3. REFERENCE SCENARIOS

Reference scenarios for all three models show significant growth in energy use and continued reliance on fossil fuels, leading to an increase in CO_2 emissions 3½ times the present level by 2100. When combined with increases in the non-CO_2 greenhouse gases and net uptake by the ocean and terrestrial biosphere, the result is radiative forcing of 4 to 6 W/m^2 above the current level, which is 2.2 W/m^2 above pre-industrial.

3.1. Introduction

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

Other than to standardize reporting conventions and greenhouse gas (GHG) emissions mitigation policies (or lack thereof), the three modeling teams developed their reference scenarios independently and as each judged most appropriate. Based on this independence, there are a variety of reasons why important aspects of the reference scenarios should be expected to differ among the modeling teams.

As noted in Chapter 2, the three models were developed on the basis of somewhat different original design objectives. They differ in (a) their inclusiveness, (b) their specifications of key aspects of economic structure, and (c) their choice of values for key parameters. These independent choices lead to different characterizations of the underlying economic and physical systems that these models represent.

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

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

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

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

A reference scenario is uncertain, a fact that is painfully obvious to those who produce scenarios and hardly news to anyone who has thought seriously about the wide range of possible futures. Thus, it should be further emphasized that the three reference scenarios were not designed in an attempt to span the full range of potential future conditions or to shed light on the probability of the occurrence of future events. That is a much more ambitious undertaking than the one reported here. Some aspects of the uncertainty of potential future reference scenarios of fossil fuel and industrial CO_2 emissions are discussed later in this chapter.

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

3.2. Socio-Economic Assumptions

> *GHGs are a product of modern life. Population increase and economic activity are major determinants of the scale of human activities and ultimately of anthropogenic GHG emissions. The reference scenarios are similar in that both population and economic activity are assumed to continue to grow substantially to the end of the century. Global population is projected to rise from 6 billion people in the year 2000 to between 8.6 and 9.9 billion people in 2100 in the three reference scenarios. Developed nations are assumed to continue to expand their economies at historical rates, and some, but not all, developing nations are assumed to make significant progress toward improved standards of living.*

Reference scenarios are grounded in a larger demographic and economic story. Each uses population as the basis for developing estimates of the scale and composition of economic activity for each region. For population assumptions, the IGSM modeling team adopted one U.N. projection for the period 2000-2050 (United Nations 2001) and then extended this projection to 2100 using information from a longer-term U.N. study (United Nations 2000). The MiniCAM assumptions are based on a median scenario by the United Nations (United Nations 2005) and a Millennium Assessment Techno-Garden Scenario from the International Institute for Applied Systems Analysis (O'Neal 2005). Near-term population assumptions for MERGE come from the Energy Information Administration's International Energy Outlook. Over the remainder of the century, regional populations converge toward a set of long-term equilibrium levels with some countries reaching these levels earlier than others.

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

Regional populations are given in Table 3.1. Population increases substantially across the reference scenarios by the end of the century, but in none of the scenarios does population exponential growth continue unabated. Most of the population growth occurs in the next four to five decades in all three scenarios. By 2050, more than 75% of all the change between the year 2000 and 2100 has occurred. A demographic transition from high birth and death rates to low death rates and eventually to low birth rates is a feature of most demographic projections, reflecting assumptions that birth rates will decline to replacement levels or below. For some countries, birth rates are already below replacement levels, and just maintaining these levels will result in population decline for these countries. An uncertainty in demographic scenarios is whether a transition to less than replacement levels is a more or less permanent feature of those countries where it has occurred and whether such a pattern will be repeated in other countries.

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

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

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

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

The alternative scenarios of population and productivity growth lead to differences among the three reference scenarios in U.S. GDP growth, as shown in Figure 3.2. There is relatively little difference among the three trajectories through the year 2020. After 2020, however, a large divergence develops, with the lowest scenario (MERGE) having roughly half of that of the highest scenario (IGSM) by the end of the century. The IGSM labor productivity growth assumptions for the U.S. were the highest of the three and its

U.S. population was also relatively high, as seen in Figure 3.1**.** The relatively lower labor productivity growth assumptions used in the MERGE and MiniCAM reference scenarios lead to lower levels of GDP. The lower population growth assumptions employed in the MERGE reference scenario give it the lowest GDP level in 2100.

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

Table 3.2 shows GDP across regions in the three reference scenarios. The absolute levels of GDP increase are the result of relatively small differences in rates of per capita growth. Although difficulties arise in comparisons of growth across countries (see Box 3.1), the growth rates underlying these scenarios are usefully compared with historical experience. Table 3.3 presents long-term growth rates from reconstructed data showing that consistent rapid growth is a phenomenon of industrialization, starting in the 1800s in North America and Europe and gradually spreading to other areas of the world. By the end of the period 1950 to 1973, it appeared that the phenomenon of rapid growth had taken hold in all major regions of the world. Since 1973, it has been less clear to what degree that conclusion holds. Growth slowed in the 1970s in most regions, the important exceptions being China, India, and several South and East Asian economies. In Africa, Latin America, Eastern Europe, and the former Soviet Union, growth slowed in this period to rates more associated with pre-industrial times.

Table 3.2. Reference GDP for Key Regions

Table 3.3. Historical Annual Average Per Capita GDP Growth

--- BOX 3.1: Exchange Rates and Comparisons of Real Income among Countries ---

Models used in this type of exercise typically represent the economy in real terms, following the common assumption that inflation and exchange-rate changes are purely monetary phenomena that do not have real effects. The models include none of the phenomena that govern exchange rate determination and so cannot project changes. However, modeling international trade in goods requires either an exchange rate or a common currency. Rather than separately model economies in native currencies and use a fixed exchange to convert currencies for trade, the equivalent and simpler approach is to convert all regions to a common currency at average market exchange rates (MER) for the base year of the model.

At the same time, it is widely recognized that using market exchange rates to compare countries can have peculiar implications. In historical data, country A might start with a larger GDP than country B when converted to a common currency using that year's exchange rates, and grow faster in real terms than B, yet could later have a lower GDP than B using exchange rates in that year. This paradoxical result can occur if A's currency depreciated relative to B's. Depreciation and appreciation of currencies by 20 to 50% over just a few years is common, and so the example is not extreme. Interest in making cross-country comparisons that are not subject to such apparent peculiarities has led to development of indices of international purchasing power. A widely used index is purchasing power parity (PPP), whose development was sponsored by the World Bank.

PPP-type indices have the advantage of being more stable over time and are thought to better reflect relative living standards among countries than MER. Thus, research that draws comparisons among countries to understand development and growth has found it preferable to use PPP-type indices rather than MER. Although the empirical foundation for the indices has been improving, the theory for them remains incomplete, and thus there is a limited basis on which changes in PPP can be projected into the future. Some hypothesize that differences close as real income gaps narrow, but the evidence for this outcome is weak, in part due to data limitations.

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

With this historical experience as background, the differences among the models in per capita income growth can be explained. With respect to the developed countries, the IGSM growth rate for the U.S. is about the average for North America for the period 1950-2000. The MiniCAM reference scenario assumes a constant labor productivity growth rate for the U.S., which is consistent with post World War II historical patterns, and combines that with demographic trends that include an aging population pattern. When the constant labor productivity growth assumption is combined with demographic maturation, the result is a lower future rate of growth of GDP compared to history. U.S. GDP growth rates in the MERGE reference scenario are similar to those of the MiniCAM reference scenario.

GDP growth patterns for Western Europe and Japan are similar to one another within reference scenarios, but vary across models. The IGSM reference scenario follows the post World War II trend in per capita GDP growth, but MiniCAM and MERGE anticipate a break from the trend, that is, with lower growth in GDP as a consequence of changes in underlying demographic trends. The MiniCAM demographic scenario exhibits rapidly aging populations and a consequent decline in average labor force participation, which, combined with a long-term trend in labor productivity growth (similar to that of the U.S.), yields lower growth in GDP compared to the IGSM reference scenario. The MERGE GDP growth pattern is similar to that of MiniCAM.

The scenarios for developing regions show greater differences from historical experience. Notably, all three modeling groups show consistent growth in many non-OECD regions at rates experienced by “industrializing” countries. However, growth rates are not homogeneous. There is consistently more optimism in all three reference scenarios regarding the prospects for China and India than for regions such as Latin America and Africa. The IGSM results for non-OECD regions show somewhat less growth compared to the MiniCAM and MERGE scenarios. These are just one set of judgments about growth prospects from each group and are not intended to be expressions of what the groups view as desirable growth rates. Clearly, more rapid growth in developing countries, if evenly distributed among income groups, could be the basis for improving the outlook for people in these areas.

3.3. Energy Use, Prices, and Technology

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

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

In all three cases, the production from non-fossil fuel resources grows substantially in comparison to today’s levels, reaching levels roughly 65 to 150% of the total global level of energy consumption in 2000. The scenarios differ in the mix of non-fossil resources that emerges. In all reference scenarios, however, the growth in non-fossil fuel use does not forestall substantial growth in fossil fuel consumption.

3.3.1. The Evolving Structure of Energy Use

Energy production is closely associated with emissions of GHGs, particularly CO_2, because of the dominant role of fossil fuels. Figure 3.3 shows global primary energy use over the century and its composition by fuel type in the three reference scenarios. Not surprisingly, given the assumptions about economic growth, all of the reference scenarios show substantial growth in primary energy use: from approximately 400 EJ/y in the year 2000 to between 1300 EJ/y and 1550 EJ/y by the end of this century. The result of a combination of the population growth and the developments in energy structure is a pattern of rising energy consumption per capita, as shown in Figure 3.4. All three models project a growing per capita use, with the MiniCAM showing the greatest increase over time in the global total, and the IGSM model showing the least change. For the U.S., because of differences in population scenarios and growth rates, the relative ranking of these growth rates is changed, with MERGE showing the greatest increase and MiniCAM the least.

Figure 3.3. Global Primary Energy Use by Fuel across Reference Scenarios

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

The growth in total and per capita primary energy consumption arises despite substantial improvements in energy technology assumed in all three scenarios. Figure 3.5 displays the ratio of U.S. energy to GDP (energy intensity) computed for each of the three reference scenarios. The ratio declines throughout the century in all three reference scenarios. These patterns are a continuation of the experience of energy-intensive change in recent decades in the U.S., and a similar pattern applies across other regions in the three models. The important point here is that these reference scenarios already incorporate substantial technological improvements. In the year 2100, each dollar of real GDP can be produced with only half the energy used in the year 2000 in the MERGE reference scenario, and only 30% of the energy in the IGSM and MiniCAM reference scenarios.

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

As shown later in this chapter, this decline in U.S. fossil fuel and industrial CO_2 emissions intensity is insufficient to keep U.S. total CO_2 emissions from rising. Without these assumed improvements in energy technology, however, energy demands and U.S. fossil fuel and industrial CO_2 emissions would be substantially higher in the reference scenarios. These same forces are at work in other regions as well. Improvements in energy-related technologies and shifts in the sectoral composition of national economies play an important role in limiting the growth of fossil fuel use and CO_2 emissions in all three reference scenarios.

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

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

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

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

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

Figure 3.3 also reflects assumptions about the availability of low-cost alternatives to conventional fossil fuels. In all three scenarios, non-fossil supplies increase both their absolute and relative roles in providing energy to the global economy, with their share growing to between 20 and 40% of total supply by 2100. The growth is substantial. In IGSM, the scenario with the lowest consumption of non-fossil resources, the magnitude of total consumption of these resources in 2100 is 65% the size of the total global primary energy production in 2000, which is a 350% increase in the level of production of non-fossil energy. In MERGE, the scenario with the highest contribution from non-fossil resources, total consumption from these resources in 2100 is 150% of total primary energy consumption in 2000. Despite this growth, the continued availability of relatively low-cost fossil energy supplies, combined with continued improvements in the efficiency with which they are used, results in fossil energy forms remaining competitive throughout the century.

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

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

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

The three scenarios for the U.S. are similar in character to the global ones, as also shown in Figure 3.3. The transition from inexpensive and abundant conventional oil to alternative sources of liquid fuels and electricity affects energy markets and patterns in the U.S. However, energy demands grow somewhat more slowly in the U.S. than in the world in general. As with the world total, the U.S. energy system remains dominated by fossil fuels in all three reference scenarios. Non-fossil energy forms expand their markets both absolutely and as a fraction of total primary energy in the MERGE and MiniCAM reference scenarios, but do not overtake fossil energy as the major provider of primary energy. In the IGSM reference scenario, non-fossil energy use remains roughly constant and, thus, declines as a fraction of total primary energy consumption. This result follows from a combination of assumptions about the social acceptability of expanded nuclear energy use and assessments about the relative cost and performance of competitors to fossil fuels.

3.3.2. Trends in Fuel Prices

From the late nineteenth century until the 1970s, world oil prices (in year 2004 dollars) ranged between $15 and $20 per barrel. Figure 3.6 plots the experience from 1947 forward and clearly shows the big price increases in the 1970s and early 1980s as a result of disruptions in the Middle East. In inflation-adjusted terms, prices declined to the earlier levels of $15 to $20 in the latter half of the 1980s and 1990s. The period 2000 to 2005 has again seen rising prices of oil and other fossil energy sources. Adding the past few years of data to the series suggests the possibility of a long-term trend toward rising prices. Depletion alone would suggest rising prices because of a combination of rents associated with a limited resource and the exhaustion of easily recoverable grades of oil. Global demand continues to grow, putting increasing pressure on supply. Opposing these forces toward higher prices has been improving technology that reduces the cost of recovering known deposits and facilitates discovery and that makes recovery of previously unrecoverable deposits economical.

Figure 3.6. Long-Term Historical Crude Oil Prices

The models employ time steps of 5 to 15 years (see Chapter 2) so that numbers for a given year should be interpreted as a multi-year average and, thus, are not set up to project short-term variability in prices. The long-term trends they project are thus best seen as multi-year averages.

The three scenarios paint similar but by no means identical pictures of future energy prices. Figure 3.7 shows mine-mouth coal prices, electricity producer prices, natural gas producer prices for the U.S., and the world oil price. The scenarios by each model for all four energy markets – oil, natural gas, coal and electricity – are shaped by the supply of and demand for these commodities. They also are interconnected because users of fuels can substitute one fuel for another, and thus higher prices in one fuel market will tend to increase demand for and the price of other fuels. Oil markets are driven by the rising cost of conventional oil and a burgeoning demand for liquid fuels to provide transportation and other energy services. This demand can be met in a variety of ways in the three models. In addition to limited conventional oil resource grades, there also are grades of oil, currently considered to be “unconventional,” that are available in quantities that put no meaningful limit on oil supply although they are more costly than conventional oil supplies. Other supply options include liquids derived from natural gas, coal, and/or biological resources. These options are also more expensive than conventional oil. The oil price scenarios in the three models are thus the result of the interplay between increasing the demands for liquid fuels, the available technology, and the availability of liquids derived from these other sources.

Figure 3.7. Indices of Energy Prices across Reference Scenarios

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

Coal prices do not rise as fast as oil and natural gas prices in any of the three reference scenarios. The reason is the abundance of the coal resource base. The different patterns of coal price movement with time in the three scenarios reflect differences in assumptions about the rate of resource depletion and technological improvement in extraction. In the MERGE reference scenario the race is won by technology and in the IGSM reference scenario by depletion of the highest quality resource grades; in the MiniCAM scenario, however, the race is a draw.

The stability of electricity prices compared with oil and natural gas prices is a reflection of the variety of technologies and of fuels available to produce electricity and their improvement over time, and the fact that fuel is just one component of the cost of electricity. The fraction of electricity produced by coal is largest, and the fraction from oil and natural gas is approximately one-quarter of the total. Nuclear power and renewable power provide significant shares of total power generation.

3.3.3. Electricity Production and Technology

The production of electricity results in more fossil CO_2 emissions than any other activity in the economy. Figure 3.8 shows electricity production – in units of electrical output, not units of energy input – by generation type in the U.S. and the world. (For the world, total production necessarily equals consumption. U.S. consumption exceeds production, however, because it is a net importer from Canada.) The three scenarios exhibit a steadily increasing production of electricity in both the U.S. and the world although the scale and generation mix differ among them. All depict a growing role for coal. Interestingly, the three show a similar use of coal in the global economy despite almost a factor-of-two difference in coal use in the U.S. None has a major role for oil.

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

There are, however, major differences across the scenarios in the use of other energy forms. The IGSM scenario is dominated by coal, which accounts for more than half of all power production by the end of the twenty-first century, a result consistent with its limited growth in nuclear power. In contrast, the MERGE scenario assumes that nuclear energy penetrates the market based on economic performance, and non-biomass renewable energy gains market share. Limits in natural gas lead to a peak and decline in gas use in the first half of the century. The MiniCAM scenario shows yet another possible development in power generation. Although coal supplies the largest share of power, natural gas is relatively abundant and provides a significant portion, as do nuclear and non-biomass renewable energy forms.

3.3.4. Non-Electric Energy Use

Figure 3.9 shows the reference scenario non-electric energy use, and Figure 3.10 shows the energy loss from conversion from fuel to electricity. Note that Figure 3.8 shows electricity production resulting from a specific fuel, not the energy content of the fuel used to produce the energy. The difference between the two measures is conversion losses. In Figure 3.10, the energy loss in the conversion from fuel to electricity is shown to be 28.1 Quads in the year 2000 (1 Quad is equal to 1.055 EJ) for the U.S., while the energy content of the electricity is 12.3 Quads. Energy not going into power generation goes directly to final uses.

Figure 3.9. Global and U.S. Primary Energy Consumed In Non-Electric Applications across Reference Scenarios

Figure 3.10. U.S. Energy Flow Diagram and Non-Electrical Energy Use for the Year 2000

In the future, other transformation sectors may become important and fundamentally change energy-flow patterns. As already discussed, the potential exists for coal and commercial biomass to be converted to liquids and gases—a technology thus far implemented only at a small scale. Furthermore, fuels and electricity may be transformed into hydrogen, creating fundamentally new branches of the system. Like electricity, these new branches will have conversion losses and those losses can be important. As a result, it is important to realize that future scenarios of non-electric use, shown in Figure 3.9, can involve significant conversion losses from non-electric fuel transformations. Currently almost all conversion losses are in electricity so that non-electricity fuel use is almost completely final energy use. This is particularly important to keep in mind when examining non-electric energy use in the MERGE reference scenario, in which coal and biomass goes into liquefaction and gasification plants. To a lesser extent, these conversions are also present in the MiniCAM and IGSM scenarios. Also, in the MiniCAM and MERGE reference scenarios, some nuclear energy appears in non-electricity uses to produce hydrogen. In the IGSM and MiniCAM scenarios, oil use is the largest single non-electric energy use, reflecting a continuing growth in demand for liquids by the transportation sectors. In the MERGE reference scenario, increasingly expensive conventional oil is supplanted by coal-based liquids. This phenomenon also has implications for energy intensity in that improvements in end-use energy intensity can be offset in part by losses in converting primary fuels to end-use liquids or gases.

3.4. Land Use and Land-Use Change

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

All of the modeling groups consider the production of biofuels for energy. Both IGSM and MiniCAM take account of the competition for scarce land resources. MERGE takes the availability of biofuels as an exogenous input based on extra-model analysis. Production of these crops is displayed in Figure 3.11. The IGSM and MiniCAM figures are based on somewhat different definitions, which account for the difference in 2000. IGSM reports only the production of modern energy crops grown explicitly for their energy content and sold in a formal market. MiniCAM accounts for traditional biofuels production, waste and residue-derived biofuels, and energy crops grown explicitly for their energy content. The waste-derived fuels do not always pass through formal markets, as occurs in the pulp and paper industry when wood waste is used for its energy content.

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

Apparent differences among the models thus need to be considered in light of this differential accounting. The MiniCAM results will tend to be significantly higher, especially in early years, because it is accounting traditional biofuels explicitly whereas the other models are not. For example, MiniCAM deploys no commercial biomass production in the U.S. in the form of energy crops grown explicitly for their energy content in the reference scenario. The IGSM reference scenario exhibits a growing production of biofuels beginning after the year 2020 to levels similar to those in the MERGE case. The IGSM deployment is driven primarily by a real-world oil price that in the year 2100 is 4.5 times the price in the year 2000. In contrast, MiniCAM, with its lower long-term world oil price, provides insufficient incentive to grow bio-crops in the reference scenario. However, MiniCAM does utilize an increasing share of the potentially recoverable bio-waste as a source of energy.

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

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

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

3.5. Emissions, Concentrations, and Radiative Forcing

The growth in the global economy that is assumed in the reference scenarios and the changes in the composition of the global energy system lead to growing emissions of GHGs over the century. Fossil fuel and cement emissions more than triple over the study period in the reference scenarios. With growing emissions, GHG concentrations are projected to rise substantially over the twenty-first century, with CO_2 *rising to more than twice the year 2000 level (2-1/2 to 3 times the pre-industrial concentration). Increases in the concentrations of the non-*CO_2 *GHGs are less dramatic but substantial nonetheless. The increase in radiative forcing ranges from 6.5 to 8.5* W/m^2 *from the year 2000 level with the non-*CO_2 *GHGs accounting for about 20 to 30% of the instantaneous forcing in 2100.*

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

3.5.1. Greenhouse Gas Emissions

3.5.1.1. Calculating Greenhouse Gas Emissions

Emissions of CO_2 are the sum of emissions from each of the different fuel types, and, for each type, emissions are the product of a fuel-specific emissions coefficient and the total combustion of that fuel. Exceptions to this treatment occur if a fossil fuel is used in a non-energy application (e.g., as a feedstock for plastic), in which case an adjustment is made to the accounts, or if the carbon is captured and stored in isolation from the atmosphere. All three of the models assume the availability of carbon-capture/storage technologies and treat the leakage from such storage as zero during the study period. The capture and storage of CO_2 incur costs additional to the generation process, so they are not undertaken in the reference scenarios.

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

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

MiniCAM builds its net terrestrial carbon flux by summing both emissions from changes in the stocks of carbon from land-use change associated with human activities and the natural system response, represented in the reduced-form terrestrial carbon module of MAGICC. As noted above, the MiniCAM model employs a simpler reduced-form representation of terrestrial carbon reservoirs and fluxes; however, its scenario is fully integrated with its agriculture and land-use module, which in turn is directly linked to energy and economic activity in the energy portion of the model.

Fossil fuel CO_2 emissions are relatively simple to calculate and are fully endogenous to all three models, but non-CO_2 GHG emissions are more difficult. CO_2 emissions are determined by energy use, which in turn is systematically coupled to the rest of the economy. In contrast, non-CO_2 GHGs often have some more narrowly defined human activity with which they are associated, e.g., the use of solvents, which does not necessarily move in a well-defined relationship with the rest of the economy. Non-CO_2 GHGs can also be associated with highly variable emissions coefficients, as, for example, in the case with methane release from incomplete combustion. Emissions of other GHGs are thus developed using a variety of techniques. In some instances, emissions are determined by endogenously computing some specific anthropogenic activity, for example, ruminant livestock herds, along with the rest of the core elements of the scenario and applying an emissions coefficient to yield the scenario's reference emission. In other instances, a scenario is developed "off-line" and is computationally independent of the model although directly linked to the reference scenario. Details on these approaches are included in the earlier referenced papers that document these models.

3.5.1.2. Reference Scenarios of Fossil Fuel CO_2 Emissions

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

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

Substantial increases in total energy use with no or little decline in carbon intensity (Figure 3.13) lead to the substantial increases in CO_2 emissions per capita (Figure 3.14) and in global totals (Figure 3.15). Emissions of CO_2 from fossil fuel use and industrial processes increase from roughly 7 GtC/y to between 22 and 24 GtC/y by 2100. This set of emissions is higher than in many earlier studies such as IS92a, where emissions were 20 GtC/y (Leggett et al. 1992). The model scenarios are closer in their emissions estimates to the higher scenarios in the IPCC Special Report on Emissions Scenarios (Nakicenovic and Swart 2000), particularly those included under the headings A1f and A2.

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

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

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

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

In contrast, the MERGE scenario assumes that liquids come primarily from coal, a fuel that is more broadly distributed around the world than unconventional oils. MERGE also exhibits higher rates of labor productivity in the non-Annex I nations than the IGSM reference scenario. Finally, MERGE has a greater deployment of nuclear generation, leading to generally lower carbon-to-energy ratios overall. These three features combine to produce lower Annex I emissions and higher non-Annex I emissions than in the IGSM reference scenario.

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

The MiniCAM reference scenario has Annex I emissions similar to those of MERGE, but higher non-Annex I fossil fuel and industrial CO_2 emissions, at least in part because MiniCAM has an aggregate carbon-to-energy ratio that rises steadily over time.

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

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

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

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

3.5.1.3. Future Scenarios of Anthropogenic CH_4 and N_2O Emissions

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

Figure 3.18. Global CH_4 and N_2O Emissions across Reference Scenarios

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

3.5.1.4. Future Scenarios of Anthropogenic F-Gas Emissions

A set of industrial products that act as GHGs are combined under the term "F-gases," which refers to a compound that is common to them, fluorine. Several are replacements for the chlorofluorcarbons that have been phased out under the Montreal Protocol. They are usefully divided into two groups: a group of hydroflurocarbons (HFCs), most of which are shorter-lived, and the long-lived perfluorocarbons (PFCs) and sulfur hexafluoride (SF_6). Figure 3.19 presents the reference scenarios for these gases. IGSM and MiniCAM show strong growth in the short-lived species, while MERGE projects about half as much growth over the century. The models also differ in their expectations for the long-lived gases. PFCs are used in semiconductor production and are emitted as a byproduct of aluminum smelting; they can be avoided relatively cheaply. Emissions from the main use of SF_6 in electric switchgear can easily be abated by recycling to minimize venting to the atmosphere. Since these long-lived gases can be avoided, IGSM and MiniCAM project limited growth even in the absence of climate policy. However, MERGE sees a strong increase, driven in part by its growing electric sector.

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

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

The stock of carbon in the atmosphere at any time is determined from an initial concentration of CO_2, to which is added anthropogenic emissions from fossil fuel and industrial sources, and from which is subtracted net CO_2 transfer from the atmosphere to the ocean and terrestrial systems. These three processes are differently represented in the three models, yet their results show a remarkably similar relationship between cumulative fossil fuel and CO_2 concentrations in the atmosphere.

The reference scenarios display increasing ocean uptake of CO_2, shown in Figure 3.20 for MiniCAM and IGSM. Ocean uptake reflects model mechanisms that become increasingly active as CO_2 accumulates in the atmosphere. The IGSM reference scenario has the least active ocean, reflecting a three-dimensional representation that displays less uptake as water temperatures and CO_2 levels in its surface layer rise, partly as a result of slow mixing into the deep ocean. MiniCAM shows a less pronounced slowing of ocean uptake.

Figure 3.20. CO_2 Uptake from Oceans across Reference Scenarios

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

3.5.3. Greenhouse Gas Concentrations

Radiative forcing is related to the concentrations of GHGs in the atmosphere and not their annual emissions rates. The relationship between emissions and concentrations of GHGs is discussed in Box 3.2. The concentration of gases that reside in the atmosphere for long periods of time, decades to millennia, is thus more closely related to cumulative emissions than to annual emissions. In particular, this is true for CO_2, the gas responsible for the largest contribution to radiative forcing. This relationship can be seen for CO_2 in Figure 3.21, where cumulative emissions over the period 2000 to 2100, from both the reference scenario and the four stabilization scenarios, are plotted against the CO_2 concentration in the year 2100. The resulting plot is roughly linear and similar across the models, despite the fact that the underlying processes that govern the relationship between emissions and concentrations are far more complex, involving both terrestrial and ocean non-linear processes, and are represented differently in the three modeling systems. This basic linear relationship also holds for other long-lived gases such as N_2O and SF_6 and the long-lived F-gases.

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

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

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

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

The projected concentrations of the short-lived and long-lived F-gases are also presented in Figure 3.22. MERGE projects slightly higher emissions than IGSM for the short-lived gases, with the roles of the two models reversed for the long-lived species. These differences then appear in the relative estimates of the resulting atmospheric concentrations. Indeed, for the long-lived species, even a very small addition to emissions in the period 2020 to 2080 leads the IGSM concentration to rise far above that projected by MERGE over a 100-year time horizon.

3.5.4. Radiative Forcing from Greenhouse Gases

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

The three models display essentially the same relationship between GHG concentrations and radiative forcing. However, the three reference scenarios also all exhibit higher radiative forcing, growing from 2.2 W/m^2 to between 6.6 and 8.6 W/m^2 between the years 2000 and 2100. (See Chapter 4 for a discussion of the consequences of limiting radiative forcing.) Given that radiative forcing targets are fixed at four different levels in the stabilization scenarios, the differences carry implications that will reverberate throughout the analysis.

All three reference scenarios show that the relative contribution of CO_2 will increase in the future, as shown in Figure 3.23. From pre-industrial times to the present, the non-CO_2 gases examined here contribute about 32% of the estimated forcing. In the IGSM reference scenario, the contribution of the non-CO_2 gases falls slightly to about 26% by 2100. The MiniCAM reference scenario includes little additional increase in forcing for non-CO_2 gases, largely as a result of assumptions regarding the control of methane emissions for non-climate reasons, and thus has their share falling to about 18% by 2100. The MERGE reference scenario is intermediate, with the non-CO_2 contribution falling to about 24%.

Figure 3.23. Radiative Forcing by Gas across Reference Scenarios

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

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

IGSM Population by Region (million)

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

MERGE Population by Region (millions)

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

MiniCAM Population by Region (millions)

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

Table 3.2. Reference GDP for Key Regions (trillions of 2000 U.S. $, MER), 2000-2100. This table reports GDP for all regions of the globe, but accounts for inconsistency in regional aggregations across models. Note that while regions are generally comparable, slight differences exist in regional coverage, particularly in aggregate regions. (Note that IGSM is in 1997$)

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

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

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

Region	2000	2020	2040	2060	2080	2100
U.S.A	9.8	16.1	21.0	26.8	33.1	39.6
Western Europe	9.8	14.4	19.9	26.9	35.0	43.6
Japan	4.6	6.0	7.7	9.6	11.7	13.9
Eastern Europe	1.0	1.9	3.6	6.6	12.0	20.4
Former Soviet Union						
China	1.2	3.1	7.4	17.3	38.5	78.7
India	0.5	1.5	3.6	8.3	18.5	39.2
Africa	5.2	12.4	24.5	45.3	79.8	135.2
Latin America						
Rest of World						

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

	2000	2020	2040	2060	2080	2100
USA	9.9	15.1	21.2	29.0	39.1	53.0
Western Europe	11.4	14.8	17.8	21.6	25.9	31.6
Japan	4.4	5.4	6.5	7.9	9.4	11.1
Former Soviet Union	0.6	1.3	2.3	3.9	6.2	9.8
Eastern Europe	0.4	0.6	1.1	1.9	3.1	5.2
China	1.3	4.1	10.0	17.9	29.5	43.1
India	0.6	2.0	5.8	12.8	23.4	38.4
Africa	0.7	1.3	2.2	4.1	8.0	14.2
Latin America	2.0	3.3	5.1	9.0	16.3	27.4
Rest of the World	3.8	7.5	14.2	25.1	40.7	60.8

Table 3.3. Historical Annual Average Per Capita GDP Growth Rates

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

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

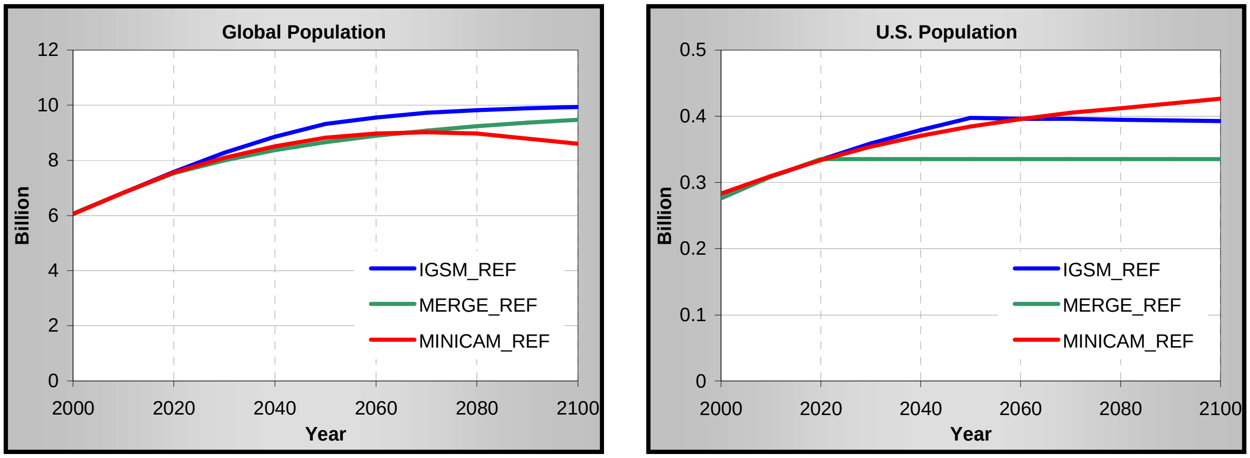


Figure 3.2. U.S. Economic Growth across Reference Scenarios. U.S. economic growth is driven in part by labor force growth, and in part by assumptions about productivity growth of labor and other factors such as by savings and investment. Projected annual average growth rates are 1.4% for MERGE, 1.7% for MiniCAM, and 2.0% for IGSM. By comparison, U.S. real GDP grew at an annual average rate of 3.4% from 1959-2004 (Economic Report of the President, CEA 2005).

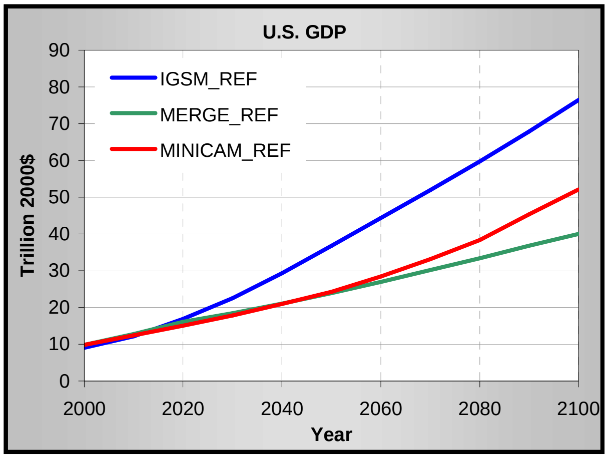


Figure 3.3. Global Primary Energy by Fuel across Reference Scenarios (EJ/y). Global total primary energy use is projected in the reference to grow by 3.5 to 4 times, while U.S. primary energy use is projected to grow by 2 to 2.5 times. Fossil fuels remain a major source. Note that oil includes that derived from tar sands and shale, and that coal use includes that used to produce synthetic liquid and gaseous fuels.

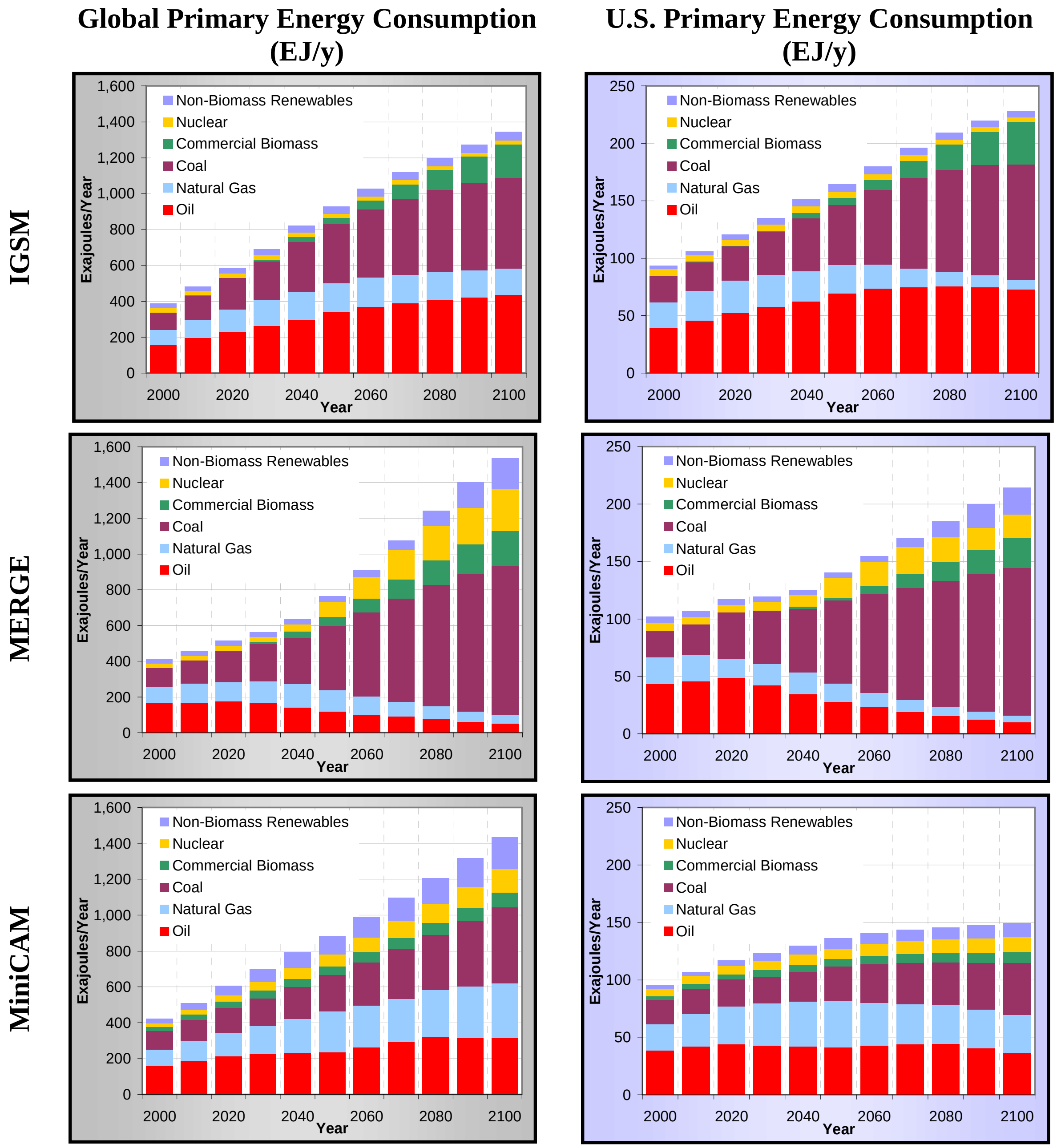


Figure 3.4. Global and U.S. Primary Energy Consumption per Capita across Reference Scenarios (gigajoules per capita). All three models project growing per capita use of energy for the world as whole and for the U.S. However, even after 100 years of growth, global per capita energy use is projected to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

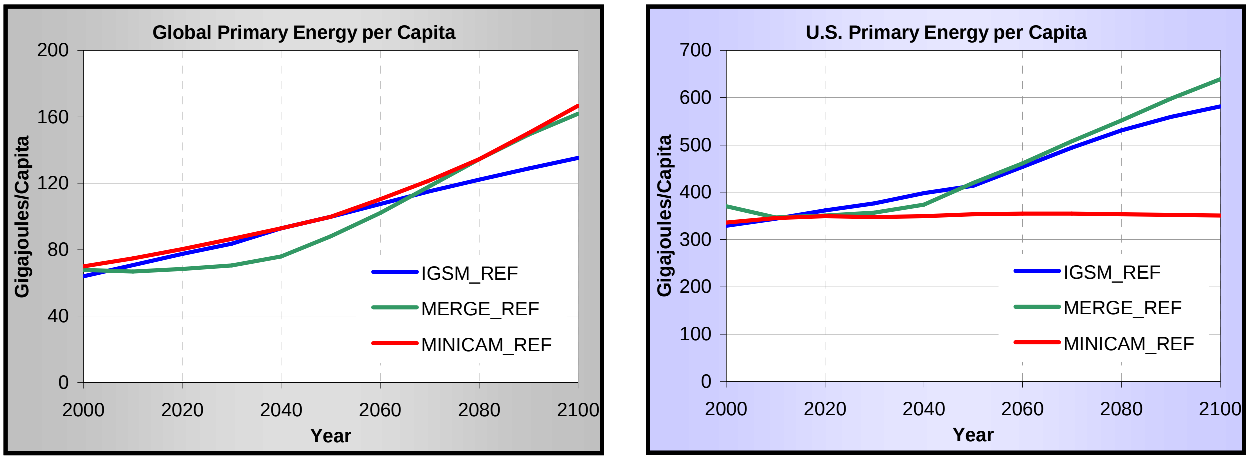


Figure 3.5. U.S. Primary Energy Intensity: Consumption per Dollar of GDP across Reference Scenarios (Index, Year 2000 Ratio = 1.0). United States total primary energy consumption per dollar of GDP is projected to continue to decline. Recent experience is a rate of decline of about 14% per decade. IGSM projects a rate of decline of about 12%, MiniCAM about 8%, and MERGE about 6.5% per decade.

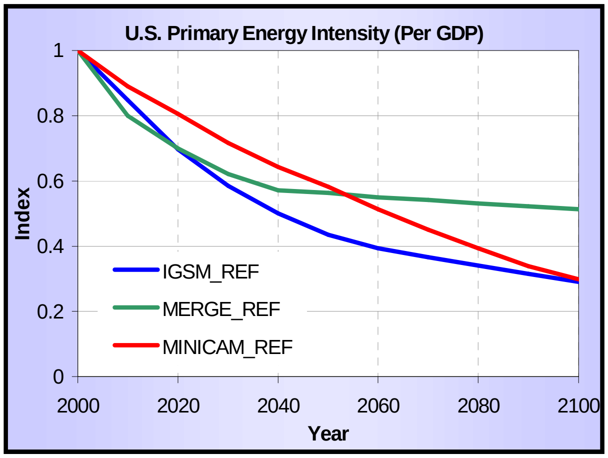


Figure 3.6. Long-term Historical Crude Oil Prices. Crude oil prices have historically been highly variable, but over the period 1947-2004 there appeared to be a slight upward trend. (Figure courtesy of James Williams, WTRG Economics)

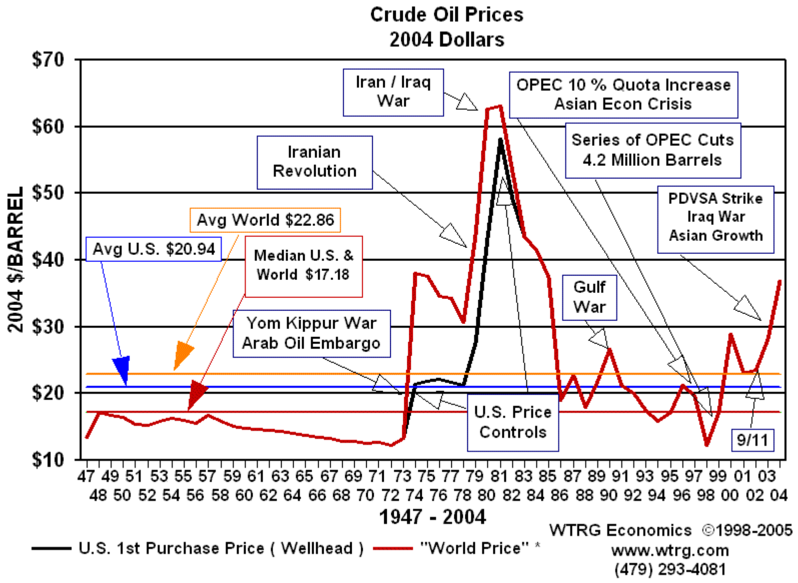
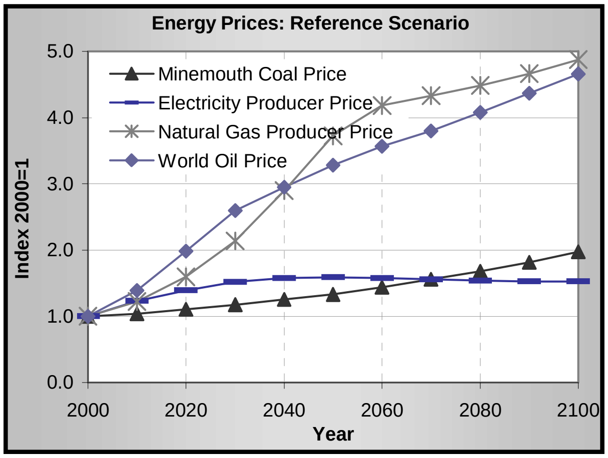


Figure 3.7. Indices of Energy Prices across Reference Scenarios (Indexed to 2000 = 1). Projected energy prices through 2100, indexed so that 2000=1.0, show a wide range among the models but generally show a rising trend relative to recent decadal averages. MERGE price projections are intermediate—by 2100 the crude oil price is about that observed in 2005 (3 times the 2000 level). MiniCAM generally projects the lowest prices, with the projected crude oil price about 2.5 times 2000 levels in 2100, somewhat below the level reached in 2005. IGSM projects the highest prices, which for crude oil, would be about 50 to 60% higher in 2100 than the price level of 2005.

IGSM



MERGE **MiniCAM**

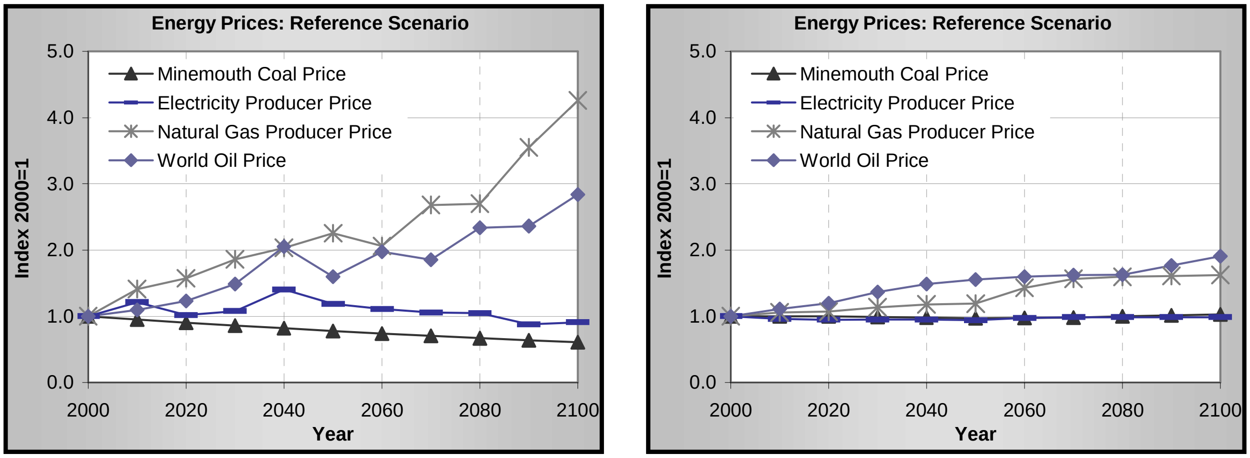
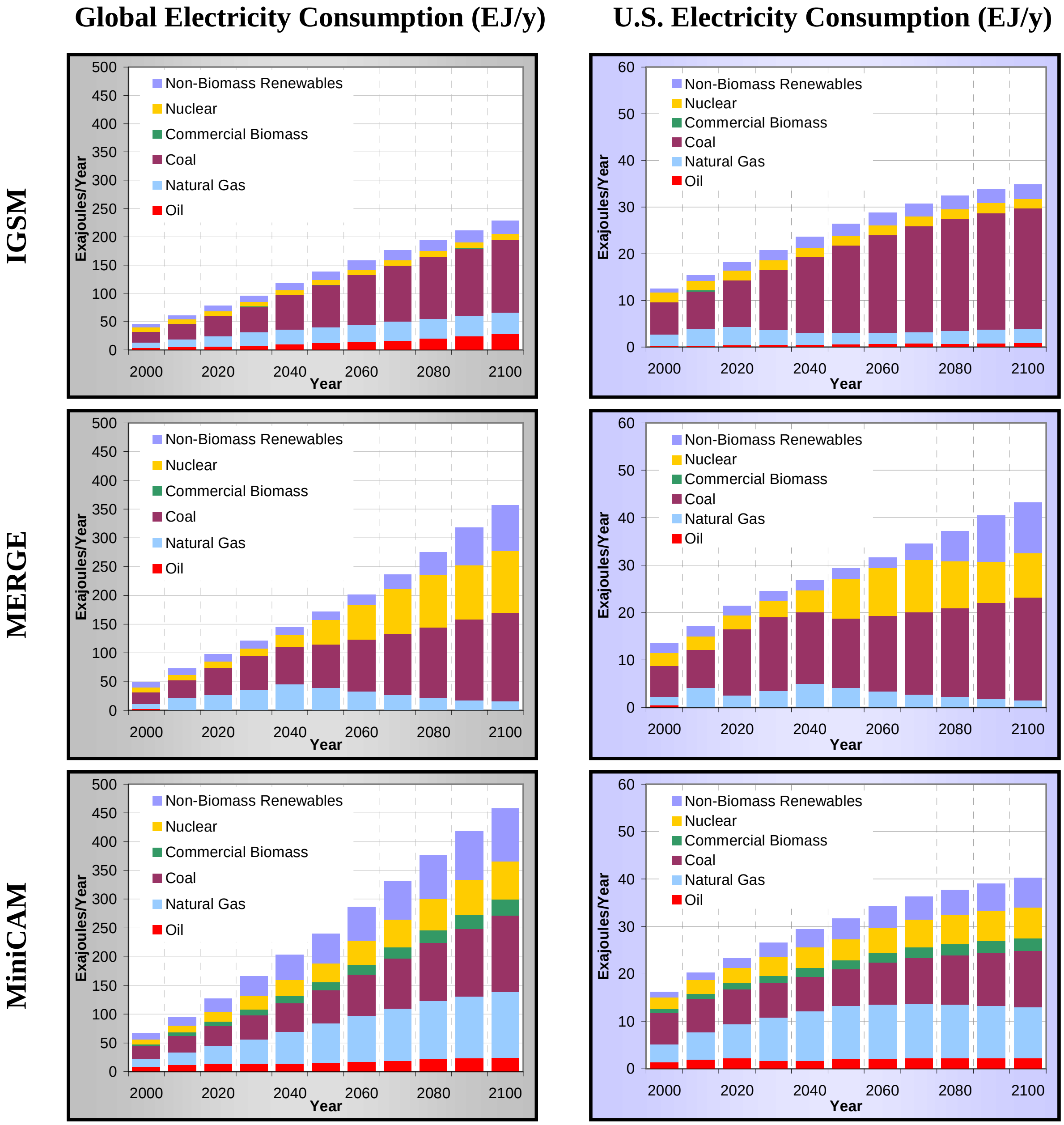


Figure 3.8. Global and U.S. Electricity Production by Source across Reference Scenarios (EJ/y). Global and U.S. electricity production show continued reliance on coal, especially in the IGSM projections, which limits nuclear production because of policy and siting issues. MERGE and MiniCAM find that nuclear is economically competitive; they also project a larger role for other non-carbon sources and greater use of electricity overall compared with IGSM. Differences among the models for the world are mirrored in differences for the U.S.


Global Electricity Consumption (EJ/y)

U.S. Electricity Consumption (EJ/y)

IGSM

MERGE

MiniCAM

Figure 3.9. Global and U.S. Primary Energy Consumed in Non-Electric Applications across Reference Scenarios (EJ/y). Non-electric energy use also remains heavily dependent on fossil fuels with some penetration of biomass energy. Primary energy is reported here, and the resurgence of coal in the projections is because of its use to produce synthetic liquids or gas.

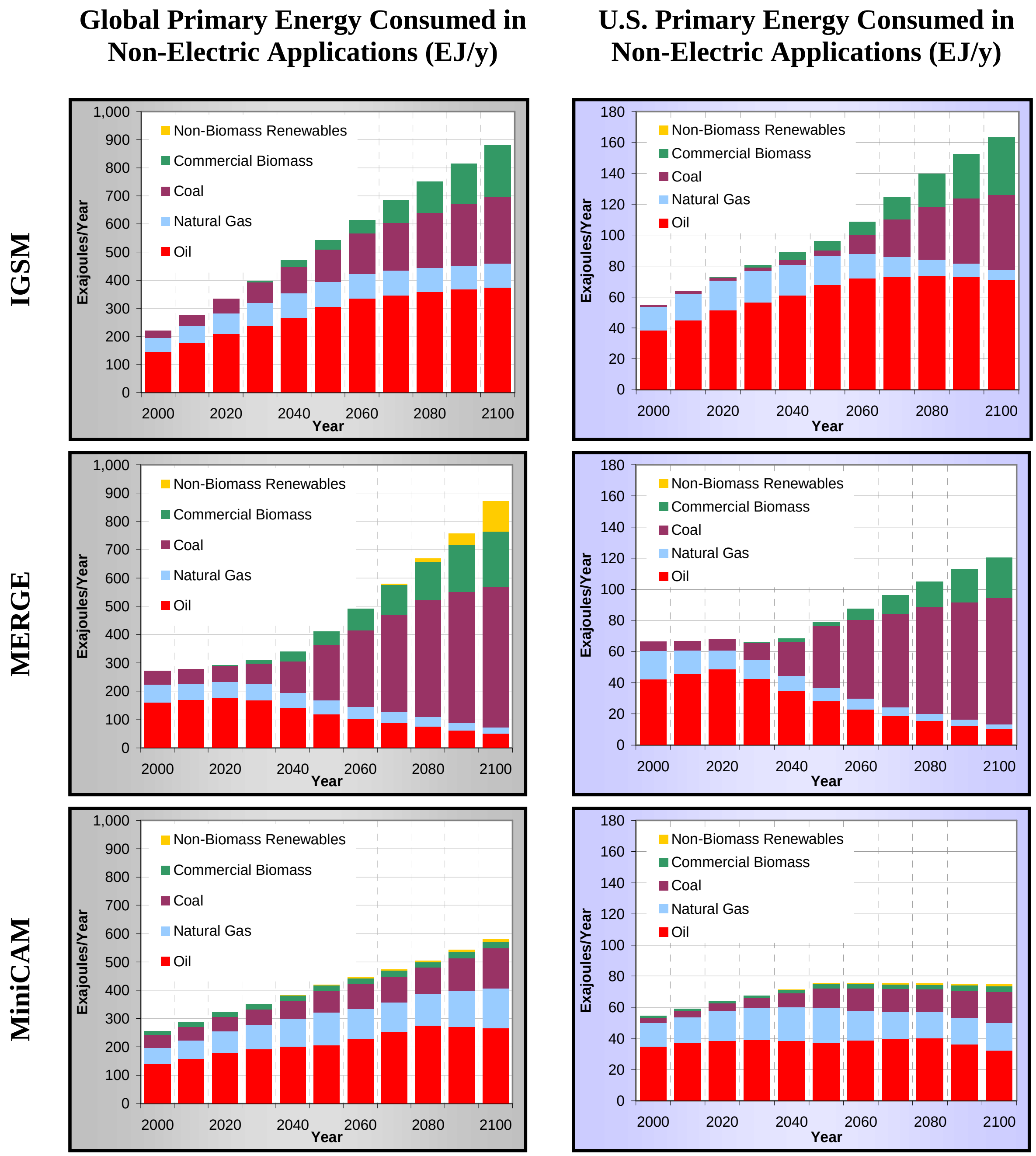
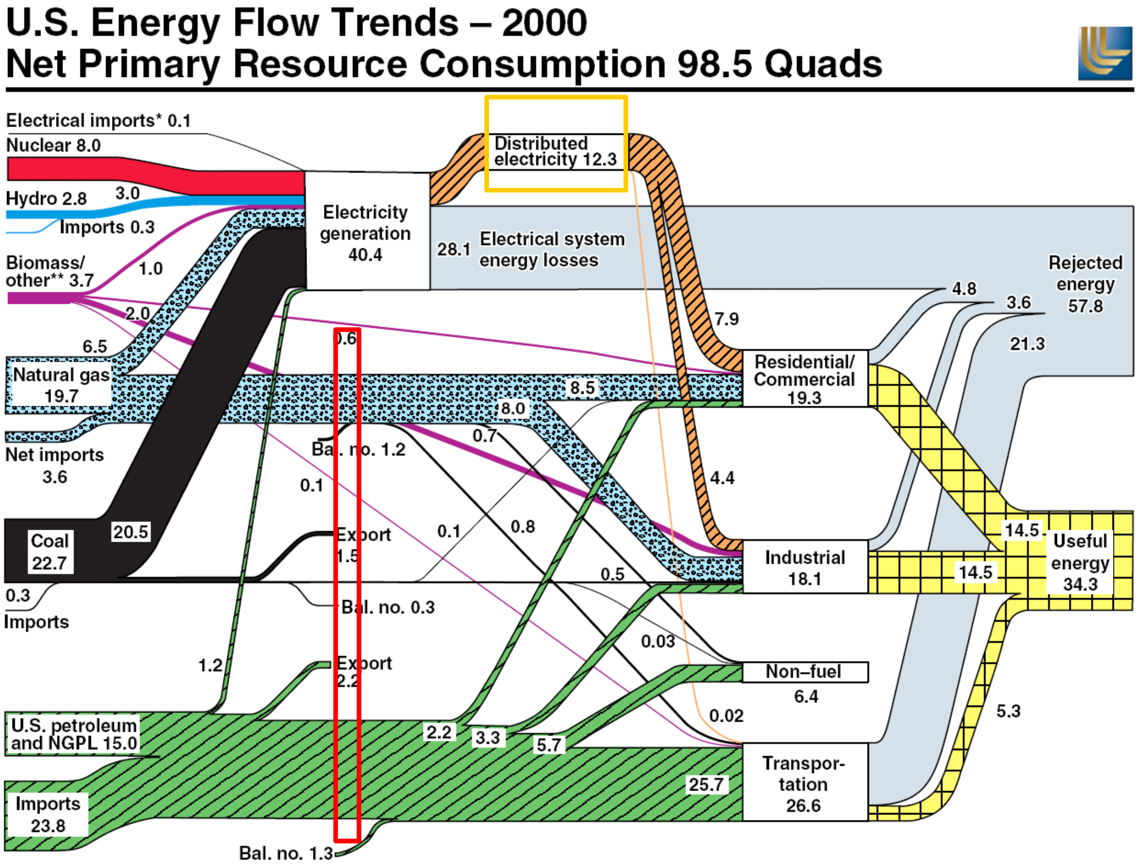


Figure 3.10. U.S. Energy Flow Diagram and Non-Electrical Energy Use for the Year 2000. Primary energy is transformed into different energy carriers that can easily be used for specific applications (e.g., space conditioning, light, and mechanical energy), but in the process losses occur. Of the 98.5 quads of primary energy used in the U.S. in the year 2000, only an estimated 34.3 quads were actually useful. Each of the models used in the study represents such conversion processes. Assumptions about efficiency improvements in conversion and end-use are one of the reasons why energy intensity per dollar of GDP is projected to fall.



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

December 2001
Lawrence Livermore
National Laboratory

Figure 3.11. Global and U.S. Production of Biomass Energy across Reference Scenarios (EJ/y). The MiniCAM scenario includes traditional as well as commercial biomass and thus shows significant use in 2000. IGSM and MERGE explicitly model only commercial biomass energy beyond that already used. Globally, both IGSM and MERGE show more biomass than does MiniCAM toward the end of the century. In some cases, biomass is reported as a liquid fuel equivalent so that the total biomass production would be 2.5 to 3 times this level, accounting for conversion losses.

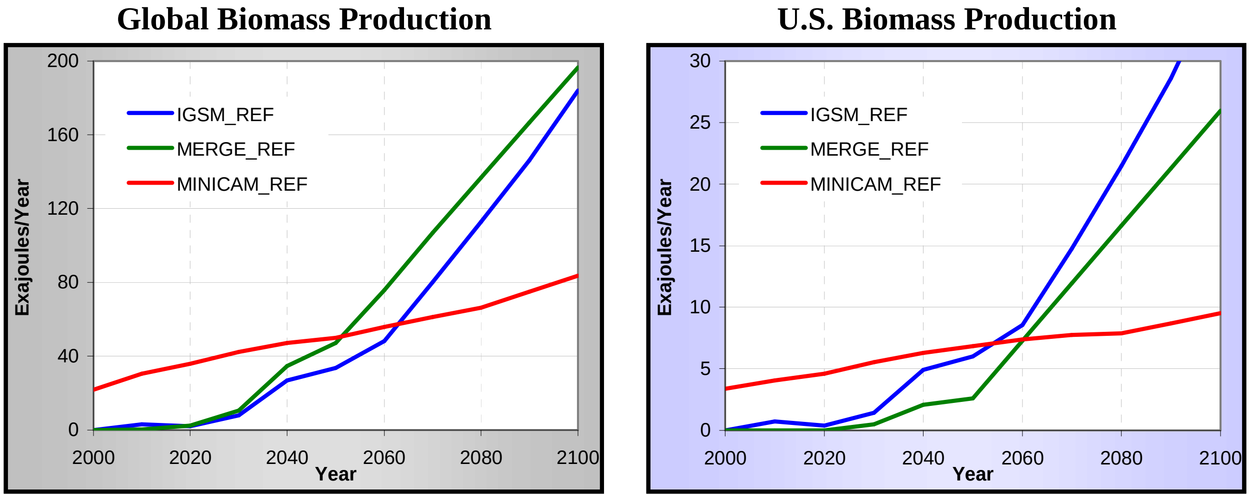


Figure 3.12. Global Net Emissions of CO_2 from Terrestrial Systems Including Net Deforestation across Reference Scenarios (GtC/y). Global net emissions of CO_2 from terrestrial systems, including net deforestation, show that MiniCAM and IGSM have a slight net sink in 2000 that grows over time due to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

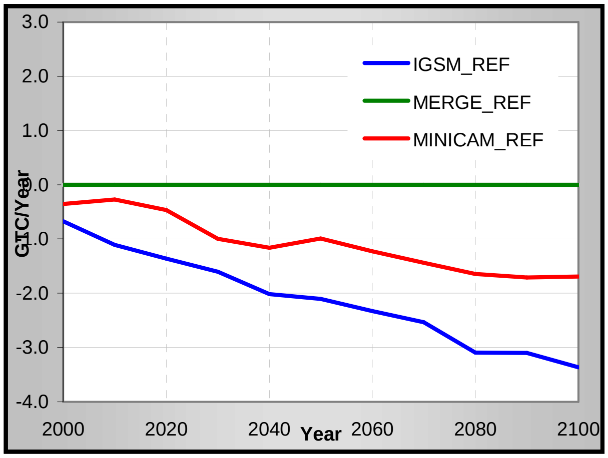
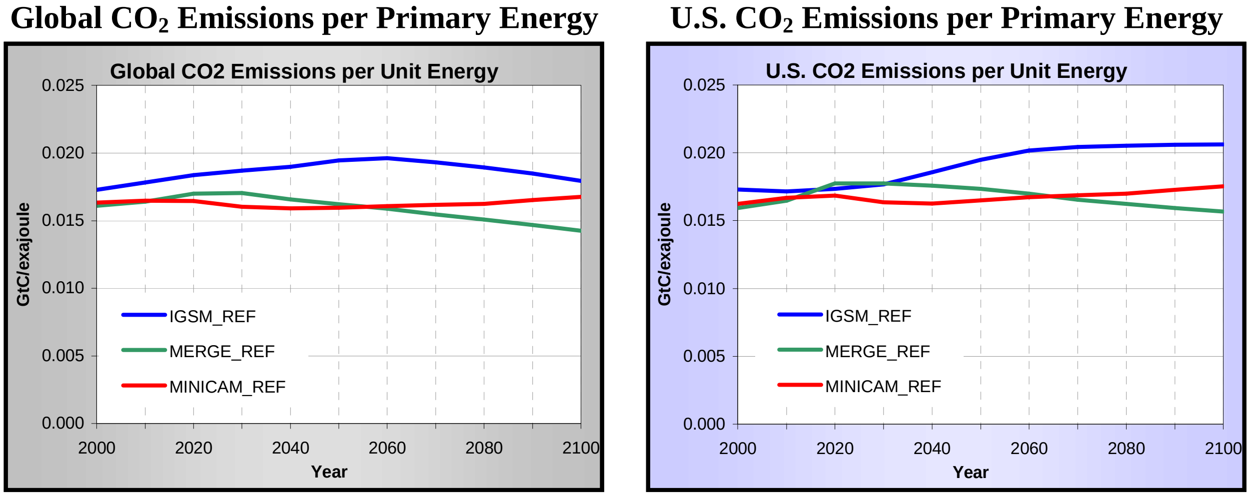
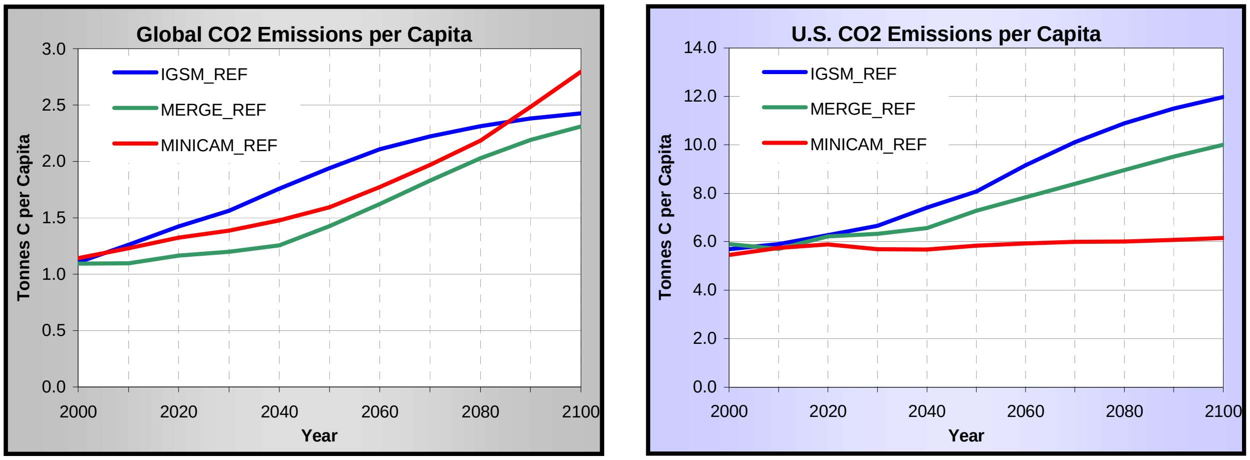


Figure 3.13. Global and U.S CO_2 Emissions from Fossil Fuel Combustion and Industrial Sources Relative to Primary Energy Consumption (GtC/exajoule). CO_2 intensity of energy use shows relatively little change in all three models, reflecting the fact that fossil fuels remain important sources of energy.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



Global CO_2 Emissions per Primary Energy **U.S. CO_2 Emissions per Primary Energy**

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



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

Figure 3.15. Global Emissions of CO_2 from Fossil Fuels and Industrial Sources (CO_2 from land use change excluded) across Reference Scenarios (GtC/y). In the absence of climate policy, all three models project increases in global emissions of CO_2 from fossil fuel combustion and other industrial sources, mainly cement production. By 2100, reference emissions reach nearly 25 GtC. Note that CO_2 from land-use change is excluded from this figure.

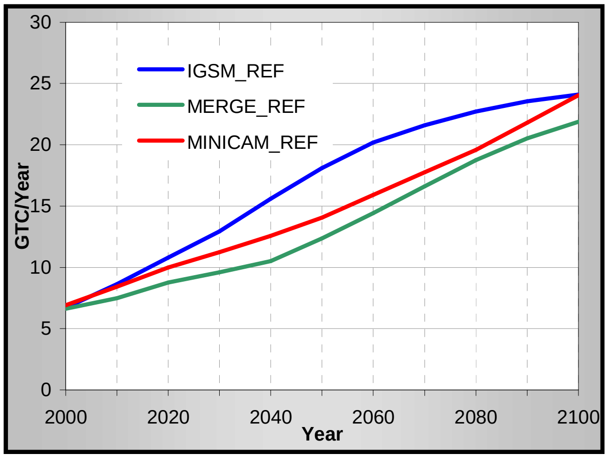
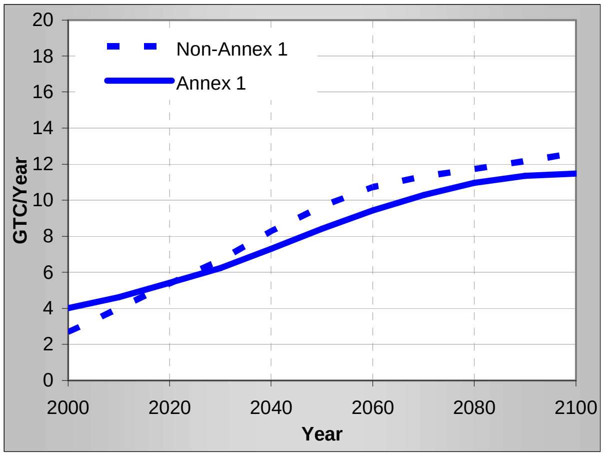


Figure 3.16. Global Emissions of Fossil Fuel and Industrial CO_2 by Annex I and Non-Annex I Countries across Reference Scenarios (GtC/y). Emissions of fossil fuel and industrial CO_2 in the reference scenarios show Non-Annex I emissions exceeding Annex I emissions for all three models by 2030 or earlier.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

IGSM



MERGE **MiniCAM**

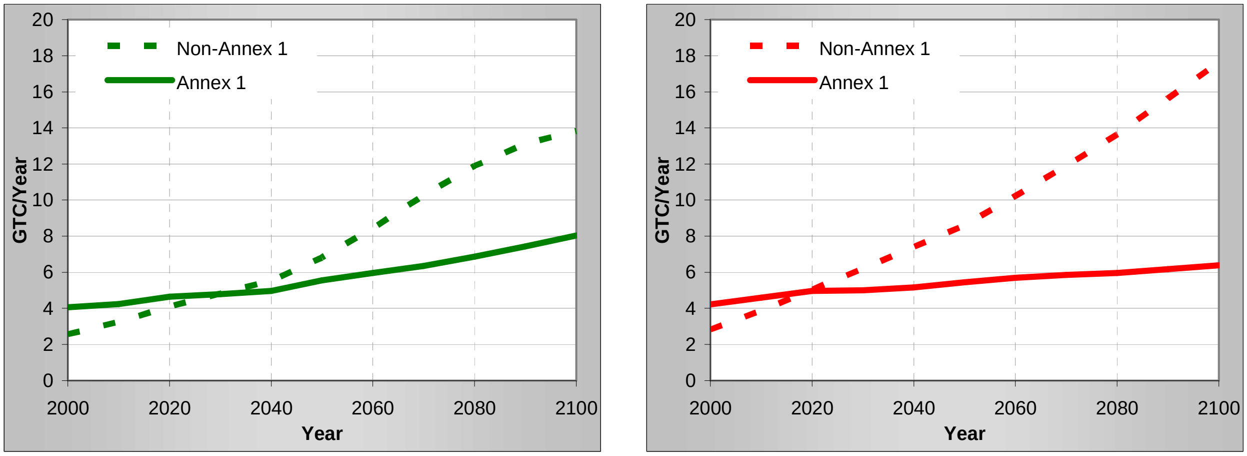
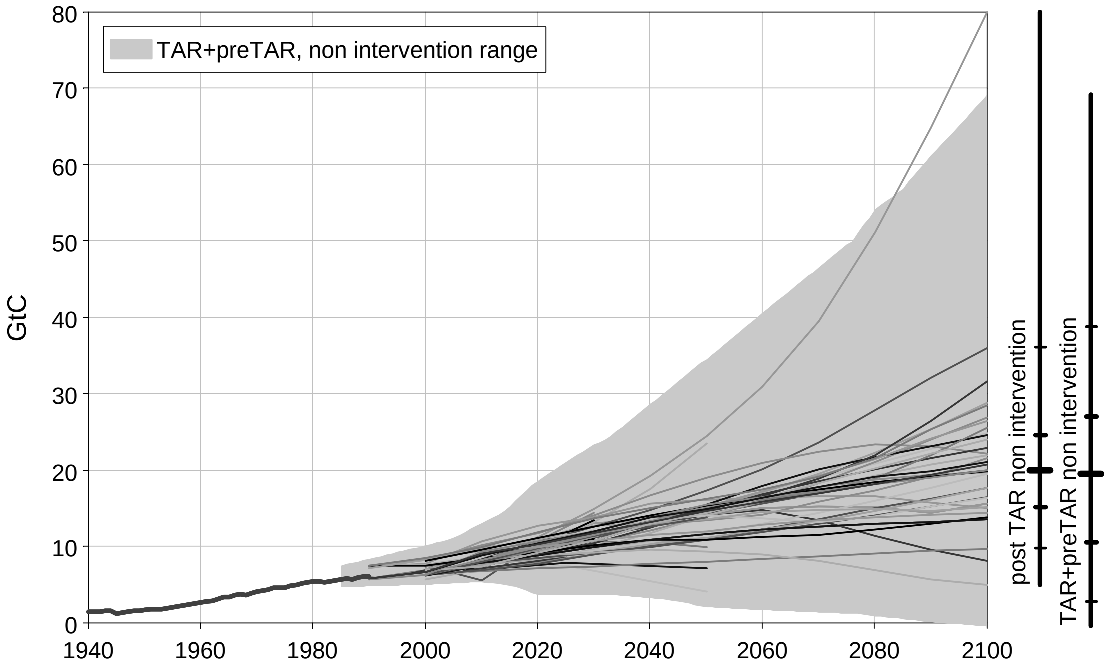
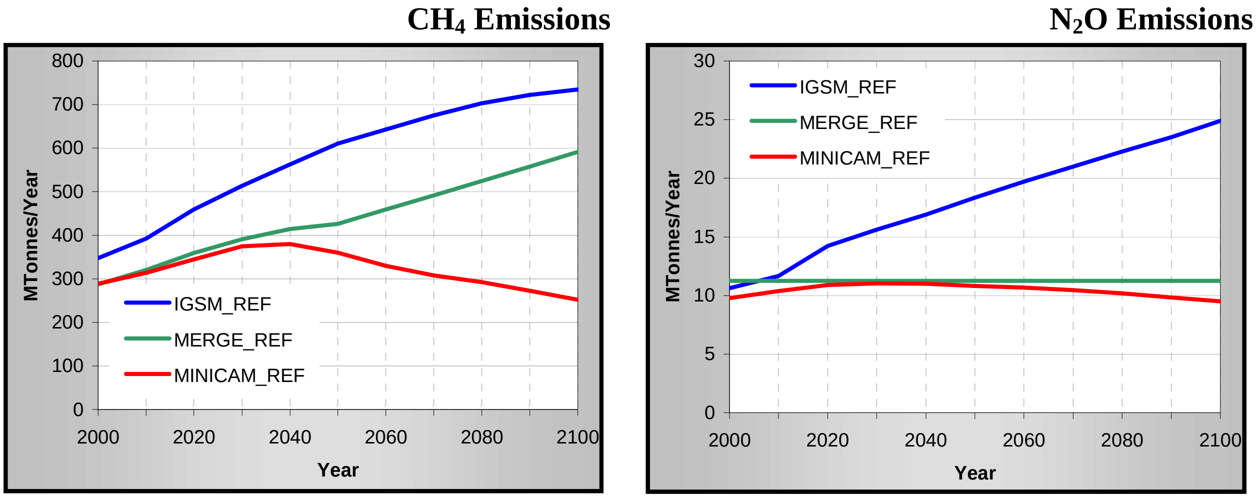


Figure 3.17. Global Fossil Fuel and Industrial Carbon Emissions: Historical Development and Scenarios (GtC/y). The 284 non-intervention scenarios published before 2001 are included in the figure as the gray-shaded range. The "spaghetti" lines are an additional 55 non-intervention scenarios published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



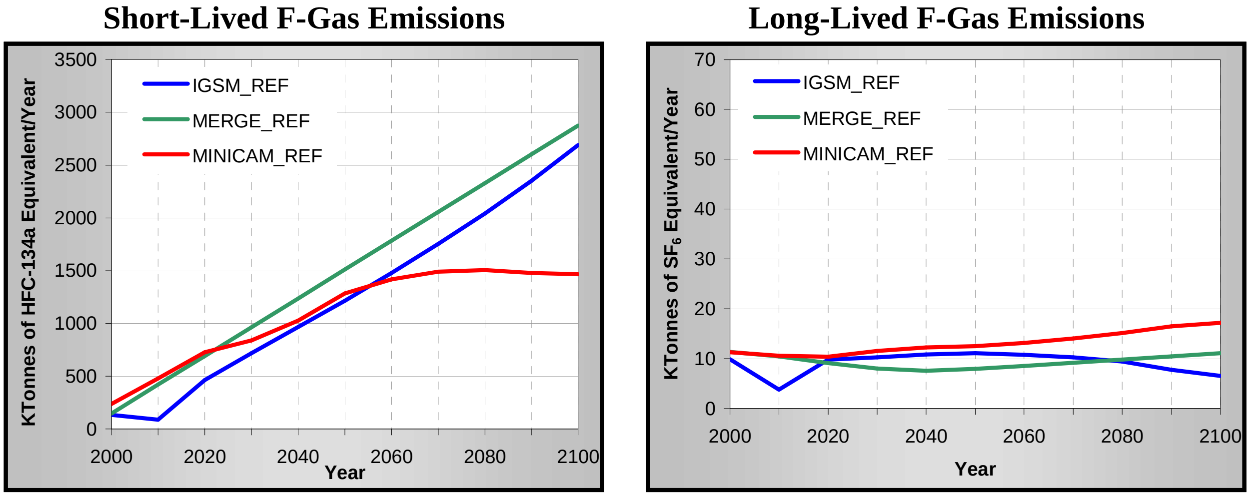
Source: Nakicenovic et al. (2006).

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



CH_4 Emissions **N_2O Emissions**

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



Short-Lived F-Gas Emissions **Long-Lived F-Gas Emissions**

Figure 3.20. CO_2 Uptake from Oceans across Reference Scenarios (GtC/y, Expressed in Terms of Net Emissions). The ocean is a major sink for CO_2. In general, as concentrations rise, the ocean sink rises, but the IGSM results that include a three-dimensional ocean suggest less uptake and, after some point, little further increase in uptake even though concentrations are rising. The MiniCAM results show some slowing of ocean uptake although not as pronounced. Overall uptake is greater even though concentrations (see Figure 3.20) for MiniCAM are somewhat lower than for the IGSM.

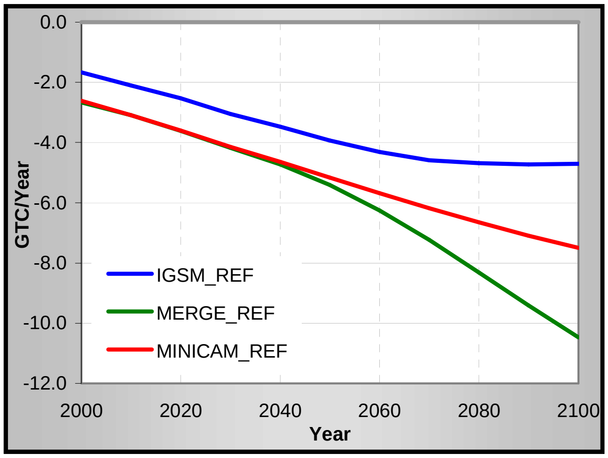


Figure 3.21. Relationship between Cumulative CO_2 Emissions from Fossil Fuel Combustion and Industrial Sources, 2000-2100, and Atmospheric Concentrations of CO_2 across All Scenarios. The relationship between cumulative carbon emissions and atmospheric concentration shows that, despite differences in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

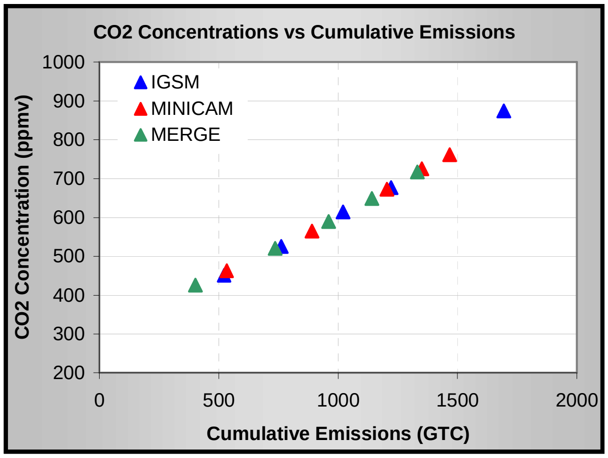
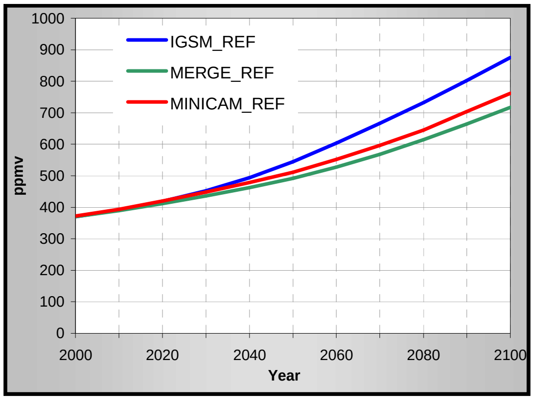
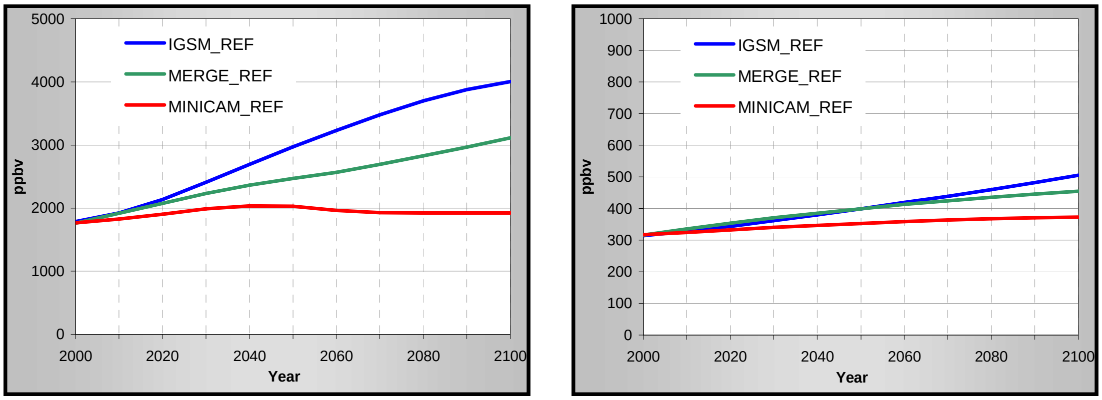


Figure 3.22. Atmospheric Concentrations of CO_2, CH_4, N_2O, and F-gases across the Reference Scenarios (Units Vary). Differences in concentrations for CO_2, CH_4, and N_2O across the three models' reference projections reflect differences in emissions and treatment of removal processes. By 2100, projected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

CO_2



CH_4 **N_2O**



Short-Lived F-Gases **Long-Lived F-Gases**

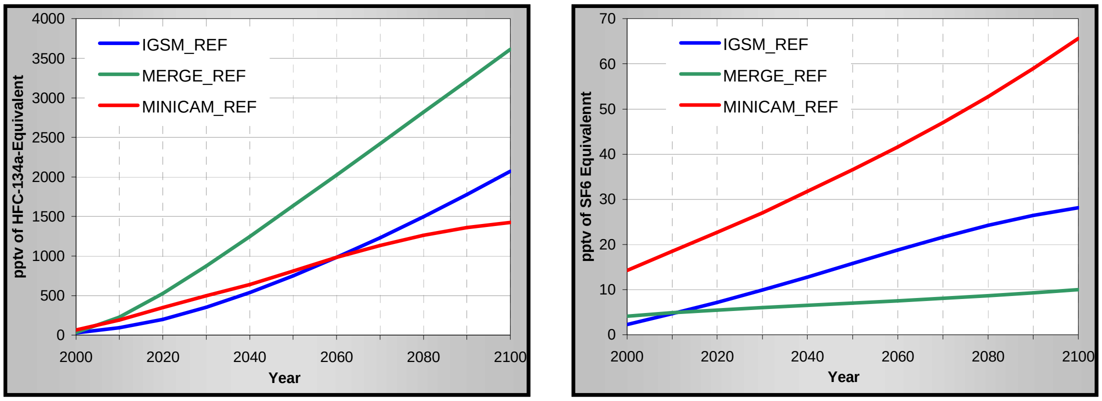
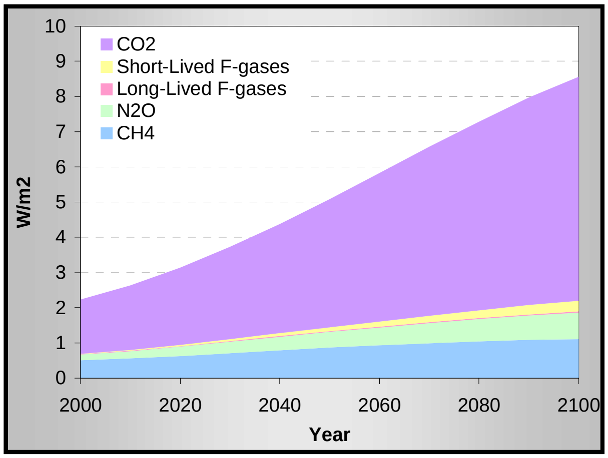
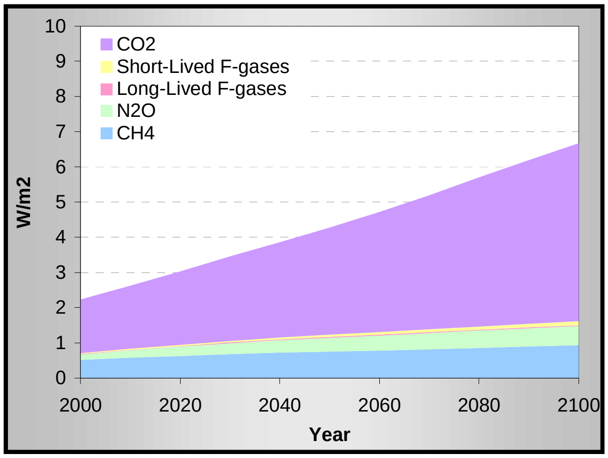


Figure 3.23. Radiative Forcing by Gas across Reference Scenarios (W/m^2). The contributions of different greenhouse gases to increased radiative forcing through 2100 show CO_2 accounting for more than 80% of the increased forcing from preindustrial for all three models. The total increase ranges from about 6.5 to 8.5 W/m^2 above pre-industrial levels.

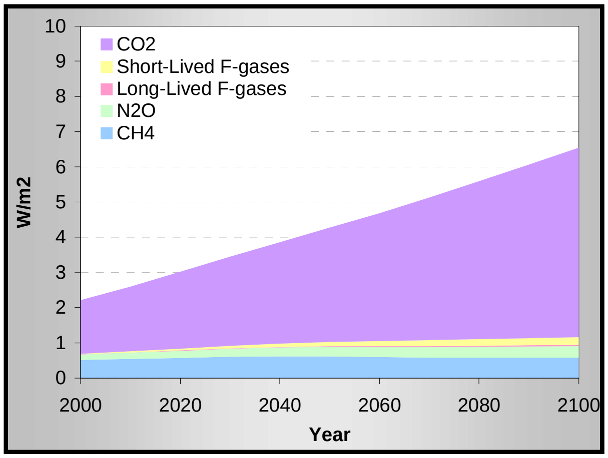
IGSM



MERGE



MiniCAM



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