively higher in the reference in the IGSM results, and relatively lower for the MiniCAM results, with MERGE intermediate.

Reference Scenarios



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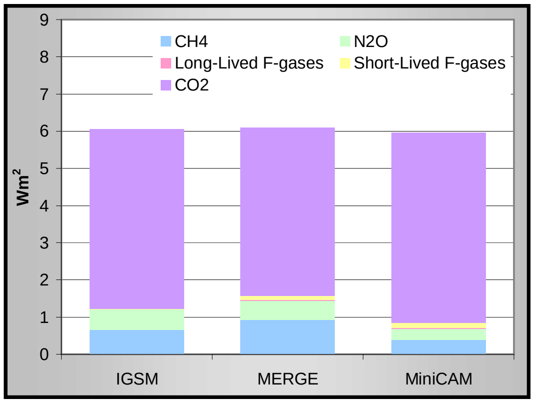
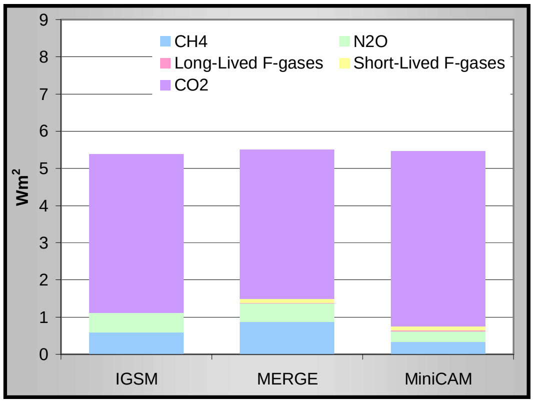


Level 3 Scenarios



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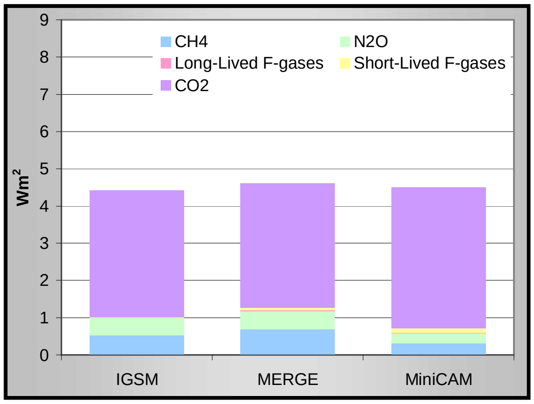


Level 1 Scenarios

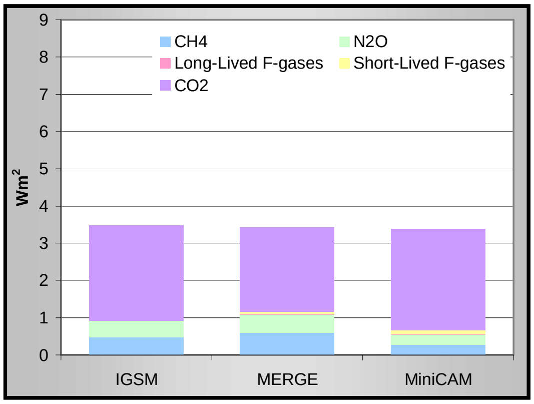
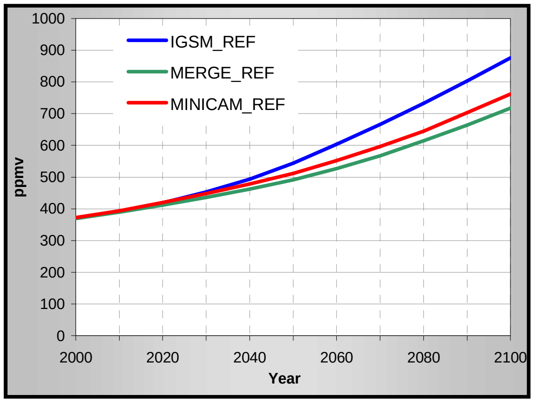
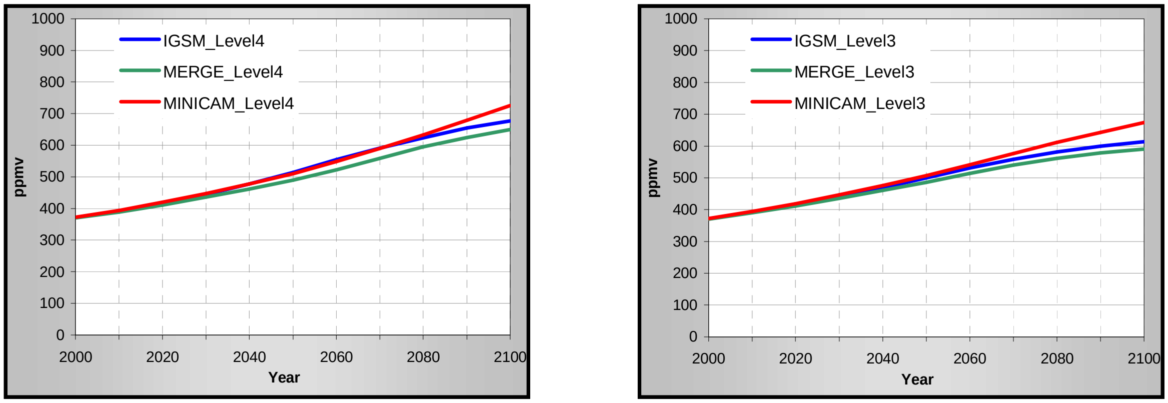


Figure 4.3. CO_2 Concentrations across Scenarios (ppmv). Atmospheric concentrations of CO_2 range from about 715 ppmv to 875 ppmv in 2100 across the models, with no sign of slowing in the reference. Radiative forcing targets were chosen so that CO_2 concentration levels would be approximately 450, 550, 650, and 750 ppmv at stabilization for Levels 1, 2, 3, and 4, respectively. Some differences among models occur because of the relative contribution of other GHGs to meeting the radiative forcing targets, and because for Levels 3 and 4 the models simulated a gradual approach to the stabilization level that will occur in the following century.

Reference Scenarios



Level 4 Scenarios **Level 3 Scenarios**



Level 2 Scenarios **Level 1 Scenarios**

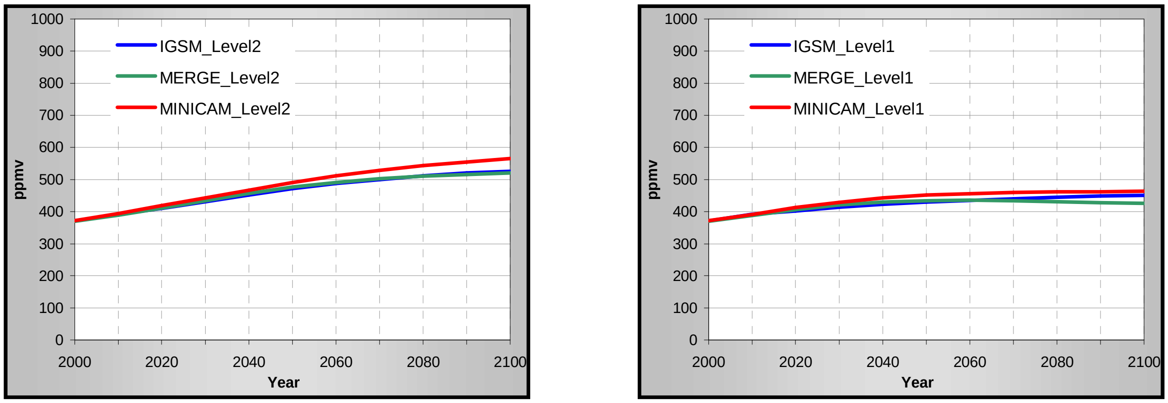
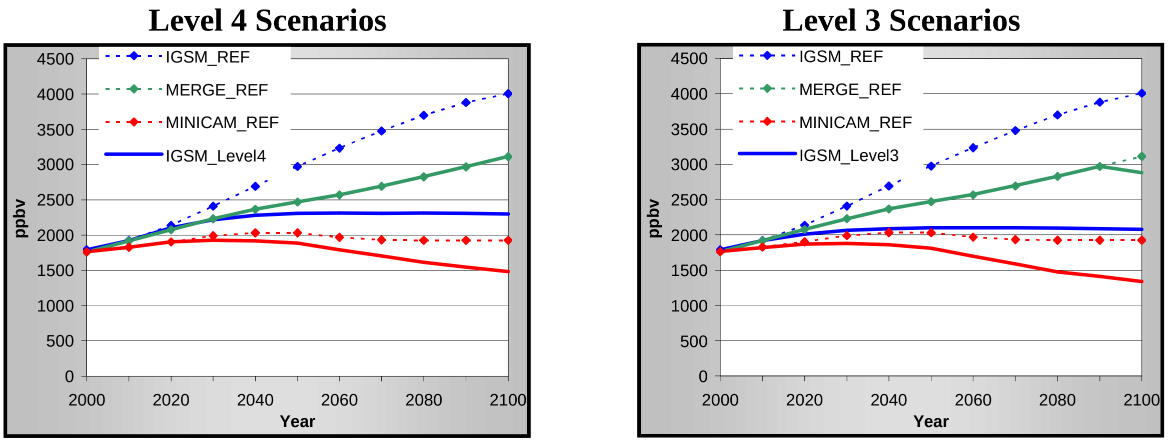


Figure 4.4. CH_4 Concentrations across Scenarios (ppbv). There are larger differences among the models for CH_4 concentrations than for CO_2. These differences stem from different reference scenarios, abatement potentials, and methods of inter-gas comparisons that determined abatement levels. MiniCAM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


Level 4 Scenarios **Level 3 Scenarios**

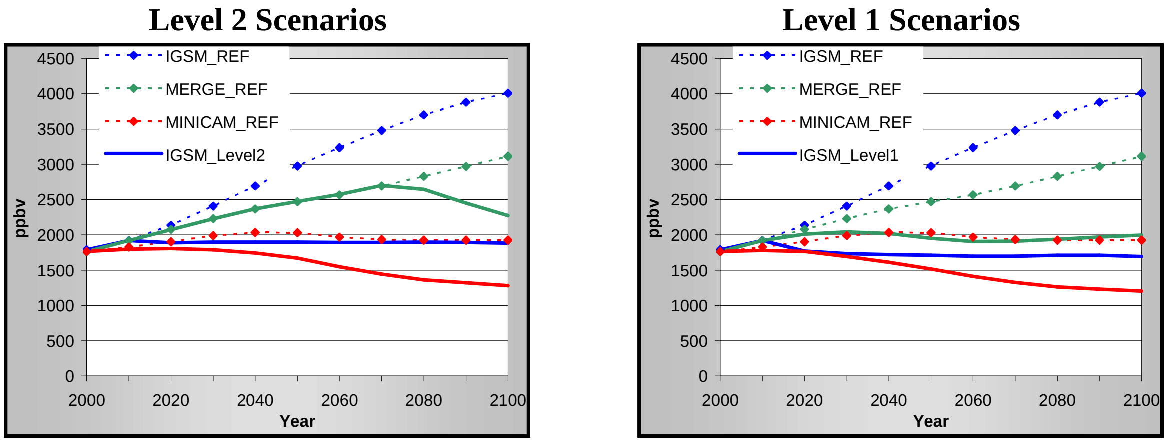
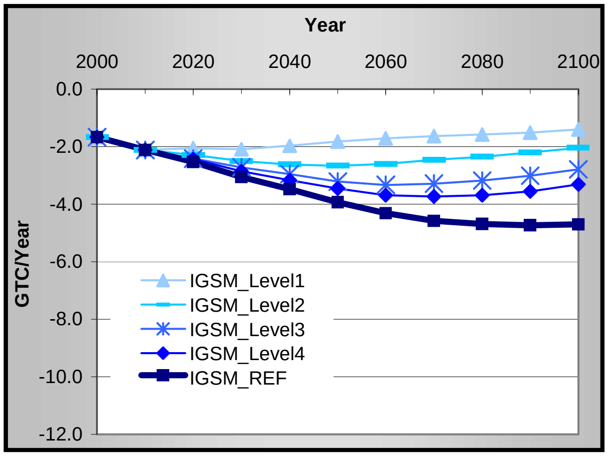
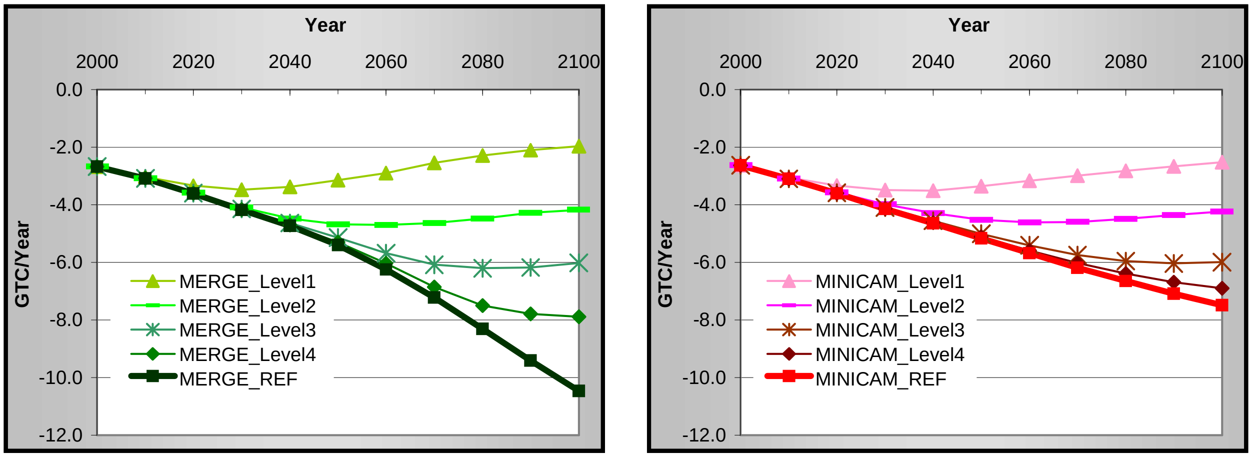

Level 2 Scenarios **Level 1 Scenarios**

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



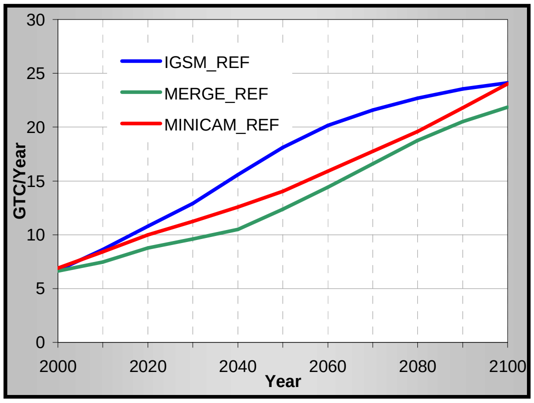
IGSM Scenarios

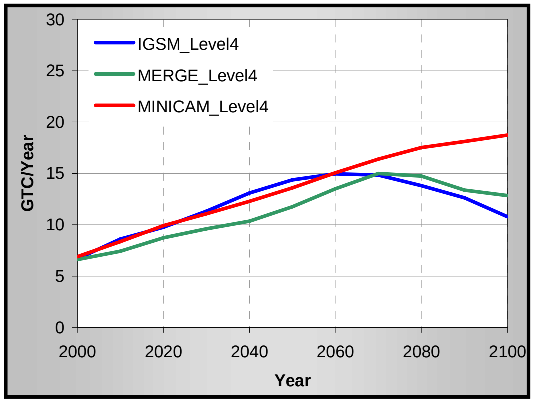


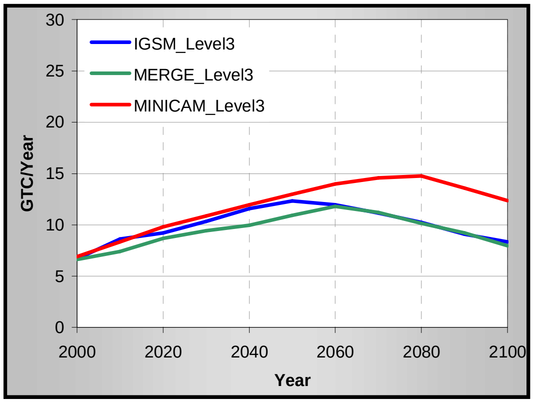
MERGE Scenarios

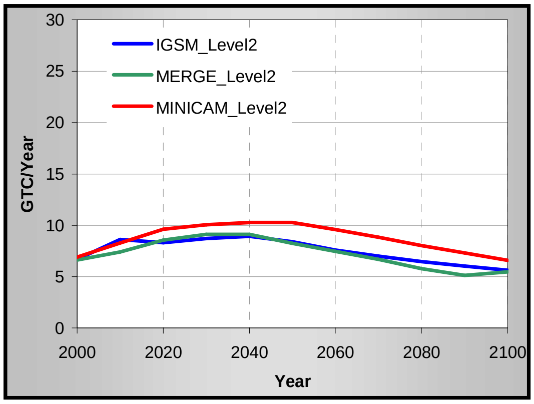
MiniCAM Scenarios

Figure 4.6. Fossil Fuel and Industrial CO_2 Emissions across Scenarios (GtC/y). Oceans have taken up approximately one-half of anthropogenic emissions of CO_2 since pre-industrial times. Thus, ocean behavior in the future is an important determinant of atmospheric concentrations. The three-dimensional ocean used for the IGSM simulations show the least ocean carbon uptake and considerable slowing of carbon uptake even in the reference when carbon concentrations are continuing to rise. MERGE shows the largest uptake in the reference, and greatest reduction from reference in the stabilization scenarios. MiniCAM results are intermediate.


Reference Scenarios


Level 4 Scenarios


Level 3 Scenarios


Level 2 Scenarios

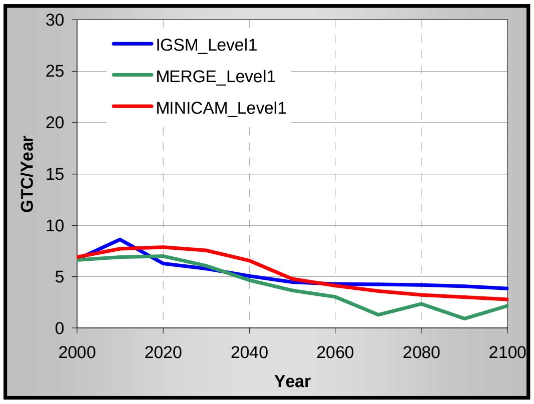
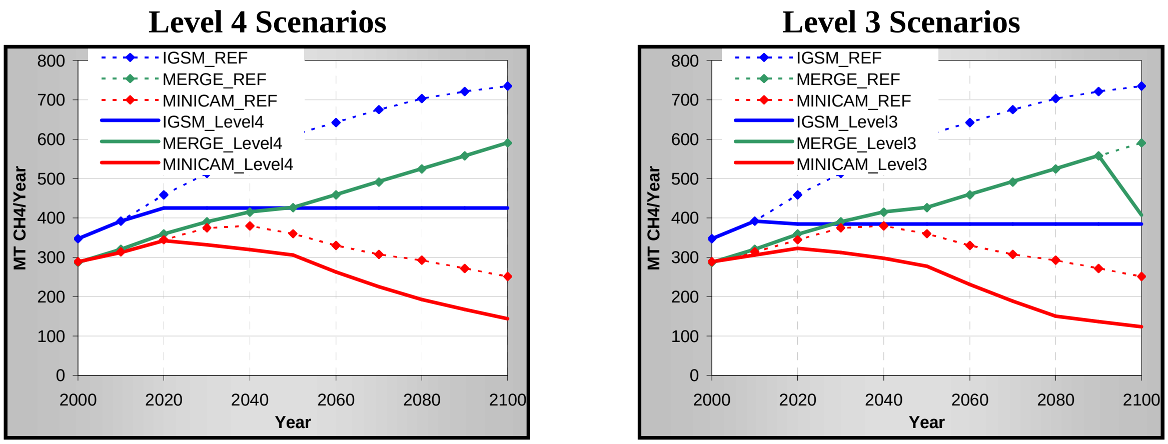

Level 1 Scenarios

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


Level 4 Scenarios **Level 3 Scenarios**

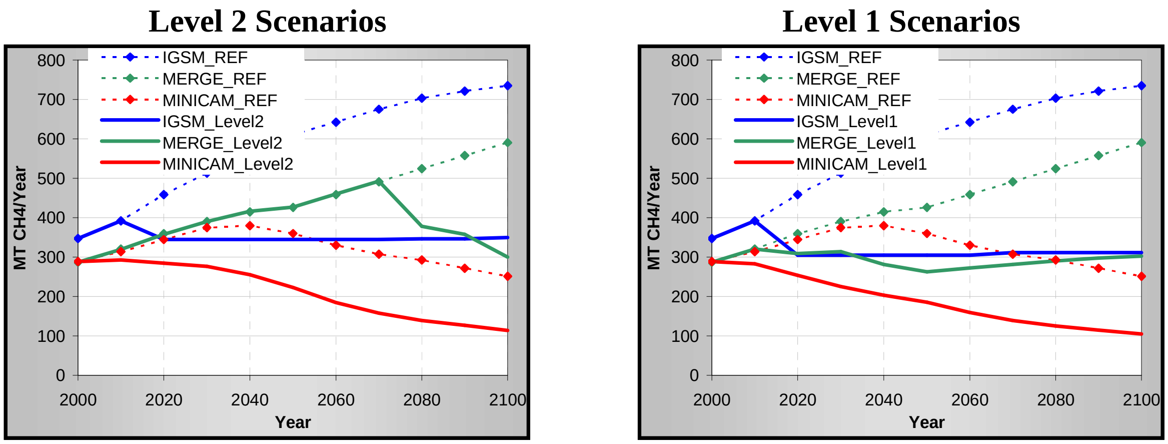
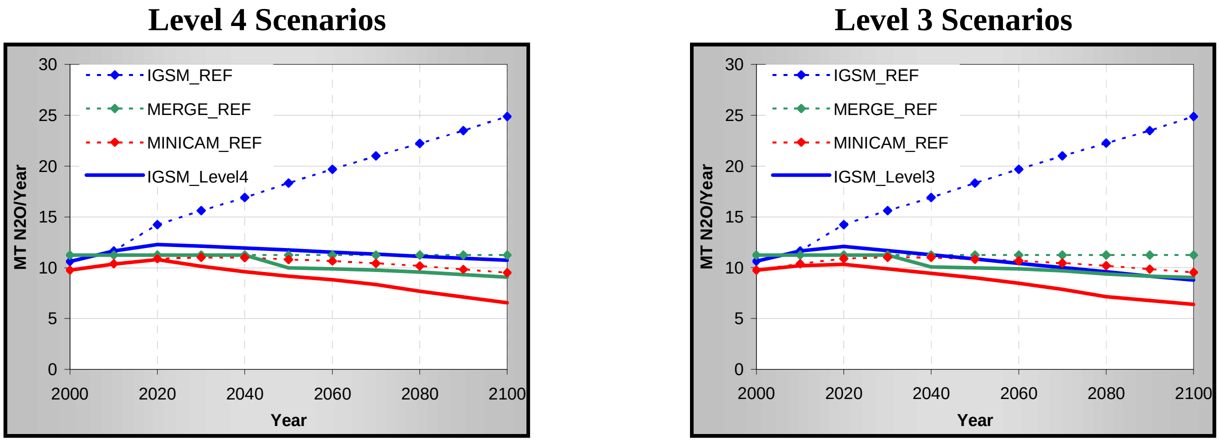

Level 2 Scenarios **Level 1 Scenarios**

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



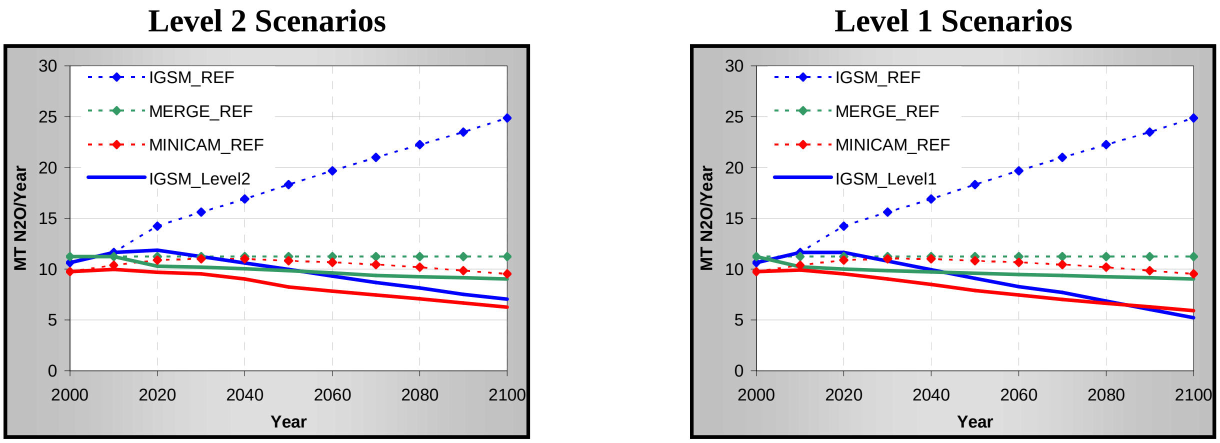


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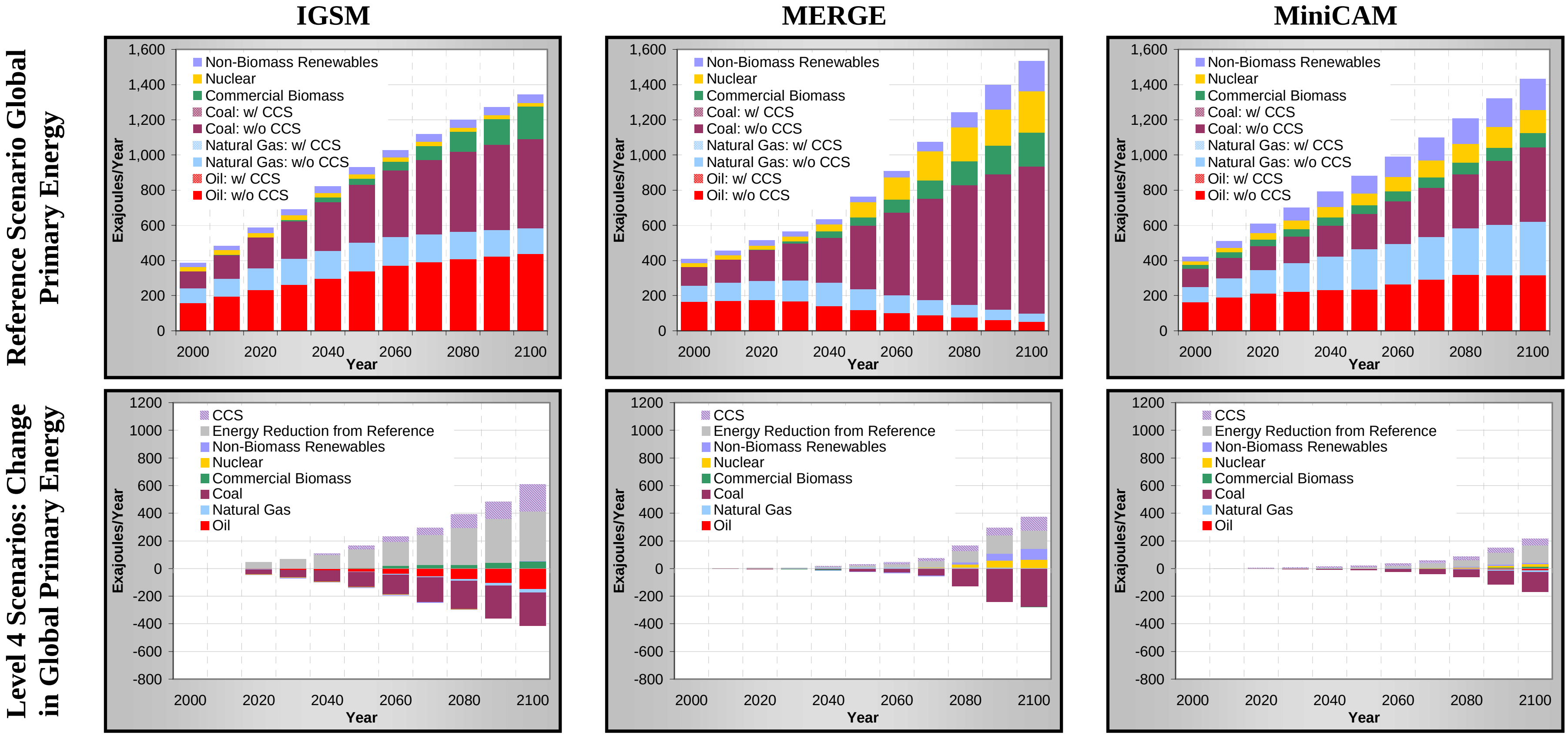
Figure 4.9. Change in Global Primary Energy by Fuel across Stabilization Scenarios, Relative to Reference Scenarios (EJ/y): Fuel-source changes from the reference to the stabilization scenarios show significant transformation of the energy system for all three models. The transformation can begin later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



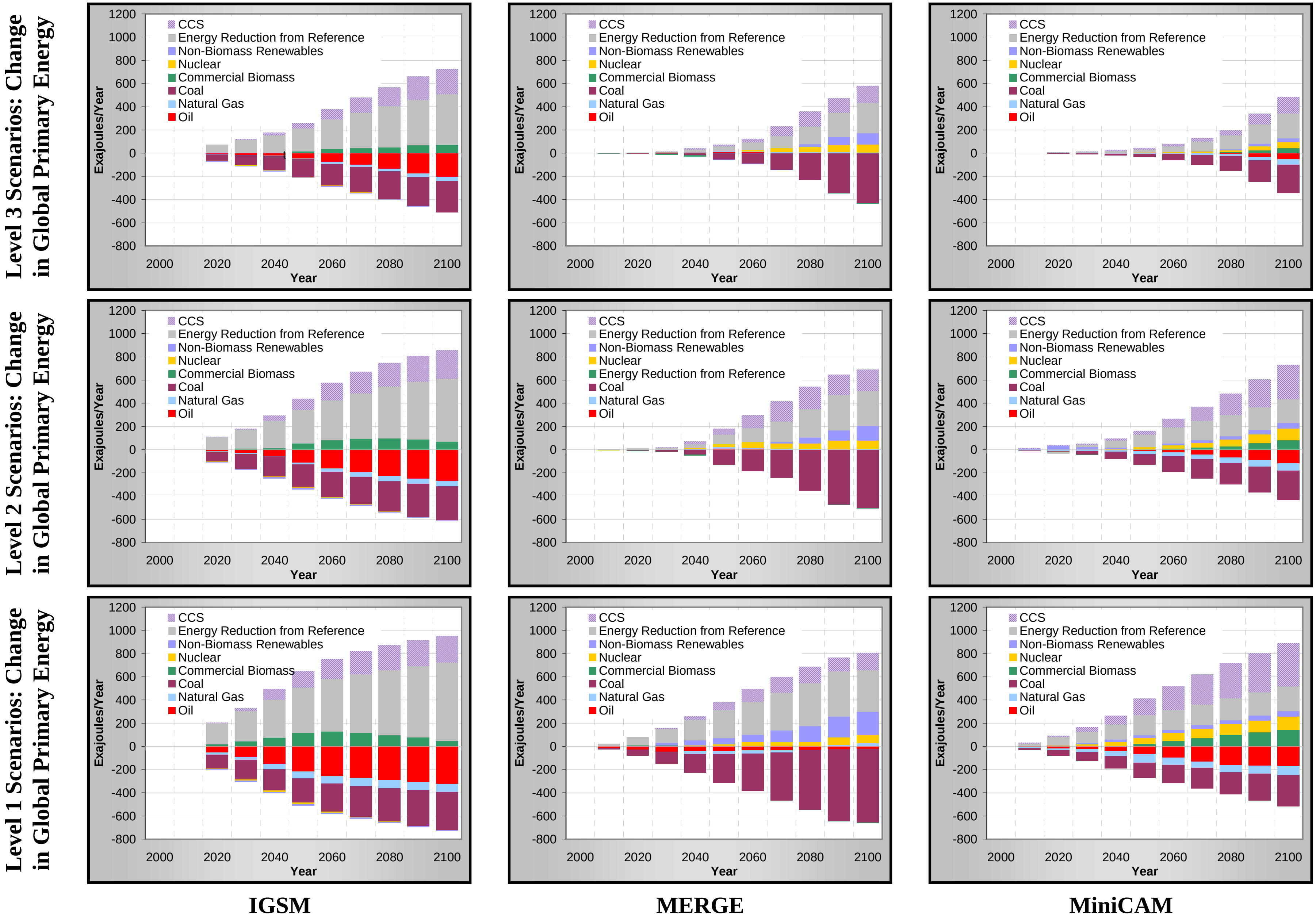
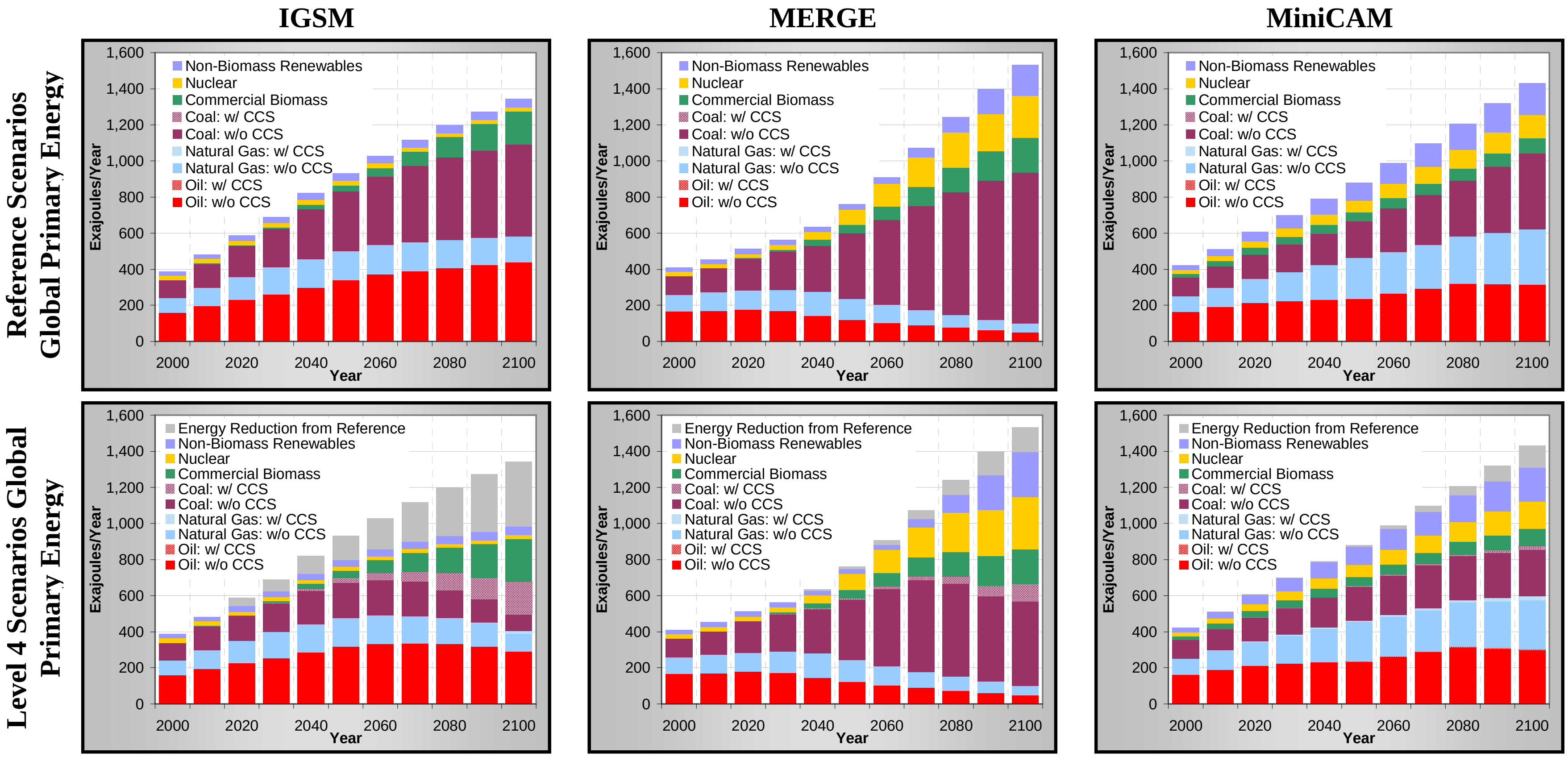

Level 3 Scenarios: Change in Global Primary Energy
Level 2 Scenarios: Change in Global Primary Energy
Level 1 Scenarios: Change in Global Primary Energy
IGSM
MERGE
MiniCAM
CCS
Energy Reduction from Reference
Non-Biomass Renewables
Nuclear
Commercial Biomass
Coal
Natural Gas
Oil
Exajoules/Year
Year
1200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

Figure 4.10. Global Primary Energy by Fuel across Scenarios (EJ/y). The transition to stabilization, reflected most fully in the Level 1 scenario, means nearly complete phase-out of fossil fuel use unless carbon capture and sequestration is employed. MiniCAM and MERGE simulations suggest a 35- to 40-fold increase in non-carbon fuels from present levels of production. IGSM simulations indicate more of the carbon reduction is met through demand reductions, with energy use cut by more than one-half from reference in 2100. Levels 2, 3, and 4 require progressively less transformation compared with the reference in the coming century, delaying these changes until the following century (beyond the simulation horizon).



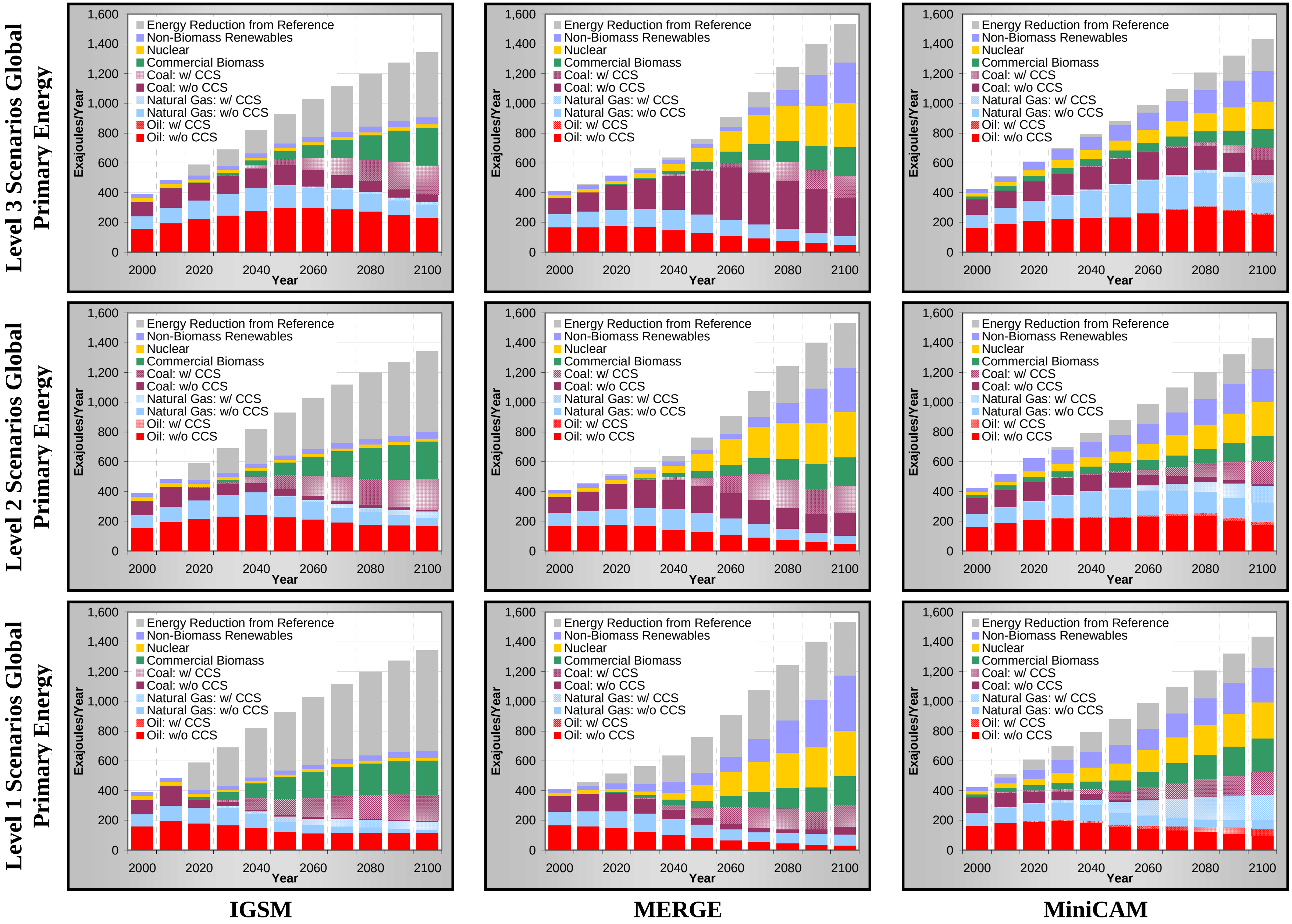
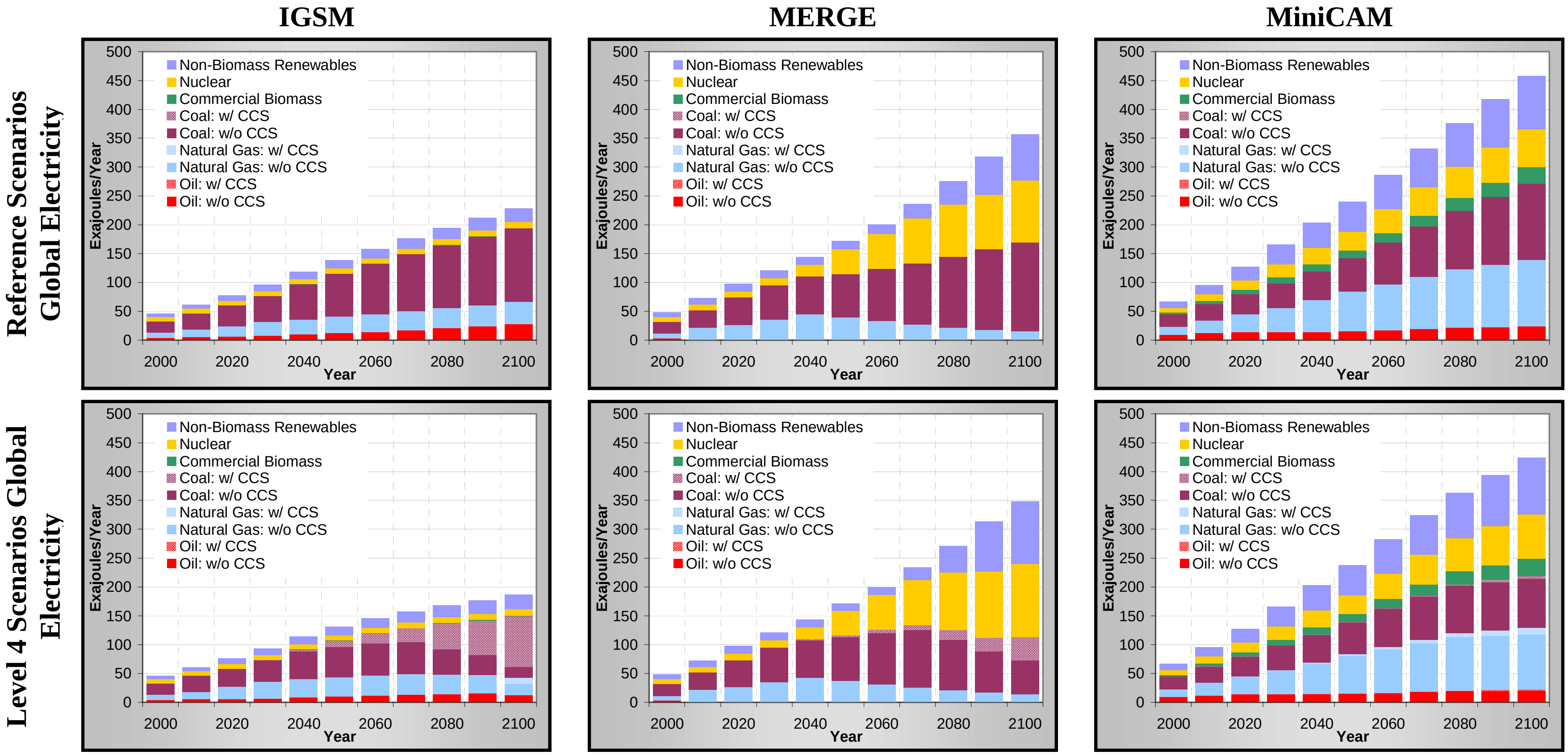

Level 3 Scenarios Global Primary Energy
Level 2 Scenarios Global Primary Energy
Level 1 Scenarios Global Primary Energy
IGSM
MERGE
MiniCAM
Exajoules/Year
Year
0
200
400
600
800
1,000
1,200
1,400
1,600
2000
2020
2040
2060
2080
2100
Energy Reduction from Reference
Non-Biomass Renewables
Nuclear
Commercial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

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



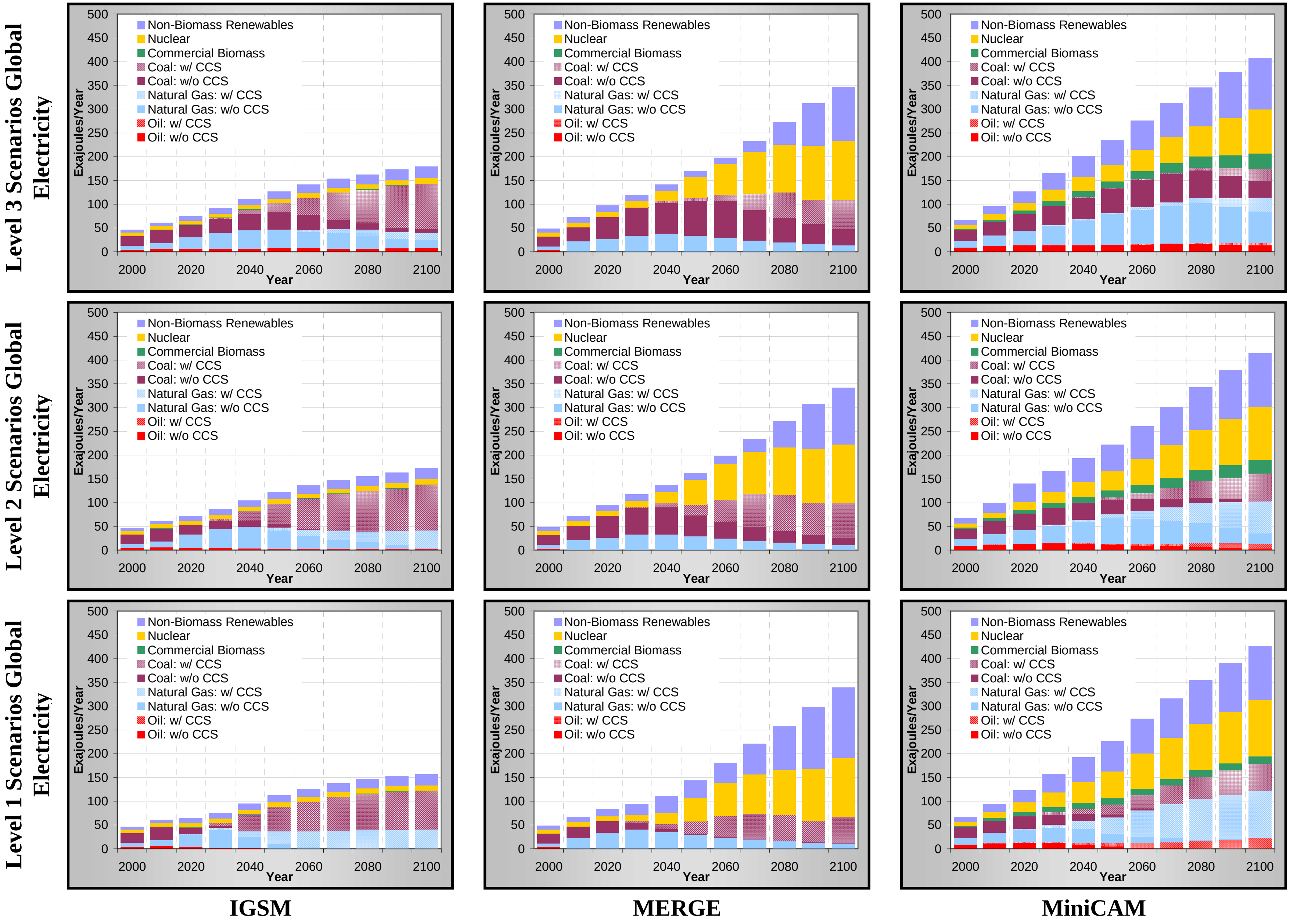
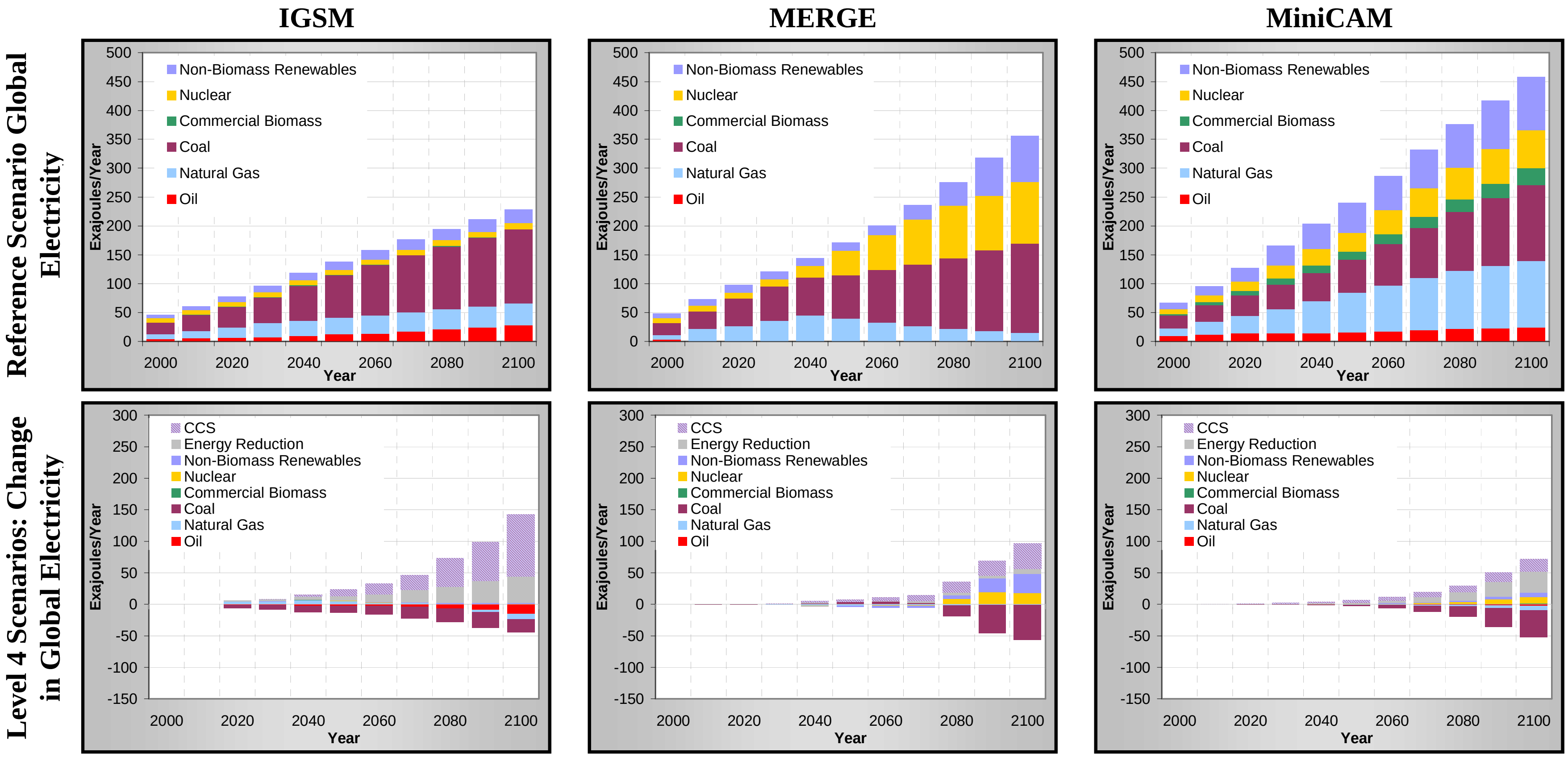

Level 3 Scenarios Global Electricity
Level 2 Scenarios Global Electricity
Level 1 Scenarios Global Electricity
IGSM
MERGE
MiniCAM
Non-Biomass Renewables
Nuclear
Commercial Biomass
Coal: w/ CCS
Coal: w/o CCS
Natural Gas: w/ CCS
Natural Gas: w/o CCS
Oil: w/ CCS
Oil: w/o CCS
Exajoules/Year
Year
0
50
100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

Figure 4.12. Changes in Global Electricity by Fuel across Stabilization Scenarios, Relative to Reference Scenarios (EJ/y). There are various electricity technology options that could be competitive in the future, and different assessments of their relative economic viability, reliability, and resource availability lead to considerably different scenarios for the global electricity sector in reference and stabilization scenarios across the models. IGSM simulations project relatively little change in the electricity sector in the reference, with continued reliance on coal. MERGE and MiniCAM project large transformations from current in the reference. All 3 forecast large changes from reference to meet the stabilization targets.



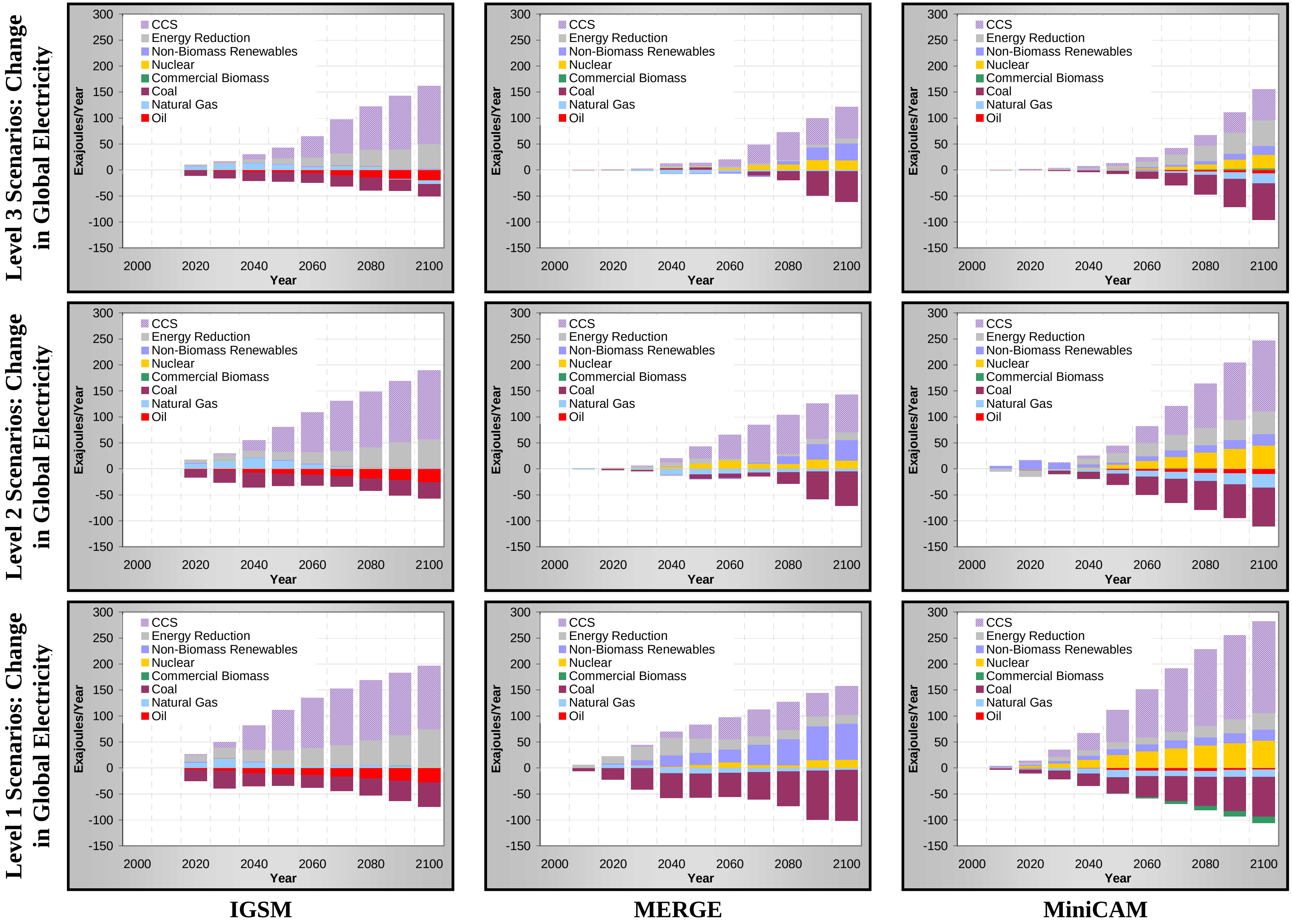
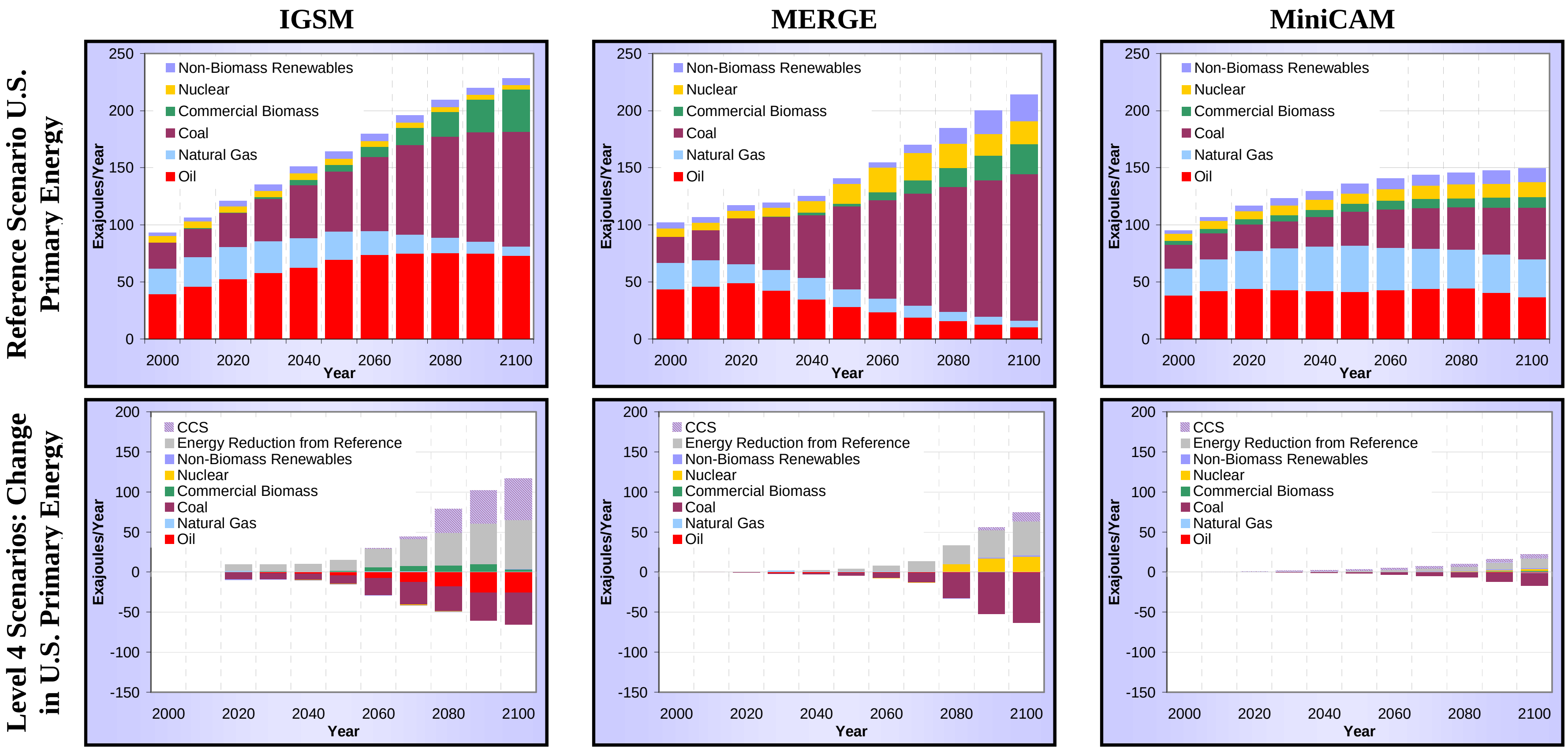

Level 3 Scenarios: Change in Global Electricity
Level 2 Scenarios: Change in Global Electricity
Level 1 Scenarios: Change in Global Electricity
CCS
Energy Reduction
Non-Biomass Renewables
Nuclear
Commercial Biomass
Coal
Natural Gas
Oil
Exajoules/Year
300
250
200
150
100
50
0
-50
-100
-150
2000
2020
2040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

Figure 4.13. Changes in U.S. Primary Energy by Fuel across Stabilization Scenarios, Relative to Reference Scenarios (EJ/y). Scenarios for the United States energy system under reference and the changes needed under the stabilization scenarios involve transformations similar to those reported for the global system (Figure 4.10). One difference not obvious from these primary fuel data is the transformation from conventional oil and gas to synthetic fuel production derived from shale oil or coal. IGSM projects heavy use of shale oil in the reference with some coal gasification, whereas MERGE simulates synthetic liquid and gaseous fuels derived from coal.



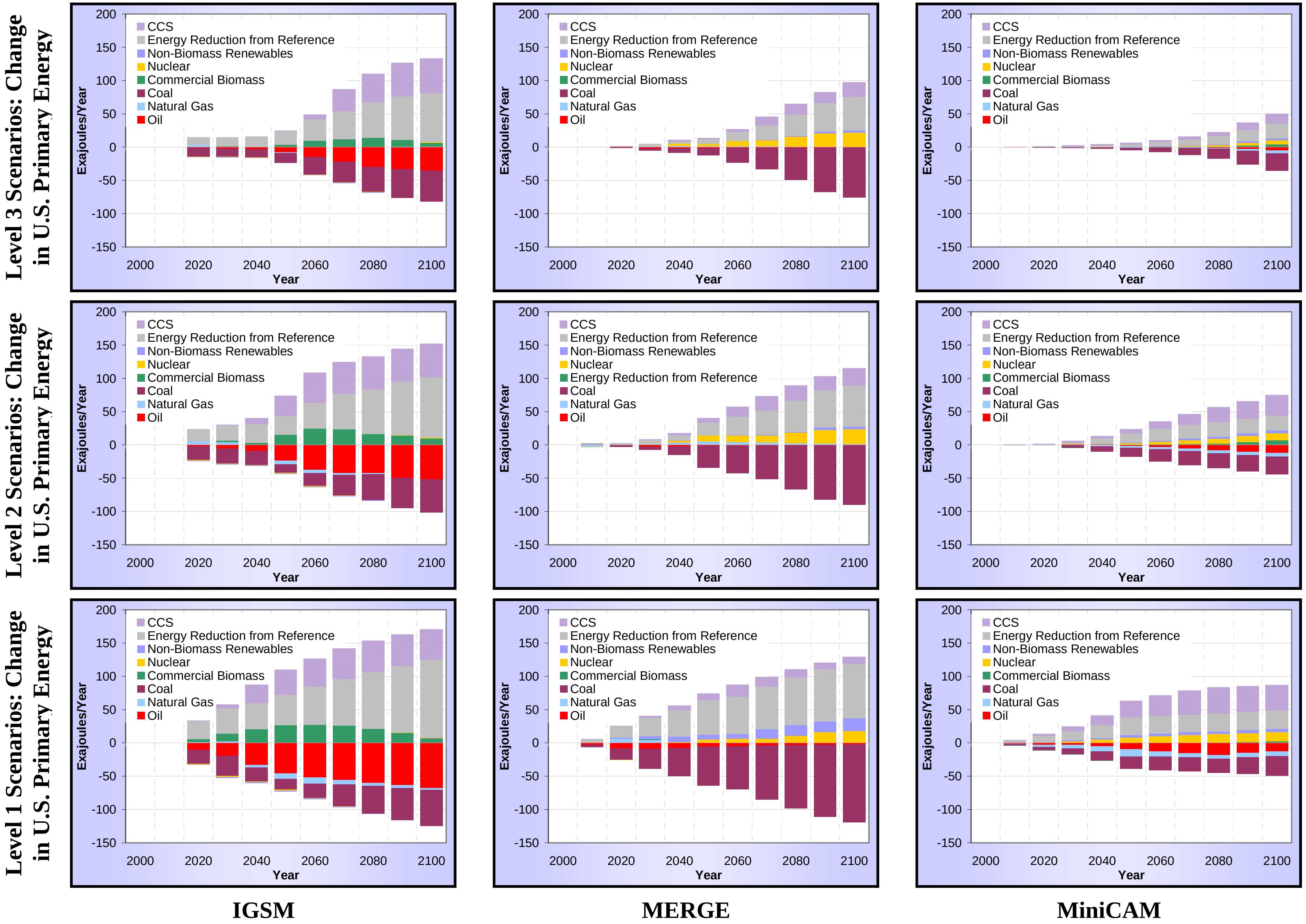
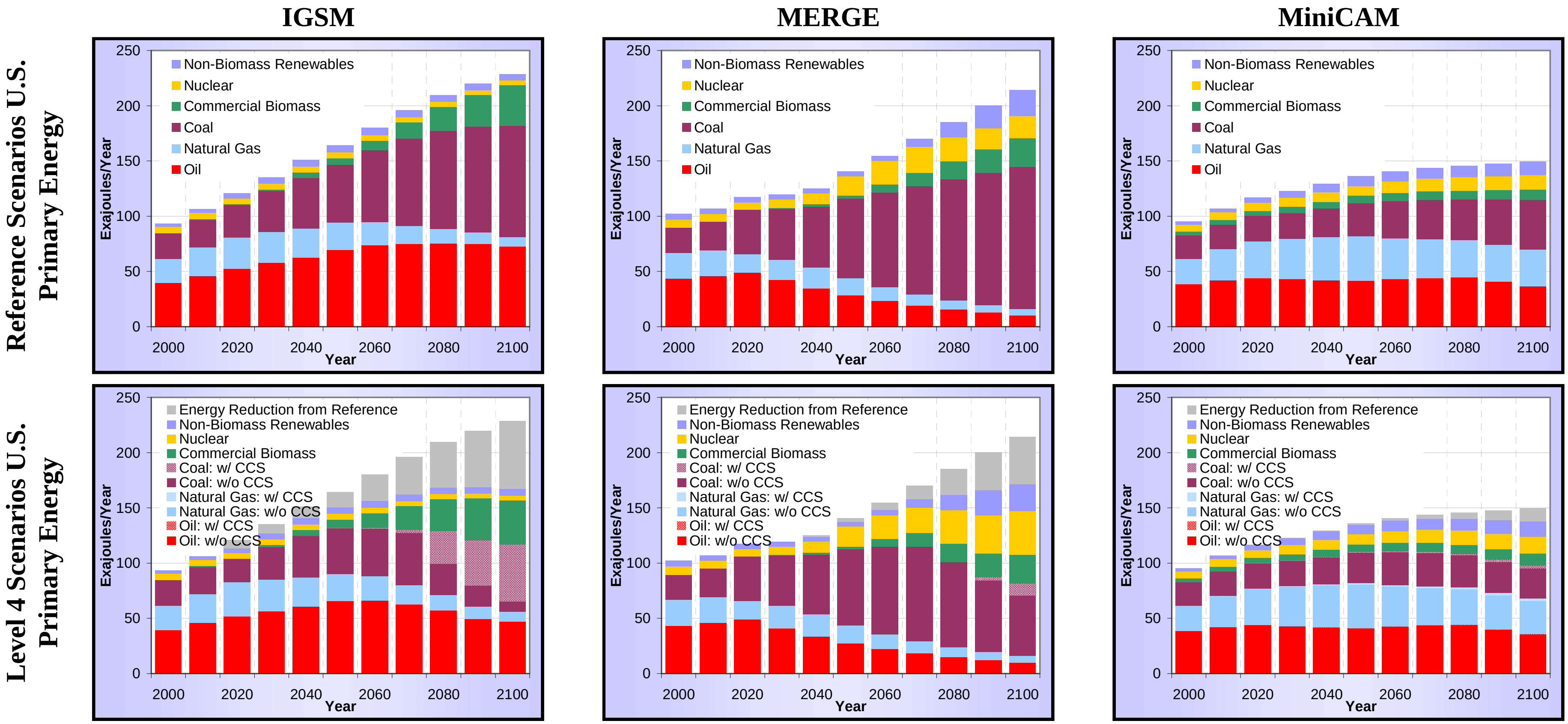

Level 3 Scenarios: Change in U.S. Primary Energy
Level 2 Scenarios: Change in U.S. Primary Energy
Level 1 Scenarios: Change in U.S. Primary Energy
IGSM
MERGE
MiniCAM
CCS
Energy Reduction from Reference
Non-Biomass Renewables
Nuclear
Commercial Biomass
Coal
Natural Gas
Oil
Exajoules/Year
200
150
100
50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

Figure 4.14. U.S. Primary Energy by Fuel across Scenarios (EJ/y). Simulated United States primary energy use under the four stabilization levels shows considerable difference among the three models. MiniCAM shows the greatest diversity of supply technologies, whereas IGSM tends to project dominant "winners" for different energy carriers. Which technologies would win likely depends on specific assumptions about cost and availability of individual technologies–assumptions that are highly uncertain. In terms of R&D, then, a broad investment portfolio, including many different technologies, is likely needed.



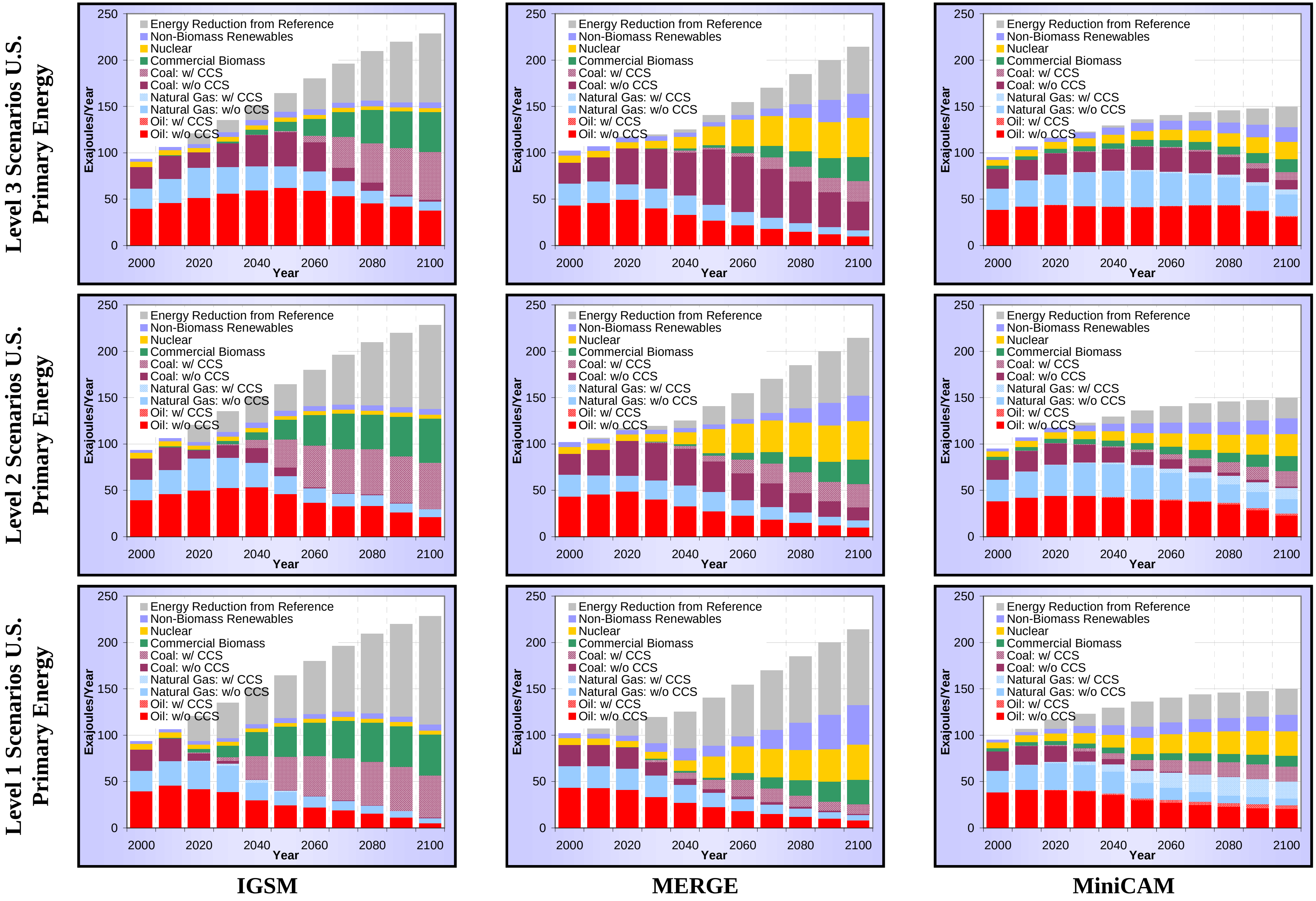
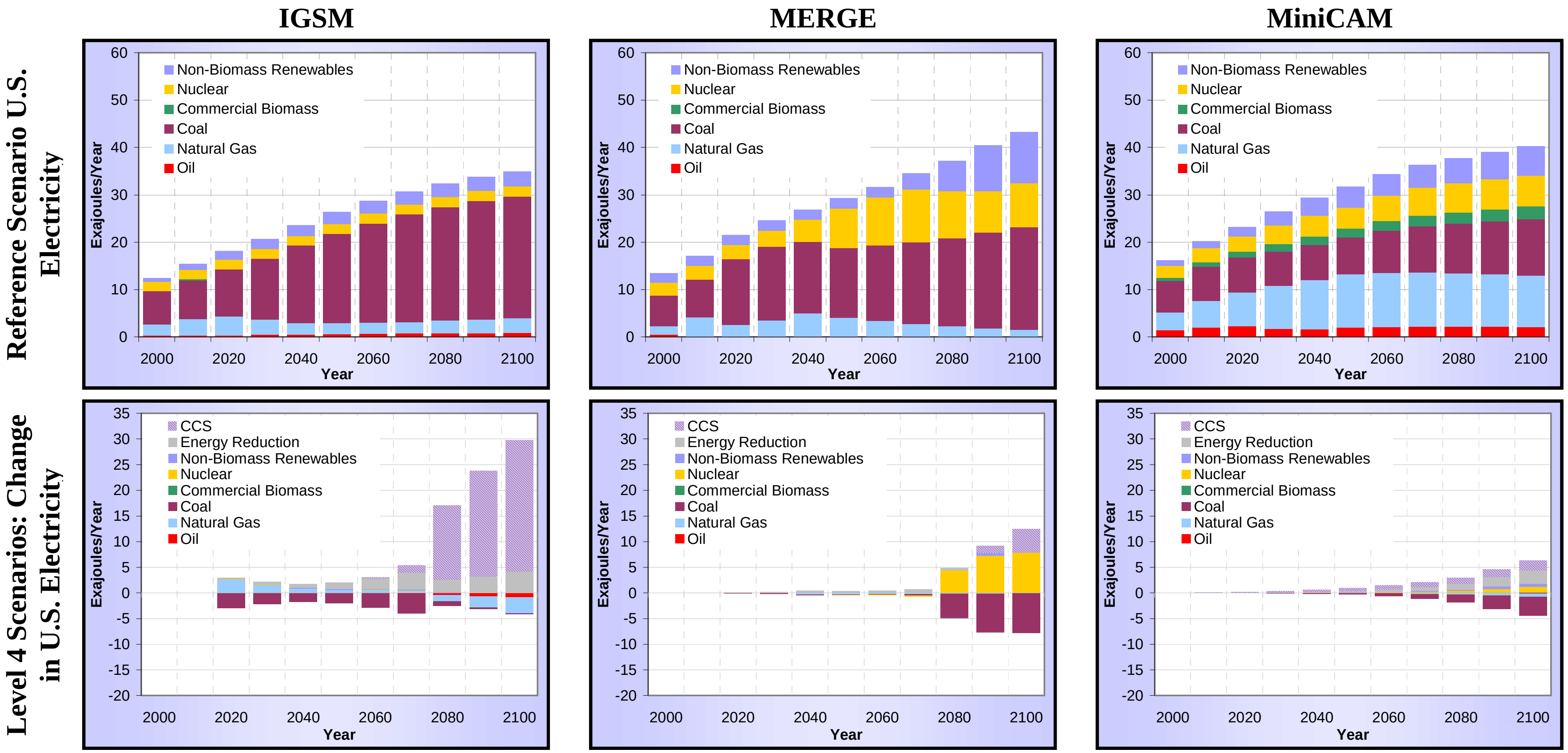
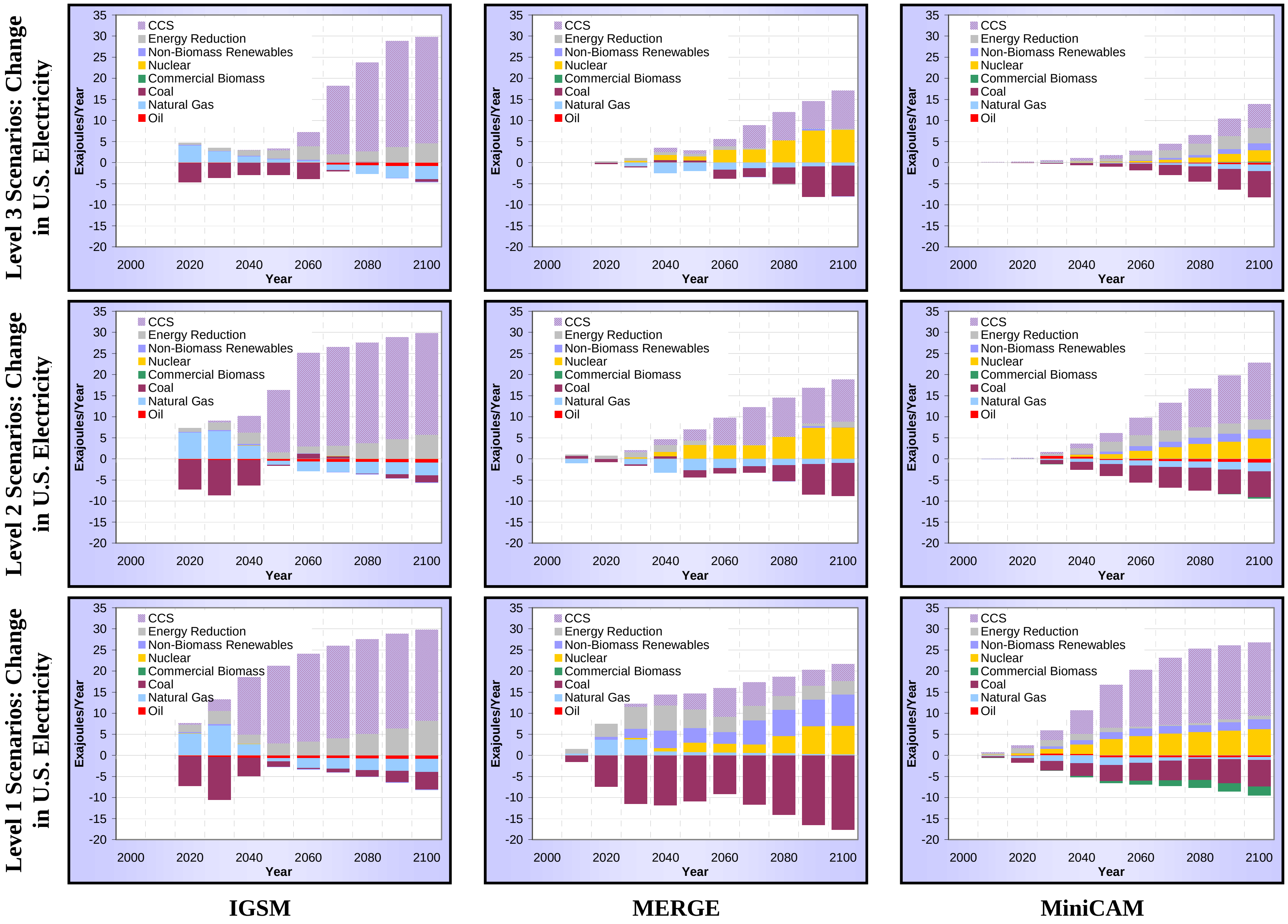

Level 3 Scenarios U.S. Primary Energy
Level 2 Scenarios U.S. Primary Energy
Level 1 Scenarios U.S. Primary Energy
IGSM
MERGE
MiniCAM
Exajoules/Year
Year
0
50
100
150
200
250
2000
2020
2040
2060
2080
2100
Energy Reduction from Reference
Non-Biomass Renewables
Nuclear
Commercial Biomass
Coal: w/ CCS
Coal: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

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




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

Figure 4.16. Global and U.S. Commercial Biomass Production across Scenarios. Scenarios of the potential for commercial biomass production for the world and the U.S. are similar in magnitude among the models although the response of biomass production under the stabilization targets differs. In MERGE, there is a maximum biomass potential that is achieved in the reference case, and so no more is forthcoming under the stabilization scenarios. IGSM biomass production increases relative to reference for Levels 2, 3, and 4, but little additional increase occurs for Level 1 because of competition for agricultural land. MiniCAM biomass competes with agricultural land, but that competition does not place as strong a limit on production as for IGSM.

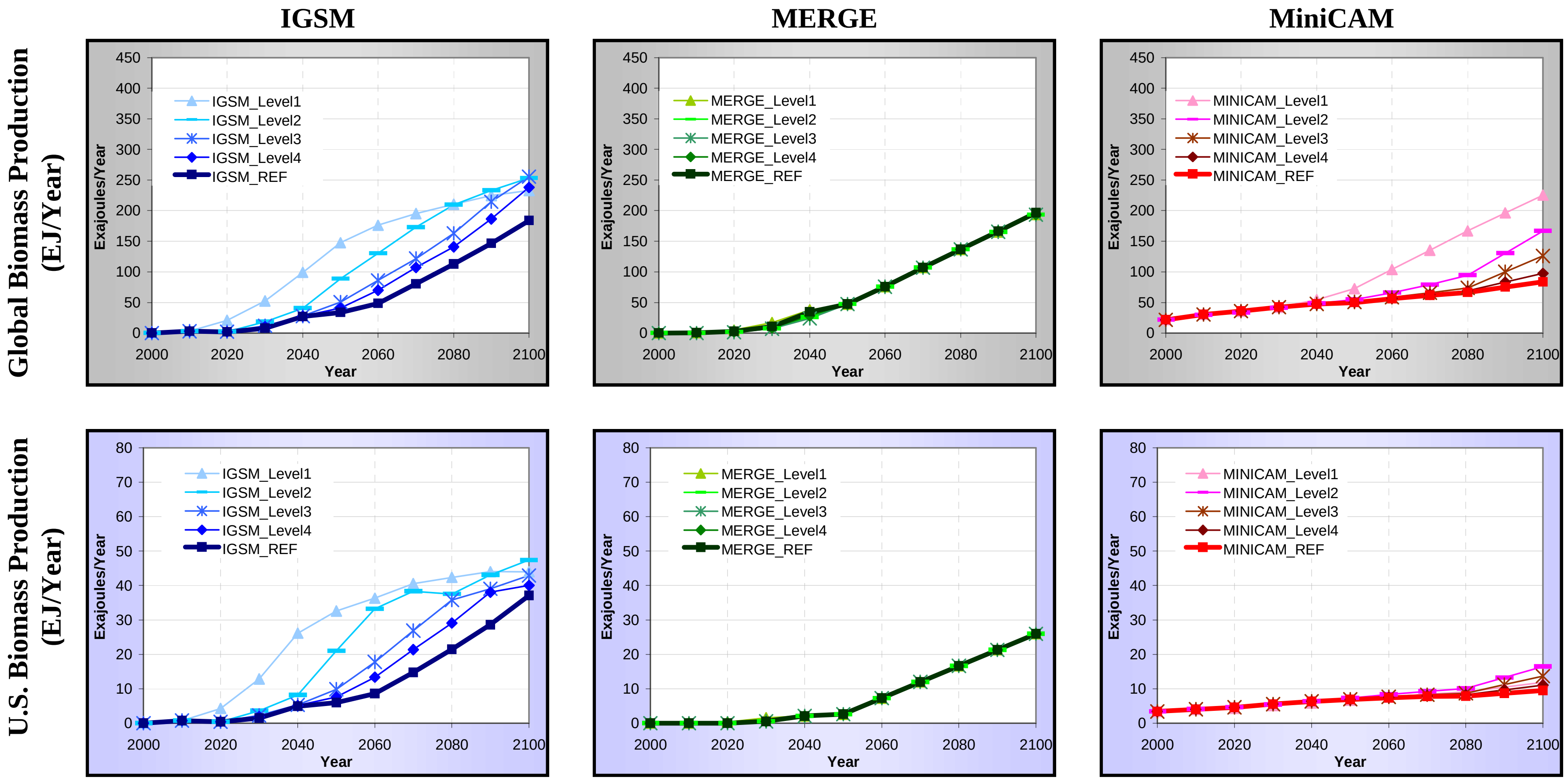
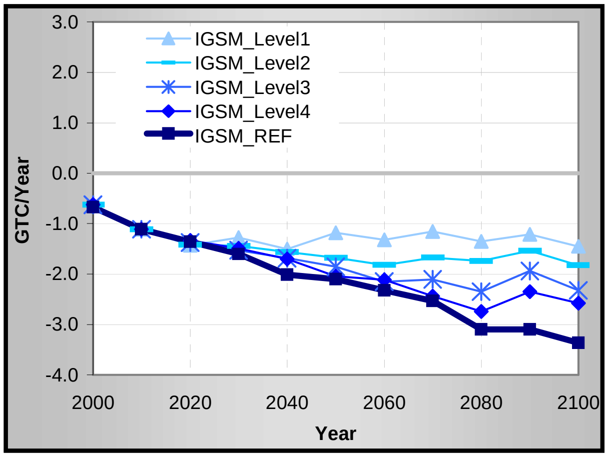


Figure 4.17. Net Terrestrial Carbon Flux to the Atmosphere across Scenarios (GtC/y). Simulated net terrestrial carbon flux to the atmosphere, under reference and stabilization levels, as simulated by the three models reflect differences in the model structures for processes that remain highly uncertain.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

IGSM Scenarios



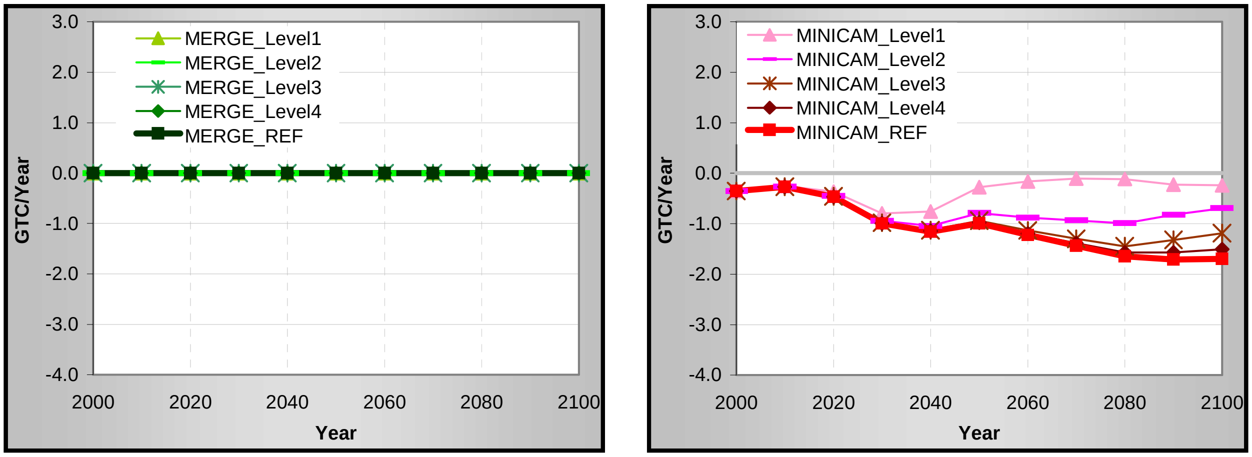

MERGE Scenarios **MiniCAM Scenarios**

Figure 4.18. Carbon Prices across Stabilization Scenarios ($/tonne C). IGSM projects relatively higher carbon prices for all levels of stabilization than the other models, exceeding $6000/tC by 2100 in the Level 1. The MERGE price is capped at in the Level 1 scenario at $1000 after 2070. MiniCAM prices reach about $800/tC by 2100 under the Level 1 targets. Given how the path of emissions reductions were designed, near-term prices are driven by the price required at stabilization, dependent as it is on highly uncertain characterizations of future technology options.

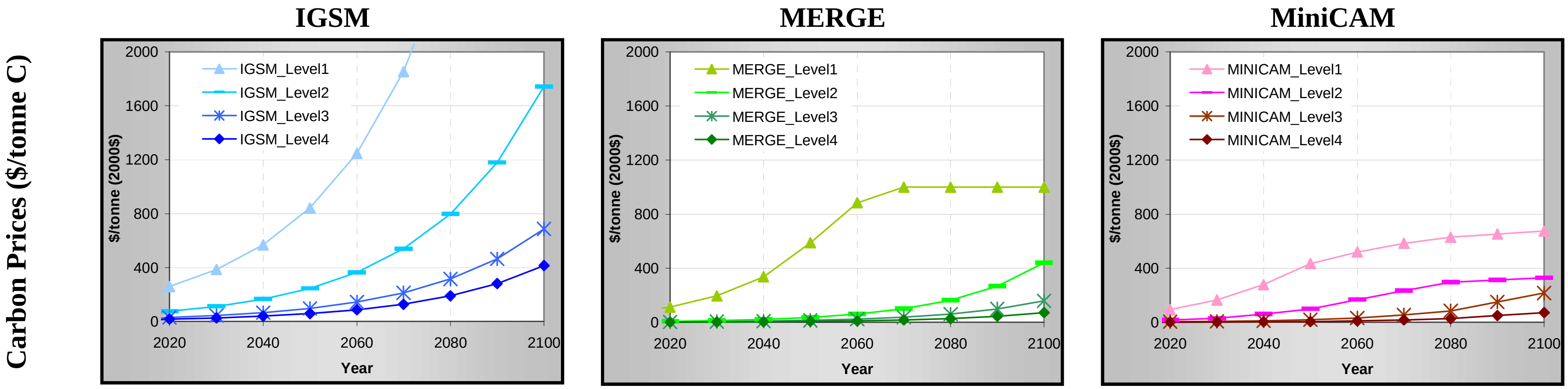
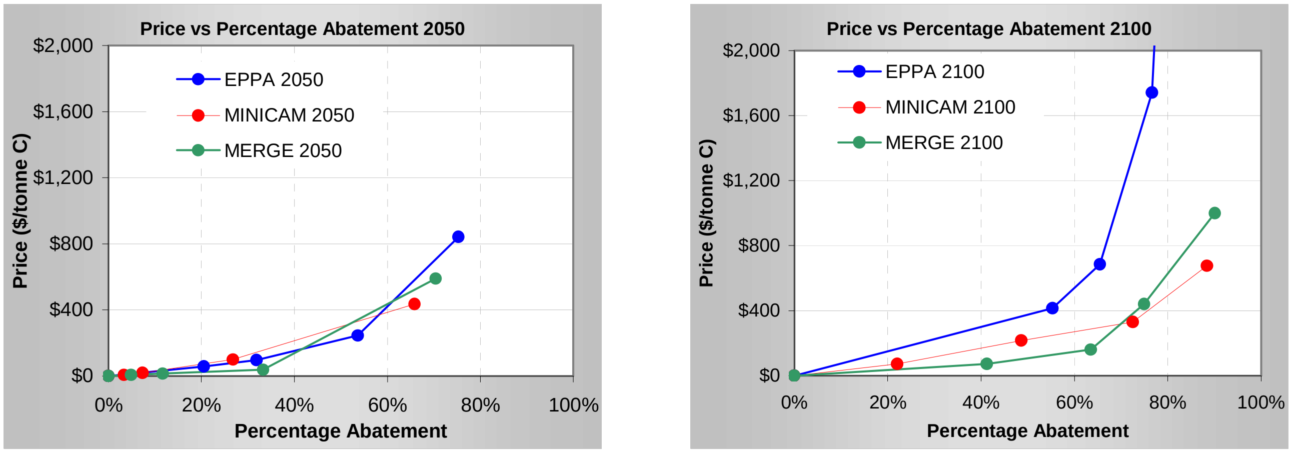


Figure 4.19. Ratio of Relationship Between Carbon Price and Percentage Abatement in 2050 and 2100. The relationship between carbon price and percentage abatement in 2050 and 2100 is similar among the models in 2050 but diverges in 2100. IGSM approaches an infeasibility for emissions reductions greater than 80%, whereas MERGE and MiniCam can achieve 90 and 95% reduction from reference at prices of $1000 or below.



2050

2100

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

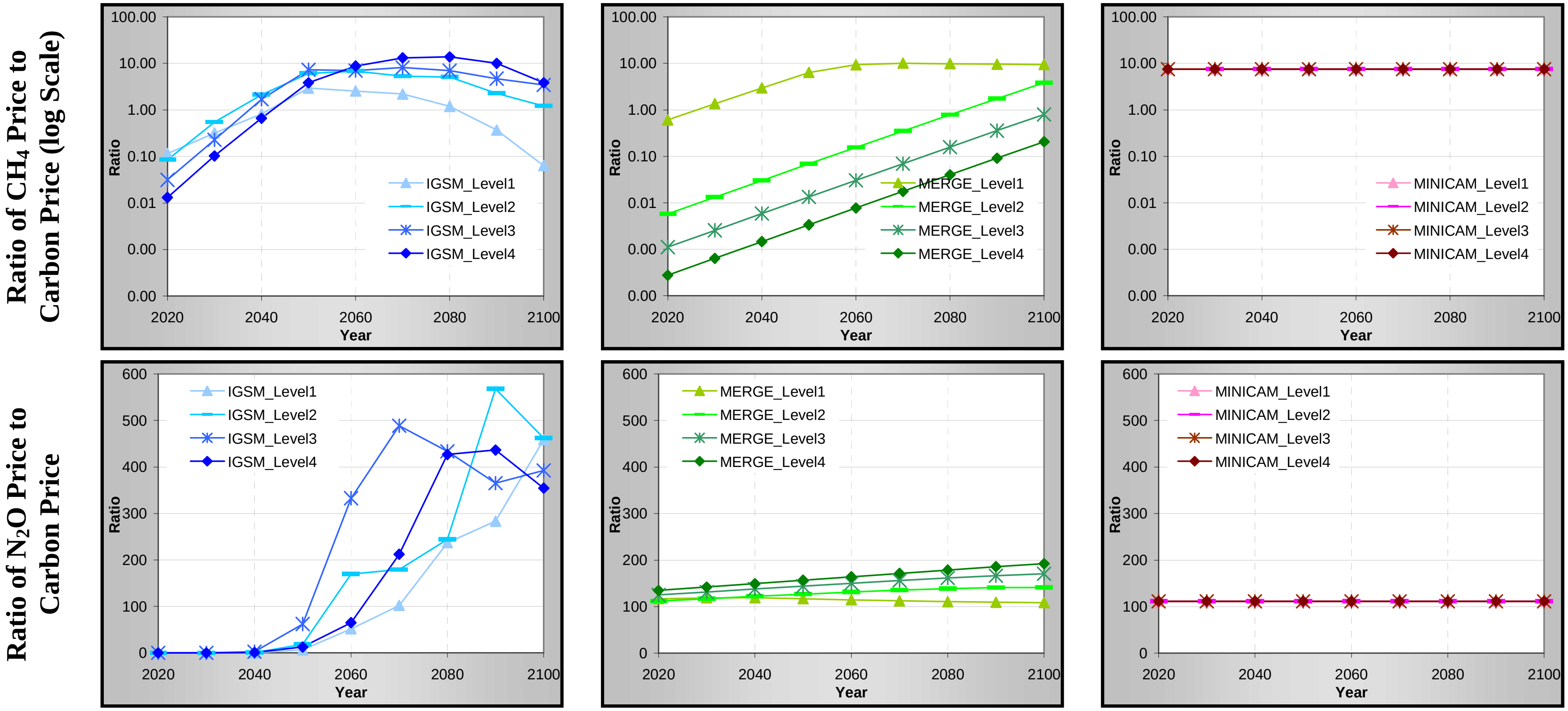
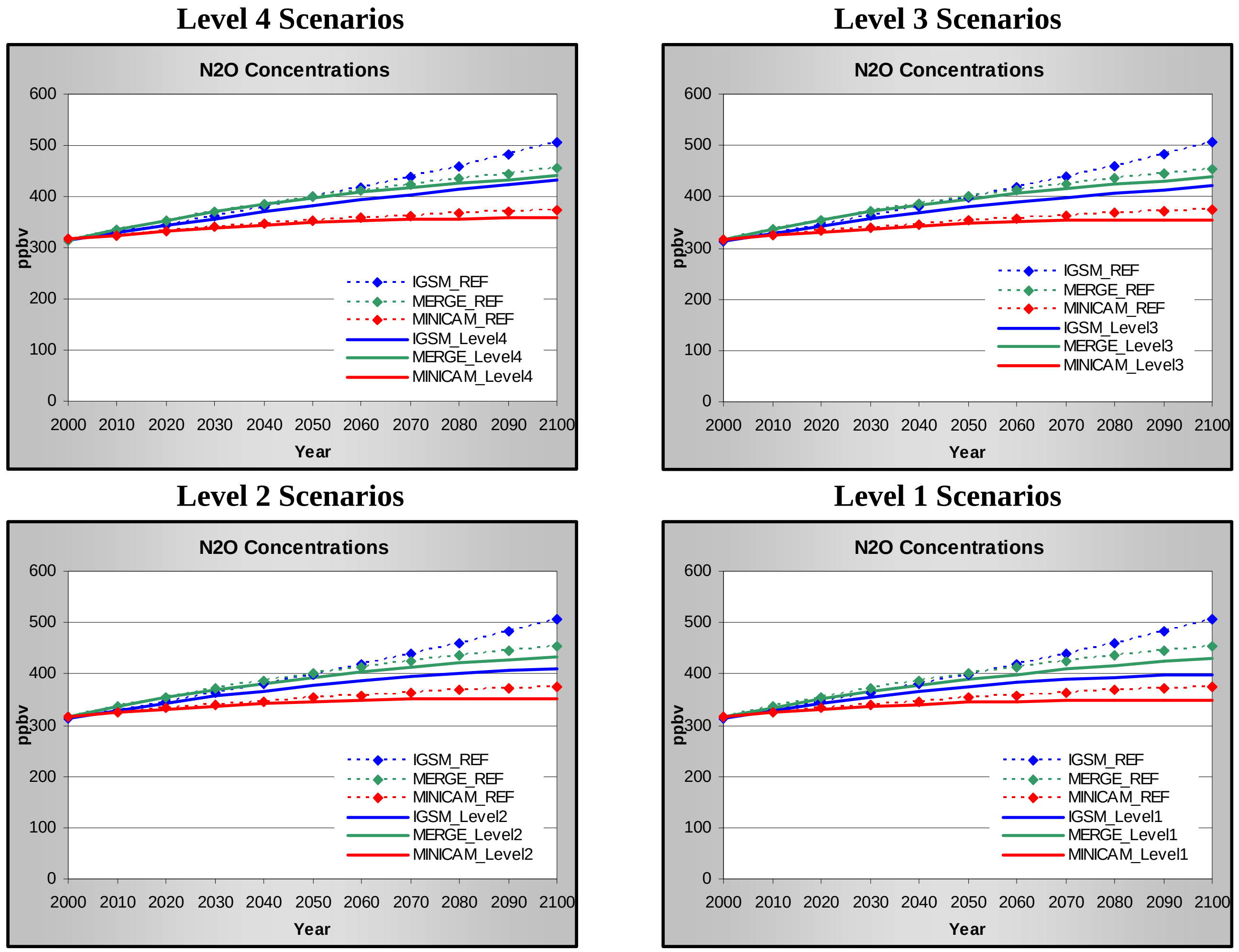


Figure 4.21. N_2O Concentrations across Scenarios (ppbv). Atmospheric concentrations of N_2O range from about 375 ppbv to 505 ppbv in 2100 across the models and with concentrations continuing to rise in the reference. Each modeling team employed a different approach to emissions limitations on N_2O, leading to differences in concentrations between the reference and stabilization cases. The largest differences between reference and stabilization cases occur in the IGSM results.



Level 4 Scenarios

Level 3 Scenarios

Level 2 Scenarios

Level 1 Scenarios

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

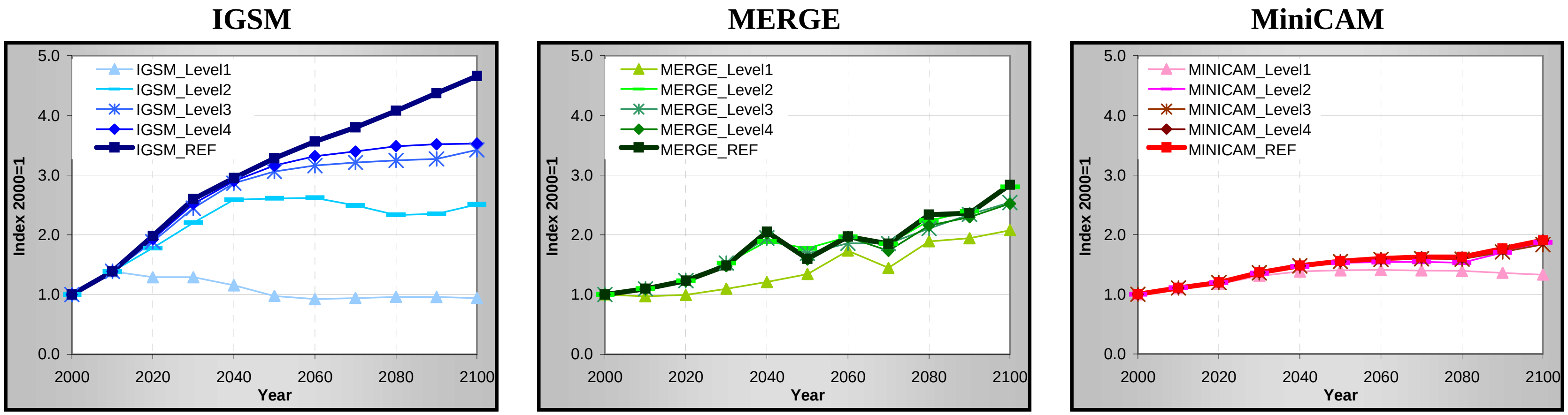


Figure 4.23. United States Mine-mouth Coal Price, Reference and Stabilization Scenarios. United States mine-mouth coal price varies in the reference across the models. IGSM and MiniCAM project coal prices to be depressed by stabilization scenarios, whereas MERGE projects no impact reflecting characterization of coal supply as an inexhaustible single grade such that there is no rent associated with the resource. Prices thus reflect the cost capital, labor, and other inputs that are little affected by the stabilization policy.

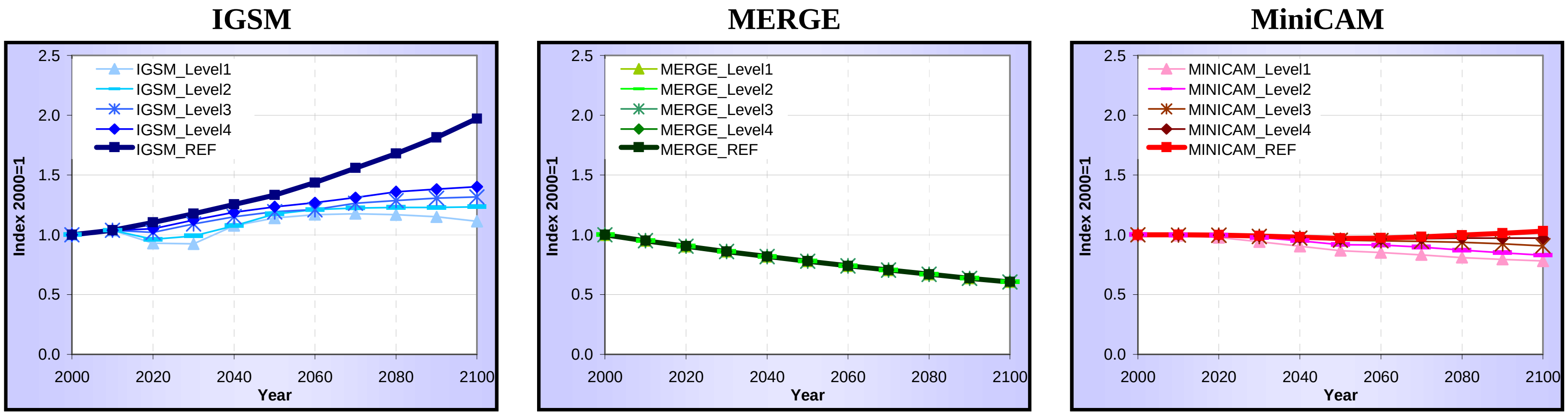


Figure 4.24. United States Natural Gas Producers' Price, Reference and Stabilization Scenarios. United States natural gas producers' prices vary in the reference across the models. MiniCAM and MERGE show little or no effect on the gas price for stabilization scenarios. IGSM projects that stabilization at Levels 2, 3, and 4 increase the price of gas because of substitution toward gas and away from coal and oil. Gas prices fall relative to reference for Level 1 stabilization because gas demand is depressed because of the tight carbon constraint.

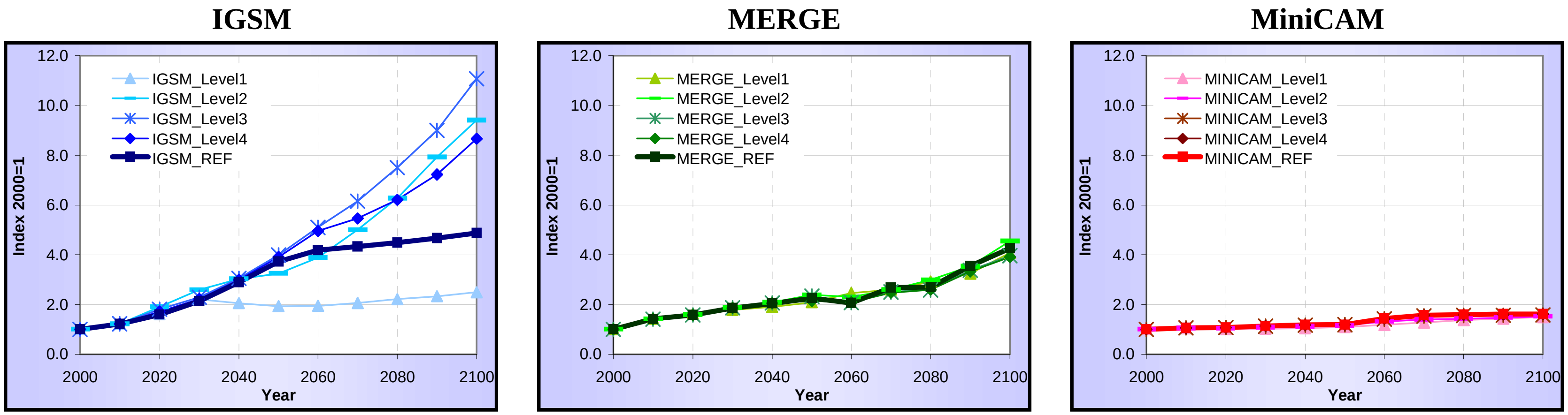
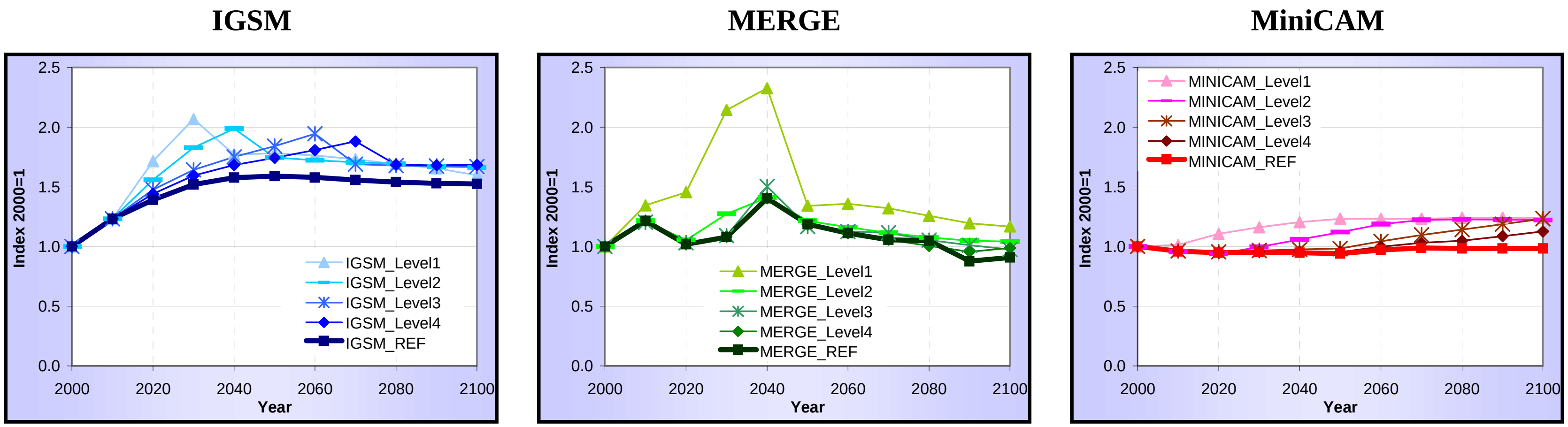


Figure 4.25. United States Electricity Price, Reference and Stabilization Scenarios. United States electricity prices as projected in the reference range from little change (MiniCam) or even a slight fall by 2100 (MERGE) to about a 50% increase from present levels (IGSM). Fuel prices affect electricity prices, but improving efficiency of electricity is an offset tending to reduce electricity prices. IGSM and MERGE show sharp increases in the near-term under those stabilization scenarios that require significant near-term action, reflecting adjustment costs associated with fixed capital.

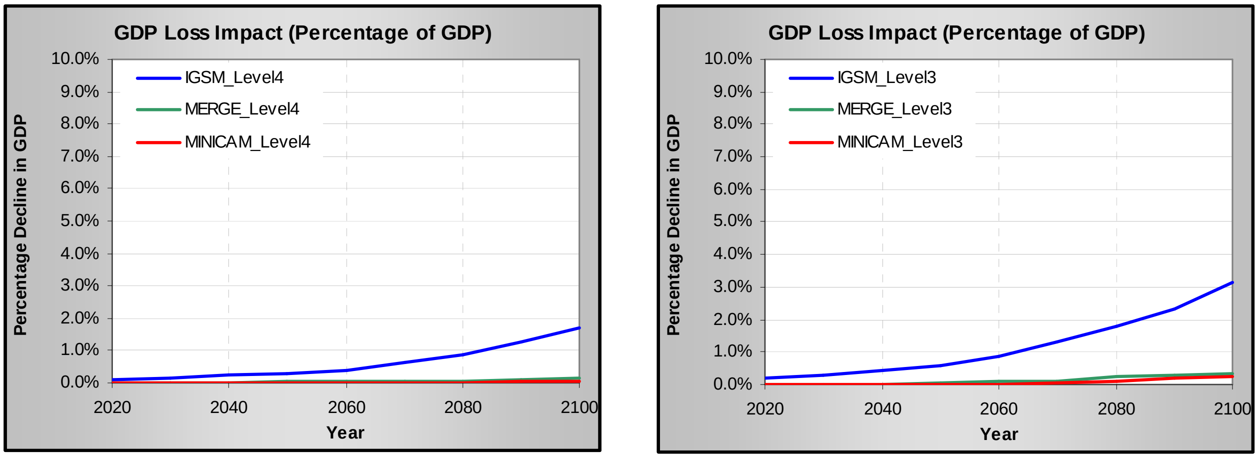


IGSM

MERGE

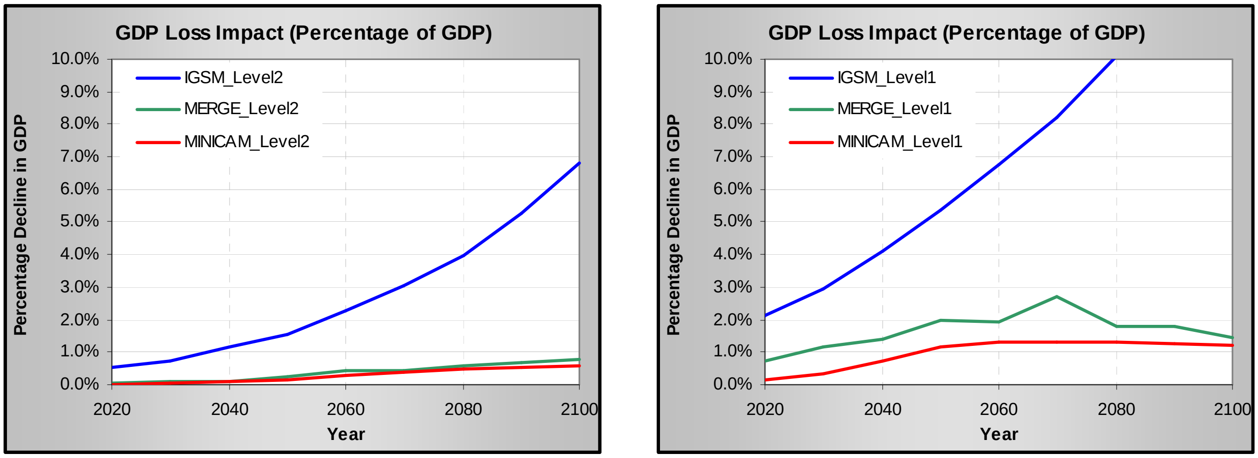
MiniCAM

Figure 4.26. Global GDP Impacts of Stabilization across Stabilization Levels (percentage)



Level 4 Scenarios

Level 3 Scenarios



Level 2 Scenarios

Level 1 Scenarios

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