Reference Scenarios

In the reference scenarios, energy consumption grows significantly and the energy system continues to rely on fossil fuels, leading to an increase in CO_2 emissions of roughly 3 to 3½ times the present level by 2100. Combined with increases in the non-CO_2 GHGs and net uptake by the ocean and terrestrial biosphere, radiative forcing from the GHGs considered in this research reaches 6.4 W/m^2 to 8.6 W/m^2 from preindustrial by 2100.

INTRODUCTION

This chapter introduces the reference scenarios developed by the three modeling groups. These scenarios are plausible future paths, not predictions, for by the very nature of their construction they lack the features of predictions or best-judgment forecasts. For example, they assume that in the post-2012 period existing measures to address climate change expire and are never renewed or replaced, which is an unlikely occurrence. Rather, they have been developed as points of departure to highlight the implications for energy use and other human activities of the stabilization of radiative forcing. Each of the modeling groups 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 GHG emissions mitigation policies (or lack thereof), the three modeling groups developed their reference scenarios independently as each judged appropriate. As noted in Chapter 2, the three models were developed with somewhat different original design objectives. They differ in (a) their inclusiveness, (b) their specifications of key aspects of economic structure, and (c) their choice of values for key parameters. These choices then lead to different characterizations of the underlying economic and physical systems that these models represent.

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

Finally, the modeling groups 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 scenario assumes a larger effect of CH_4 emission-control technologies deployed for economic reasons, which leads to lower reference scenario CH_4 emissions than in the reference scenarios from the other modeling groups. Similarly, the IGSM modeling group assumed that non-climate concerns would limit the deployment of nuclear power, while the MERGE and MiniCAM modeling groups assumed that nuclear power would be allowed to participate in energy markets on the basis of energy cost alone.

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

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

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

The remainder of this chapter describes the reference scenarios developed by the three modeling groups working forward from underlying drivers to implications for radiative forcing. (Chapter 4 proceeds in the other direction, imposing the stabilization levels on radiative forcing and exploring the implications.) The presentation begins with a summary of the underlying socioeconomic assumptions, most notably for population and economic growth. There follows a discussion of 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. The next section shows how the three reference scenarios handle this aspect of the interaction of human activity with natural Earth systems. Finally, the anthropogenic emissions are described, taking into account both the energy sector and other sources, such as agriculture and various industrial activities. This last 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 research: atmospheric concentrations and global radiative forcing.

SOCIOECONOMIC 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. In the reference scenarios, the global population rises from 6 billion in the year 2000 to between 8.6 and 9.9 billion in 2100. Economic activity grows through 2100 across the globe. Developed nations continue to expand their economies at historical rates, and developing nations 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 scenarios of the scale and composition of economic activity for each region. For population assumptions, the IGSM modeling group adopted a regionally detailed United Nations (U.N.) projection for the period 2000-2050 (UN 2001) and extended this scenario to 2100 using information from a longer-term U.N. study (UN 2000). The Mini-CAM assumptions are based on a median scenario by the U.N. (UN 2005) and a Millennium Assessment Techno-Garden Scenario from the International Institute for Applied Systems Analysis (O'Neill 2005). Near-term population assumptions for the MERGE scenarios come from the Energy Information Administration's International Energy Outlook.

Population increases substantially across the scenarios by the end of the century, but all of the scenarios portray the population growth rate as slowing to near zero, if not turning negative, by the end of the century (Table 3.1 and Figure 3.1). As a result, by 2050 more than 75% of all the change between the year 2000 and 2100 has occurred. A demographic transition from high birth and death rates to low death rates and eventually to low birth rates is a feature of most demographic scenarios, reflecting assumptions that birth rates will decline to replacement levels or below. For some countries, birth rates are

IGSM Population by Region (million)

Region	2000	2020	2040	2060	2080	2100
U.S.	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 (million)

Region	2000	2020	2040	2060	2080	2100
U.S.	276	335	335	335	335	335
Western Europe	390	397	397	397	397	397
Japan	127	126	126	126	126	126
Former Soviet Union/Eastern Europe	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 (million)

Region	2000	2020	2040	2060	2080	2100
U.S.	283	334	371	396	412	426
Western Europe	457	486	481	456	421	399
Japan	127	127	121	113	103	95
Former Soviet Union	283	284	283	275	261	253
Eastern Europe	124	119	111	100	87	80
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 3.1. Population (million) by Region Across Models, 2000-2100.

Regional aggregations are different in the three models. For example, MiniCAM includes Turkey in Western Europe, but IGSM and MERGE do not.

already below replacement levels, and just maintaining these levels would result in population decline for these countries. A key uncertainty in all demographic scenarios is whether a transition to less-than-replacement levels is a more or less permanent feature of those countries where it has occurred and whether such a pattern will be repeated in other countries.

The differences among the scenarios lie in nuances of this pattern. The MiniCAM scenarios exhibit 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. The MERGE and IGSM scenarios, on the other hand, both employ demographic assumptions by which the global population stabilizes but does not decline during this century. By 2100, populations range from 8.6 to 9.9 billion across the scenarios, which is an increase of roughly 40% to 65% from the 6 billion on Earth in 2000. In total, the difference between the demographic scenarios is relatively small: they differ by only 3% in 2030 and by less than 10% until after 2080.

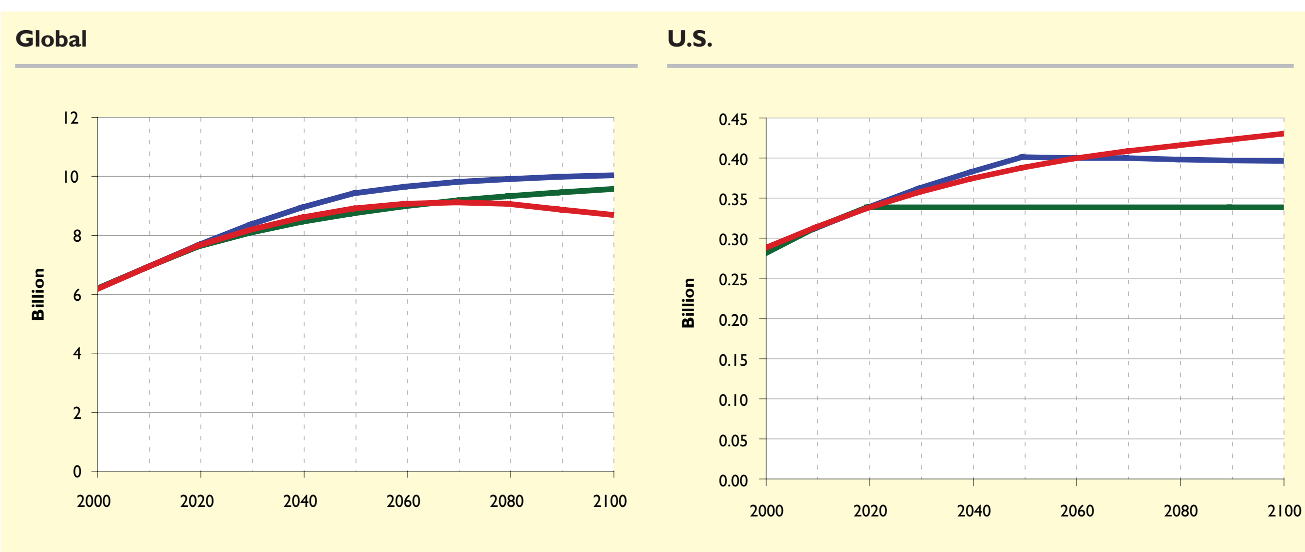
The variation in population among the scenarios is greater for the U.S. than for the globe. The U.S. population (Figure 3.1) increases from about 280 million in the year 2000 to between 335 million and 425 million by 2100. Although the MiniCAM global population is the lowest of the three scenarios in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

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

The alternative scenarios of population and productivity growth lead to differences among the three reference scenarios in U.S. GDP growth (Figure 3.2). There is relatively little difference among the three trajectories through the year 2020. After 2020, however, the scenarios diverge, with the lowest scenario of U.S. GDP

Figure 3.1. World and U.S. Population Across Models. Assumed growth in global and U.S. population is similar among the three models. Global population in 2100 spans a range from about 8.5 to 10 billion. U.S. population in 2100 spans a range from less than .35 to over .45 billion.

IGSM_REF
MERGE_REF
MINICAM_REF



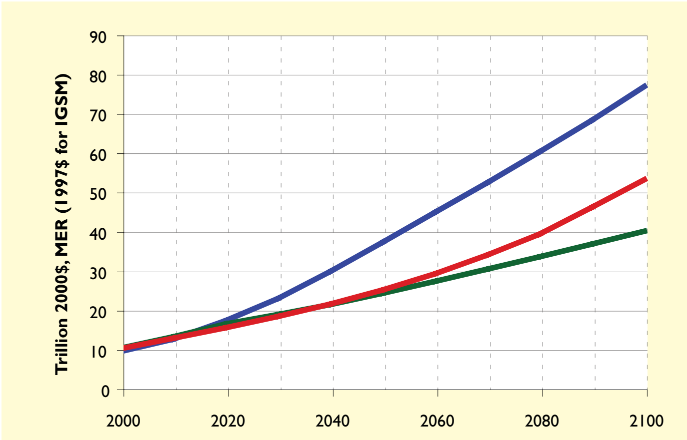


Figure 3.2. U.S. GDP Across Reference Scenarios (1997$ for IGSM, 2000$ for MERGE and MiniCAM, MER). U.S. economic growth is driven, in part, by labor force growth and, in part, by assumptions about productivity growth of labor and, in part, by other factors such as by savings and investment. Annual average growth rates are 1.4% for the MERGE reference scenario, 1.7% for the MiniCAM reference scenario, and 2.2% for the IGSM reference scenario. By comparison, U.S. GDP grew at an annual average rate of 3.4% from 1959-2004 (CEA 2005).

(MERGE) at roughly half of that of the highest scenario (IGSM) by the end of the century. The labor productivity growth assumptions for the U.S. in the IGSM scenario are the highest of the three, and the U.S. population assumptions are also relatively high in the IGSM scenarios. The relatively lower labor productivity growth assumptions used in the MERGE and MiniCAM scenarios lead to lower levels of GDP. The lower population growth assumptions employed in the MERGE scenarios give the MERGE reference scenario the lowest GDP in 2100.

Table 3.2 shows GDP across regions in the three reference scenarios. Differences in the absolute levels of GDP increase result from relatively small differences in rates of per capita growth. Although difficulties arise in comparisons of GDP across countries (see Box 3.1), the growth rates underlying these scenarios are usefully compared with historical experience. Long-term growth rates developed from reconstructed data (Table 3.3) show 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 preindustrial times.

With this historical experience as background, the differences in GDP growth among the reference scenarios can be explained. Demographic trends, slowing population, and labor force growth all combine to influence overall GDP growth in the scenarios. With respect to the developed countries, the per capita income growth rate for the U.S. in the IGSM reference scenario is about the average for North America for the period 1950-2000. The MiniCAM reference scenario has lower growth, reflecting an assumption that an aging population will lead to lower labor force participation, and the result of this demographic maturation is a lower future rate of per capita GDP growth compared to history. U.S. growth rates in the MERGE reference scenario are similar to those of MiniCAM 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 the MiniCAM and MERGE scenarios anticipate a break from the trend with lower per capita growth in GDP as a consequence of changes in underlying demographic trends. As with the U.S., the MiniCAM reference scenario exhibits a decline in average labor force participation in other developed regions as populations age, resulting in lower growth in per capita GDP compared to the IGSM reference scenario. The GDP growth pattern in the MERGE reference scenario is similar to that of MiniCAM reference scenario.

GDP growth patterns for developing regions show greater differences from historical experience. Notably, all three modeling groups chose assumptions leading to consistent growth in many non- Organization for Economic Cooperation and Development (OECD) regions at rates

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

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

Region	2000	2020	2040	2060	2080	2100
U.S.	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, MER)

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

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

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

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

ENERGY USE, PRICES, AND TECHNOLOGY

The Evolving Structure of Energy Use

In the reference scenarios, global primary energy consumption expands dramatically over the century, growing to between 3 and

Region	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
Former U.S.SR	0.10	0.63	1.06	1.76	3.35	-0.96
Eastern Europe	0.10	0.63	1.39	0.60	3.81	0.68
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

Table 3.3. Historical Annual Average per Capita GDP Growth Rates. *Source: Maddison, 2001*

BOX 3.1 Exchange Rates and Comparisons of Real Income Among Countries

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

At the same time, it is widely recognized that using market exchange rates to compare countries can have peculiar implications. Country A might start with a larger GDP than country B when converted to a common currency using that year's exchange rates, and grow faster in real terms than B, yet could later have a lower GDP than B using exchange rates in that year. This paradoxical situation can occur if A's currency depreciates relative to B's. Depreciation and appreciation of currencies by 20% to 50% over just a few years is common, so the example is not extreme. Interest in making cross-country comparisons that are not subject to such peculiarities has led to development of indices of international purchasing power. A widely used index is purchasing power parity (PPP), whose development was sponsored by the World Bank. PPP-type indices have the advantage of being more stable over time and are thought to better reflect relative living standards among countries than MER. Thus, analysts drawing comparisons among countries have found it preferable to use PPP-type indices rather than MER. Although the empirical foundation for the indices has been improving, the theory for them remains incomplete, and thus there is a limited basis on which scenarios of future changes in PPP can be developed. 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 SRES produced by the IPCC (Nakicenovic et al. 2001) because they were reported to model economic convergence among countries, yet reported economic attributes of the scenarios 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 research, no assumptions were made regarding convergence. Growth prospects and other parameters for the world's economies were assessed relative to their own historical performance. The models used in this research are simulated in MER, as this is consistent with modeling of trade in goods. To the extent GDP results are provided, international comparisons are to made with great caution; for example, even global GDP for an historical period will differ if exchange rates of different years are used.

4 times its 2000 level of roughly 400 EJ. This growth results from a combination of forces, including rising economic activity, increasing efficiency of energy use, and changes in energy consumption patterns. Growth in per capita energy consumption occurs despite a continuous decline in the energy intensity of economic activity. The improvement in energy intensity reflects, in part, assumptions of substantial technological change in all three reference scenarios.

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

In all three reference scenarios, non-fossil fuel energy use grows substantially, reaching levels in 2100 that range from around half to levels that exceed total global energy consumption in 2000. The reference scenarios differ in terms of the mix of non-fossil resources. The substantial growth in non-fossil fuel energy use does not forestall substantial growth in fossil fuel consumption.

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

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

Globally and in the U.S., primary energy consumption over the century remains dominated by fossil fuels. In this sense, the three reference scenarios tell a consistent story about future global energy, and all three run counter to the view that the world is running out of fossil fuels. Although reserves and resources of conventional oil and gas are limited in all three reference scenarios, the same cannot be said of coal and unconventional liquids and gases. In all three reference scenarios, the world economy moves from current conventional fossil resources to increased exploitation of some combination of the extensive (if more costly) global resources of heavy oils, tar sands, and shale oil, and to synfuels derived from coal. The three reference scenarios exhibit a different mix of these sources. The IGSM reference scenario exhibits

Figure 3.3. Global and U.S. Primary Energy Consumption by Fuel Across Reference Scenarios (EJ/yr). Global total primary energy consumption grows to between three and four times today's levels over the century in the reference scenarios, while U.S. primary energy consumption grows to between 1 and 2½ times today's levels. Fossil fuels remain a major energy source, despite substantial increases in the consumption of non-fossil energy sources. *[Notes. i. Oil consumption includes that derived from tar sands and oil shales, and coal consumption includes that used to produce synthetic liquid and gaseous fuels. ii. Primary energy consumption from nuclear power and non-biomass renewable electricity are accounted for at the average efficiency of fossil-fired electric facilities, which vary over time and across scenarios. This long-standing convention means that, all other things being equal, increasing efficiency of fossil-electric energy lowers the contribution to primary energy from these sources.]*

- 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

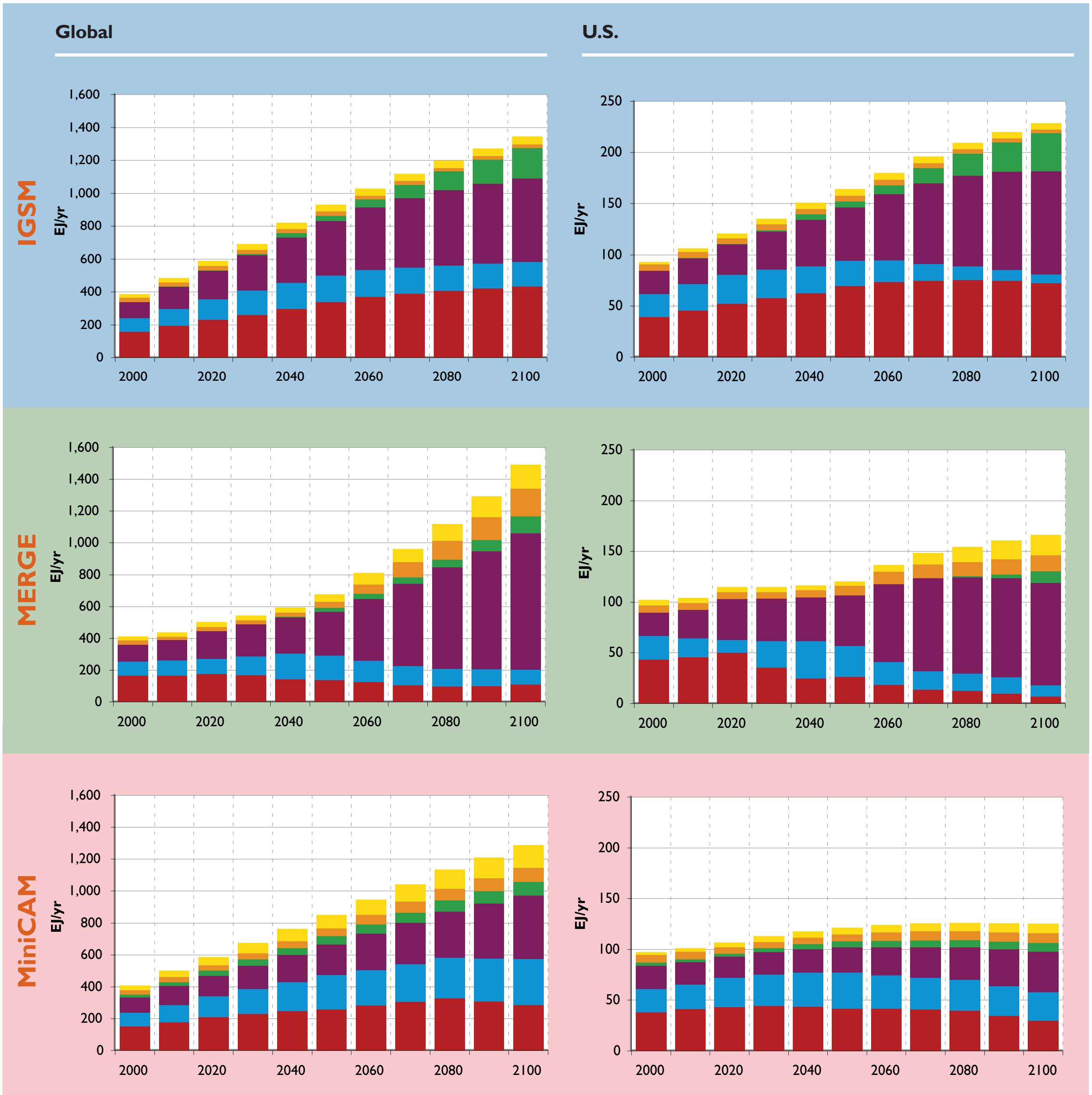
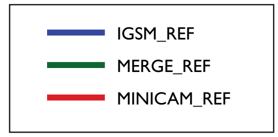
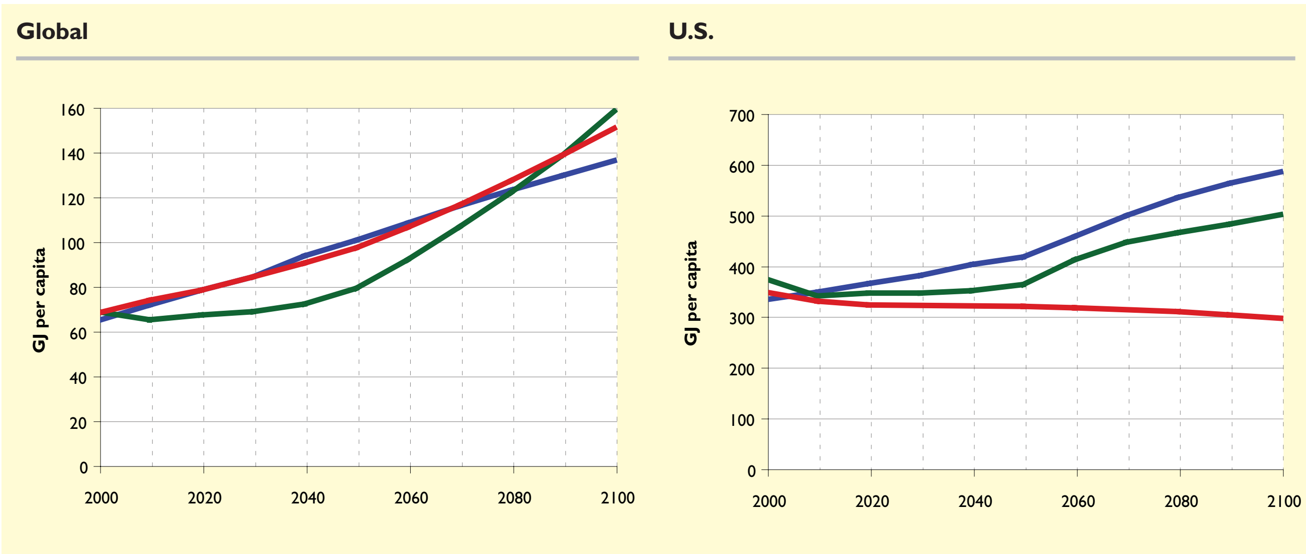


Figure 3.4. Global and U.S. Primary Energy Consumption per Capita Across Reference Scenarios (GJ per capita). All three reference scenarios include growing global per capita primary energy consumption. However, even after 100 years of growth, global per capita primary energy consumption is about ½ of the current U.S. level. U.S. per capita primary energy consumption varies more substantially among the reference scenarios. *[Note. Primary energy consumption from nuclear power and non-biomass renewable electricity are accounted for at the average efficiency of fossil-fired electric facilities, which vary over time and across scenarios.]*





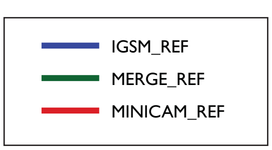
a relatively higher share of oil production (including unconventional oil); the MERGE reference scenario exhibits a relatively higher coal share; and the MiniCAM reference scenario exhibits a higher share for natural gas.

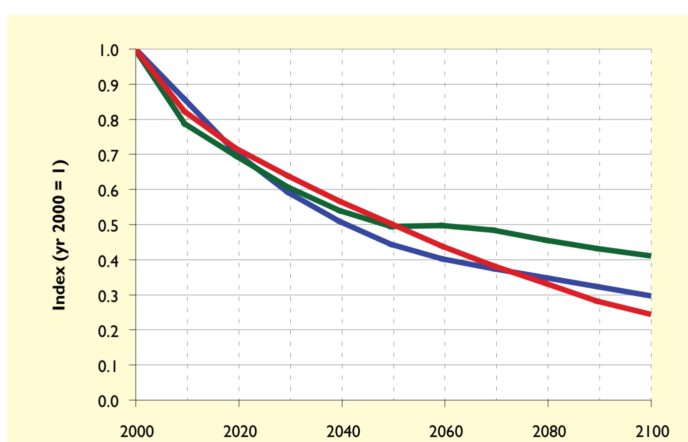
The relative contribution of oil to primary energy supply differs across the reference scenarios, but all three include a decline in the share of conventional oil. Thus, these scenarios represent three variations on a theme of energy transition precipitated by limited availability of conventional oil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

In the IGSM reference scenario, limits on the availability of conventional oil resources lead to the development of technologies to exploit unconventional oil, such as 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

Figure 3.5. U.S. Primary Energy Intensity: Consumption per Dollar of GDP Across Reference Scenarios (Index, yr 2000 = 1.0). U.S. total primary energy intensity – primary energy consumption per dollar of GDP – continues to decline in the reference scenarios. In recent decades, the rate of decline has been about 14% per decade. U.S. primary energy intensity declines about 12% per decade in the IGSM reference scenario, about 13% per decade in the MiniCAM reference scenario, and about 9% per decade in the MERGE reference scenario. *[Note. Primary energy consumption from nuclear power and non-biomass renewable electricity are accounted for at the average efficiency of fossil-fired electric facilities, which vary over time and across scenarios.]*





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 the MERGE and IGSM scenarios regarding primary oil thus reflects the role of coal liquefaction rather than a fundamentally different scenario of the need for liquid fuels.

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

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

The three reference scenarios tell different stories about non-fossil energy (much of which is covered below in the discussion of electricity generation). The IGSM reference scenario assumes political limits on the expansion of nuclear power, so it grows only to about 50% above 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 consumption.

In contrast, the MERGE reference 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 reference scenario. Non-biomass renewable energy supplies become increasingly competitive as well. In the MiniCAM reference scenario, bioenergy production is predominantly recycled wastes, with a modest contribution from commercial biomass farming toward the end of the century.

The three reference scenarios for the U.S. are similar in character to the global ones (Figure 3.3). The transition from conventional oil to alternative sources of liquid fuels and changes in electricity production affect energy markets and patterns in the U.S. However, primary energy consumption grows 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. The MERGE and IGSM reference scenarios have similar contributions from non-fossil energy, but the sources in the MERGE reference scenario are predominantly nuclear and other renewables, whereas it is biomass in the IGSM reference scenario. The MiniCAM reference scenario has the smallest overall contribution from non-fossil sources split relatively evenly between nuclear, biomass, and other renewables.

Trends in Fuel Prices

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

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

The three reference scenarios paint similar, but by no means identical, pictures of future energy prices. The price paths in the three reference scenarios reflect assumptions regarding both energy resources and energy technologies, and they shed light on these assumptions. For example, the price of oil is related to the marginal cost of bio-fuels, and the prices of both reflect, among other things, the technology options assumed to be available for their production.

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

Natural gas prices tell a similar story. Assumptions regarding the ultimately recoverable natural gas resource vary, as does the cost structure of the resource, leading to differences among the models. Like the demand for oil, the demand for natural gas grows, driven by increasing population and per capita incomes. As is the case for oil, the price of natural gas tends to be driven higher in the transition from inexpensive

Figure 3.6. Long-Term Historical Crude Oil Prices. Crude oil prices have historically been highly variable. *(Figure courtesy of James Williams, WTRG Economics)*

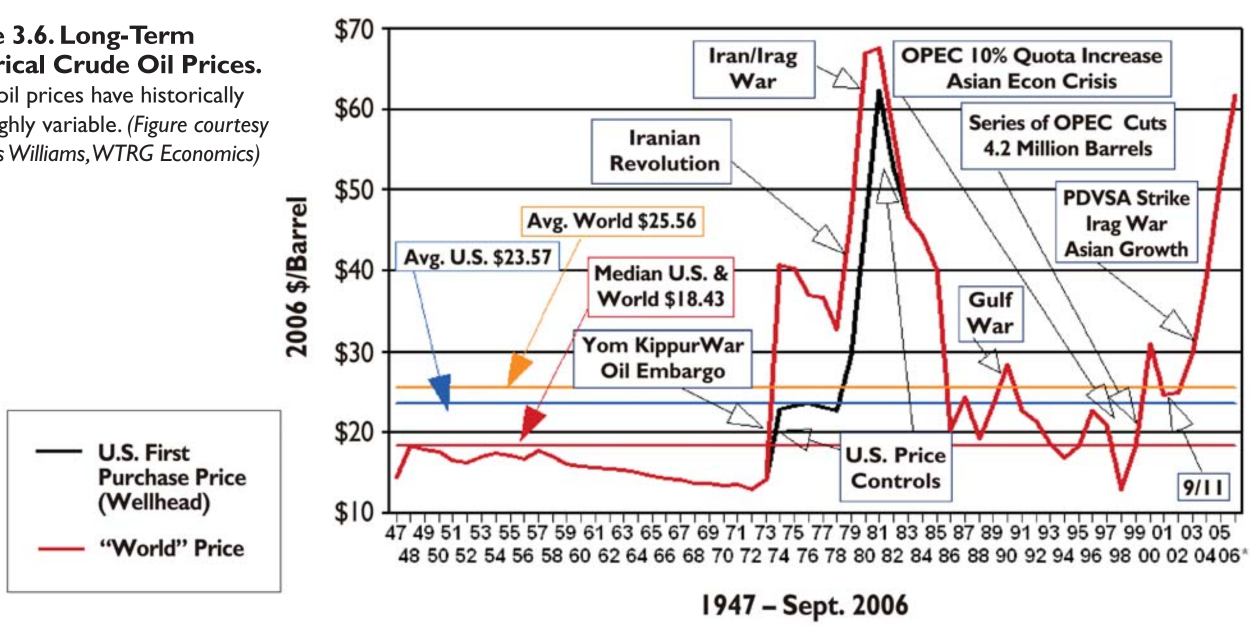
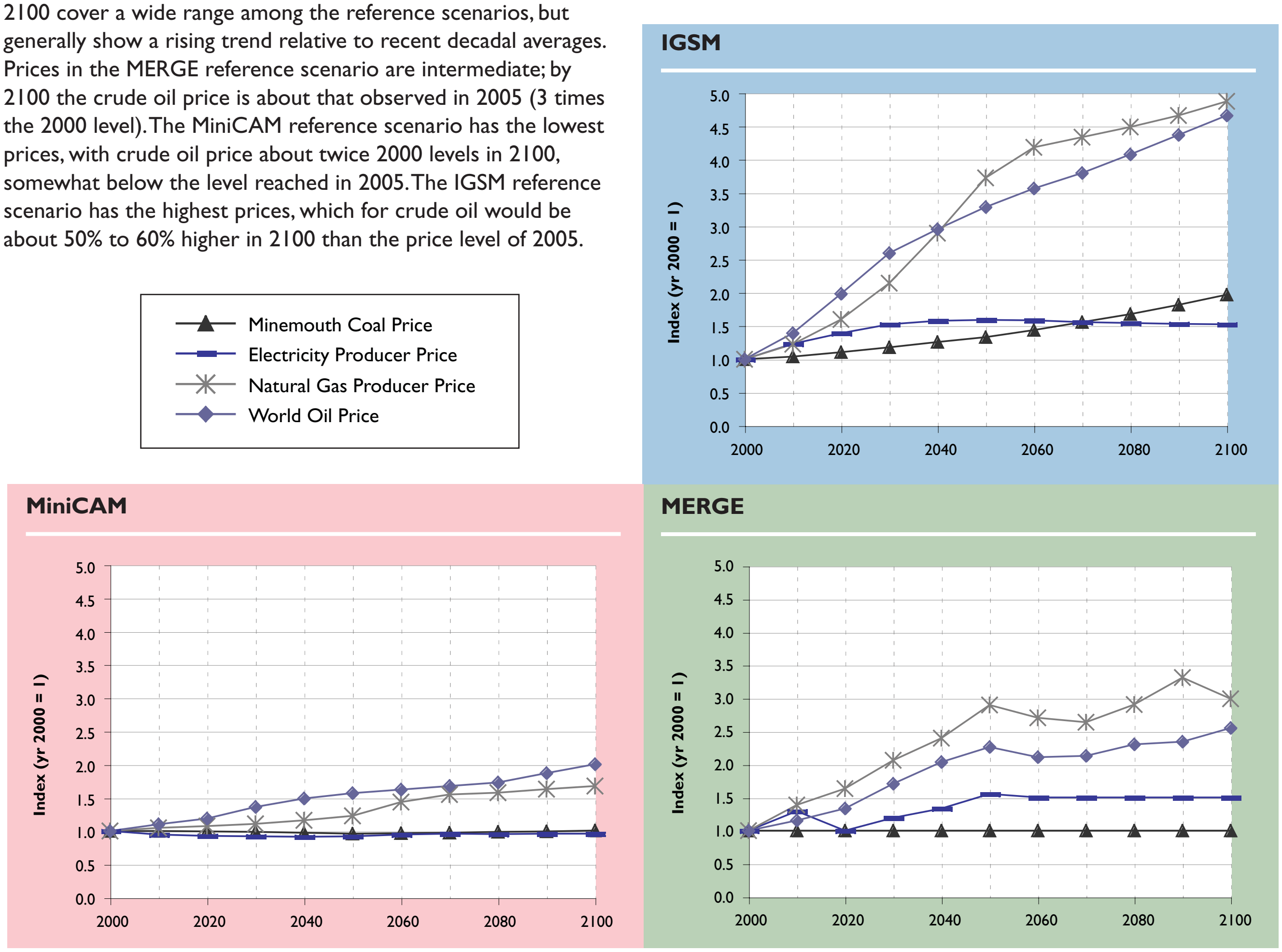


Figure 3.7. Indices of Energy Prices Across Reference Scenarios (Indexed to yr 2000 = 1.0). Energy prices through 2100 cover a wide range among the reference scenarios, but generally show a rising trend relative to recent decadal averages. Prices in the MERGE reference scenario are intermediate; by 2100 the crude oil price is about that observed in 2005 (3 times the 2000 level). The MiniCAM reference scenario has the lowest prices, with crude oil price about twice 2000 levels in 2100, somewhat below the level reached in 2005. The IGSM reference scenario has the highest prices, which for crude oil would be about 50% to 60% higher in 2100 than the price level of 2005.



conventional resources to less easily accessible grades of the resource and to substitutes, such as gas derived from coal or biological sources. The different degrees and rates of price escalation reflect different technology assumptions in the three reference scenarios.

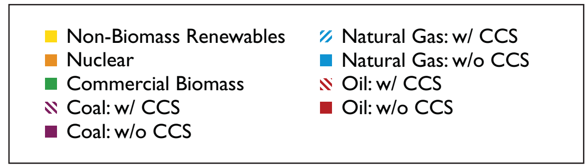
Coal prices do not rise as fast as oil and natural gas prices in any of the three reference scenarios. The reason is the abundance of the coal resource base. The different patterns of coal price movement with time in the three scenarios reflect differences in assumptions about the rate of resource depletion,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

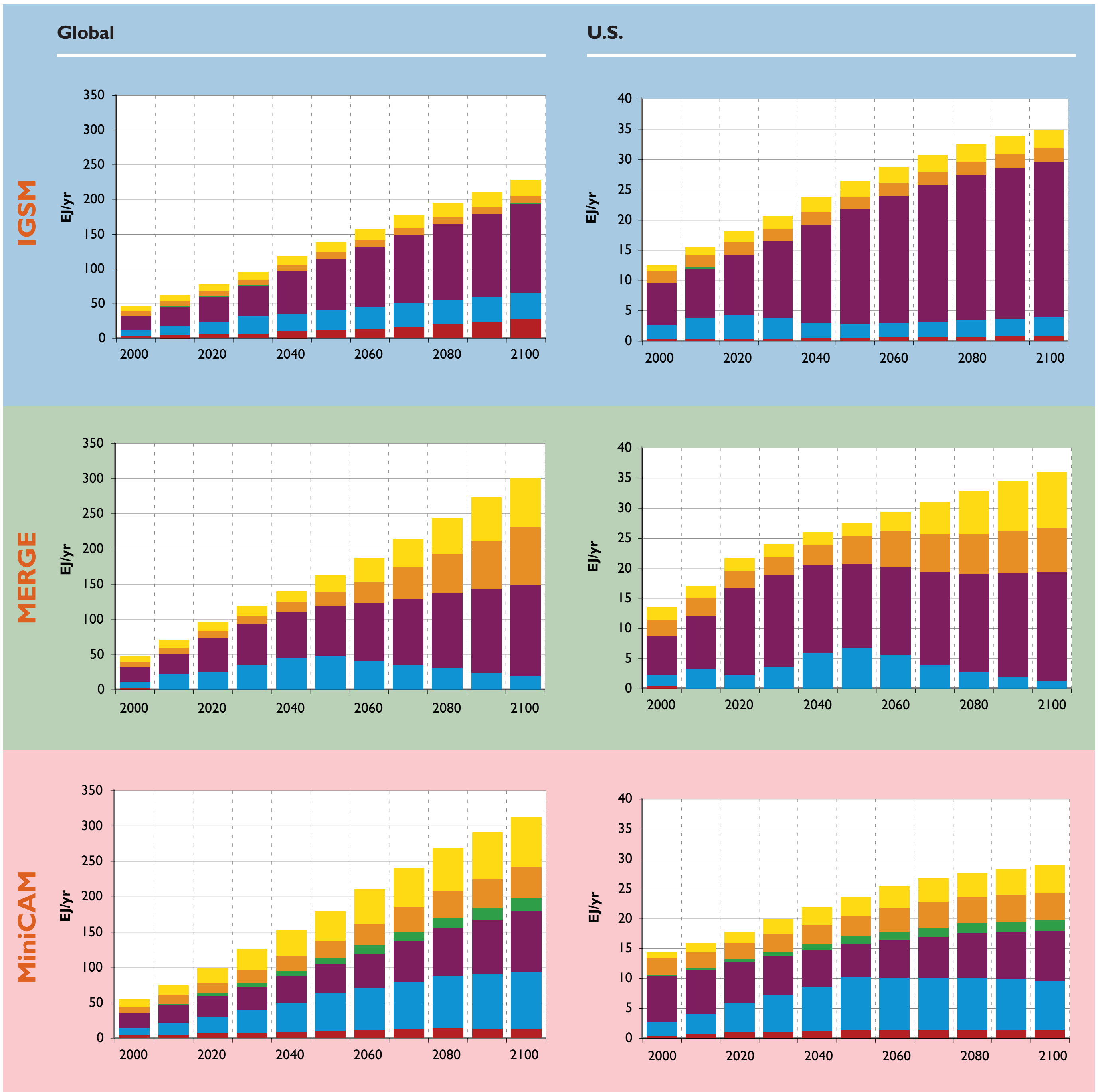
The stability of electricity prices compared with oil and natural gas prices is a reflection of the variety of technologies and fuels available to produce electricity, their improvement over time, and the fact that fuel is just one component of the cost of electricity. The details underlying this electric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

Electricity Production and Technology

Electricity production steadily increases in both the U.S. and the world in the reference scenarios, although the scale and generation mix differ among the three reference scenarios (Figure 3.8). All the reference scenarios depict a continued role for coal. The IGSM reference scenario is dominated by coal, which accounts for more than half of all power production by the end of the twenty-first century. This characteristic of the IGSM reference scenario is consistent with its limited growth in nuclear power. In contrast, nuclear power penetrates the market based on economic performance, and non-biomass renewable energy gains market share in the MERGE reference scenario. Limited natural gas resources lead to a peak and decline in gas

Figure 3.8. Global and U.S. Electricity Production by Source Across Reference Scenarios (EJ/yr of electricity). Global and U.S. electricity production in the reference scenarios show continued use of coal, especially the IGSM reference scenario, which assumes that nuclear energy expansion is limited by safety, waste, and proliferation concerns. The MERGE and MiniCAM reference scenarios are based on the assumption that nuclear energy is unconstrained by non-climate concerns, so these scenarios exhibit greater expansion. They also include greater contributions from renewable energy sources and somewhat greater use of electricity overall compared with IGSM reference scenario.





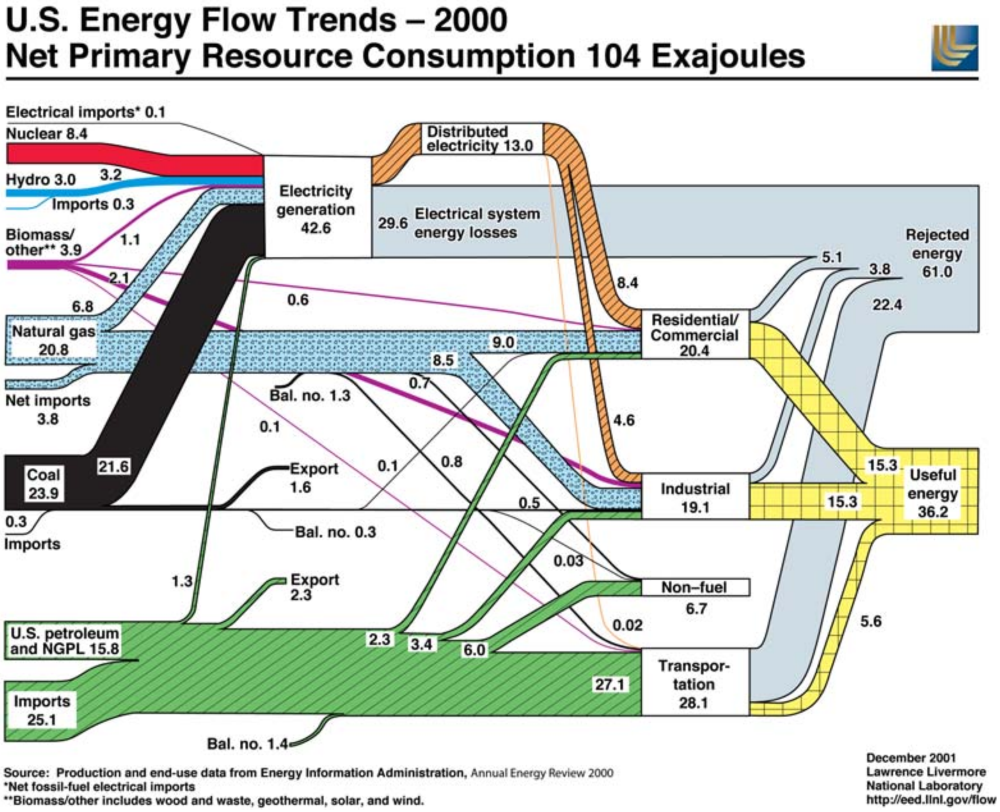


Figure 3.9. U.S. Energy Flow Diagram and Non-Electrical Energy Use for the Year 2000. Primary energy is transformed into different energy carriers that can easily be used for specific applications (e.g., space conditioning, light, and mechanical energy), but in the process losses occur. Of the 104 exajoules, of primary energy consumed in the U.S. in the year 2000, only an estimated 36 exajoules, were actually useful. Each of the models used in this research 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 falls in the reference scenarios.

use in the first half of the century. In the MiniCAM reference scenario, coal supplies the largest share of power, but natural gas is relatively abundant and provides a significant portion as well, as do nuclear and non-biomass renewable energy forms.

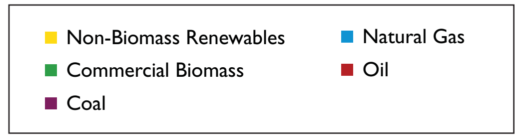
Non-Electric Energy Use

An important consideration in scenarios of the future energy system is conversion losses as relatively lower-grade resources are converted to higher-grade fuels for use in final applications such as space conditioning, lighting, and mechanical power. Figure 3.9 identifies the energy content of primary fuels for the U.S. in the year 2000 and where conversion losses occur. It shows the energy loss in the conversion from fuel to electricity to be 29.6 exajoules while the energy content of the electricity is 13.0 exajoules. Other losses occur when fuels are used to create the mechanical power to, for example, propel vehicles or when efficiency of conversion to heat, light, or mechanical energy is less that 100%. The potential for reducing such losses is one reason why energy intensity of the economy can continue to improve.

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

Figure 3.10 shows non-electric energy use in the reference scenario, and it is important to realize that these patterns of non-electric use also can imply significant conversion losses. This prospect plays a strong role in the MERGE reference scenario, in which coal and biomass go into liquefaction and gasification plants. To a lesser extent, these conversions are also present in the MiniCAM and IGSM scenarios. In addition, in the MiniCAM reference scenario some nuclear and renewable energy appears in non-electricity uses to produce hydrogen. In the IGSM and MiniCAM reference scenarios, oil

Figure 3.10. Global and U.S. Primary Energy Consumption in Non-Electric Applications Across Reference Scenarios (EJ/yr). As with electricity production, non-electric energy consumption remains heavily dependent on fossil fuels with some penetration of biomass energy. Primary energy is reported here, and the resurgence of coal in the reference scenarios is due to its use to produce synthetic liquids or gas. *[Notes. Oil consumption includes that derived from tar sands and oil shales, and coal consumption includes that used to produce synthetic liquid and gaseous fuels.]*



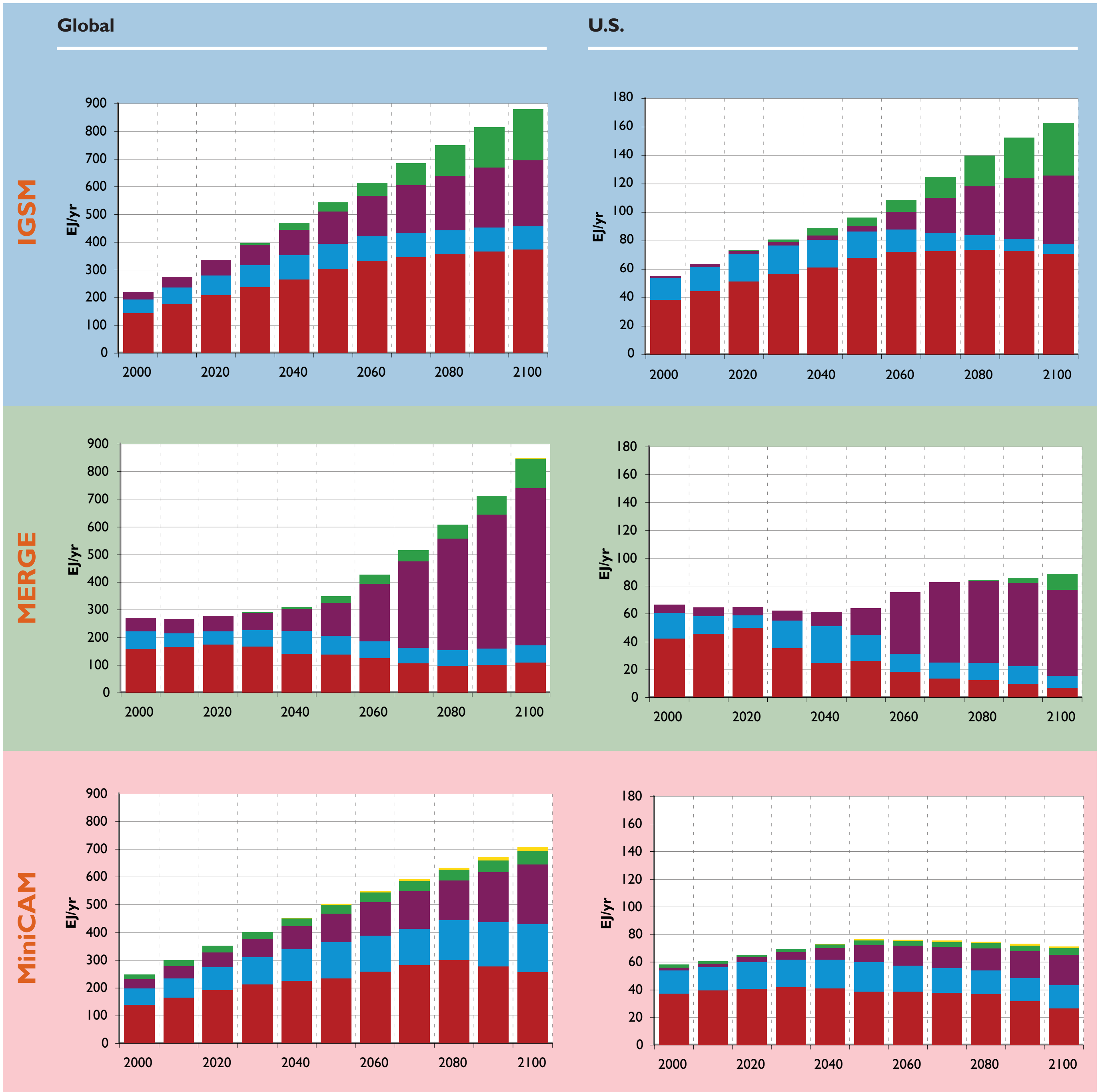
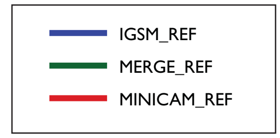
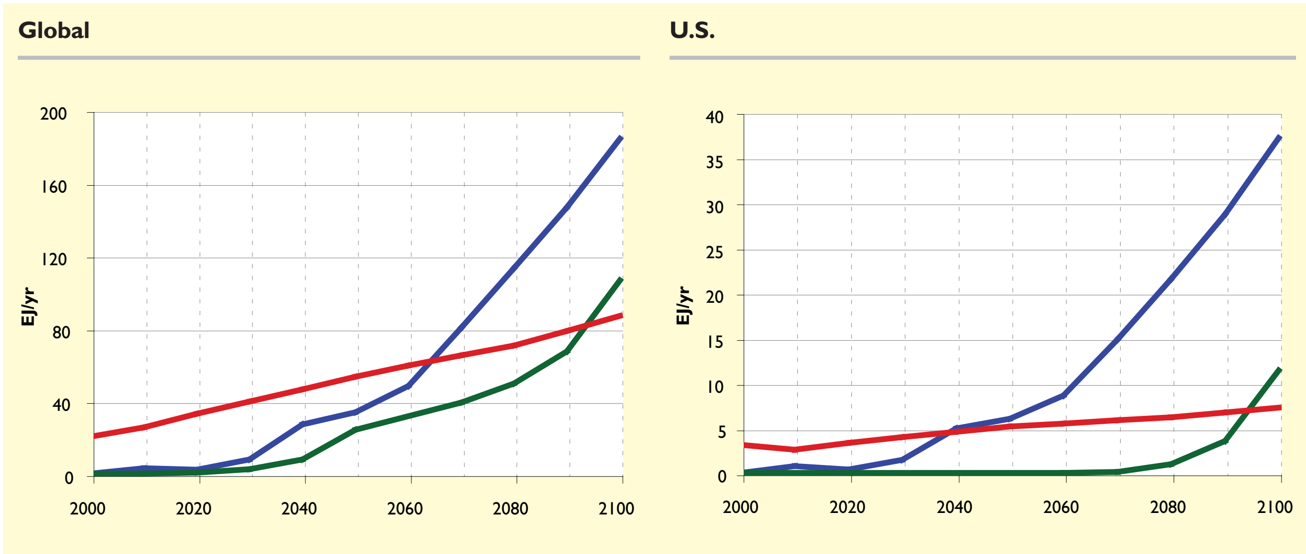


Figure 3.11. Global and U.S. Production of Biomass Energy Across Reference Scenarios (EJ/yr). The MiniCAM scenarios include waste-derived biomass fuels as well as commercial biomass and, thus, show significant use in 2000. The IGSM and MERGE scenarios include only commercial biomass energy beyond that already used. Globally, the IGSM and MERGE reference scenarios include more biomass production than does the MiniCAM reference scenario toward the end of the century.





use is the largest single non-electric energy source, reflecting continued 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.

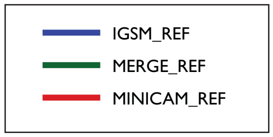
LAND USE AND LAND-USE CHANGE

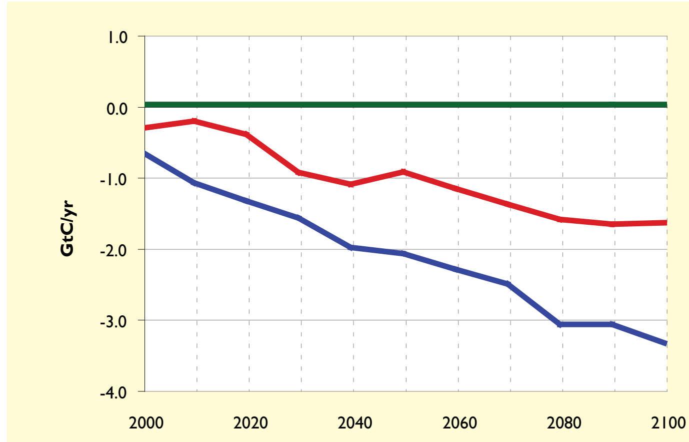
The three reference scenarios take different approaches to emissions from land use and land-use change. The MERGE reference scenario assumes that the biosphere makes no net contribution to the carbon cycle. In the IGSM and MiniCAM reference scenarios, the net contribution of the terrestrial biosphere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

An important aspect of land use and land-use change in the scenarios from all three modeling groups is the production of bio-fuels for energy. Both IGSM and MiniCAM take account of the competition for scarce land resources in developing scenarios of bioenergy production and consumption. MERGE takes the availability of bio-fuels as an exogenous input based on extra-model analysis. Global and U.S. biomass production is displayed in Figure 3.11. The IGSM and MiniCAM scenarios use somewhat different definitions, which account for the difference in 2000. The numbers presented for the IGSM scenarios account only the production of biomass energy beyond that now used and do not include traditional use of biomass or, for example, the own-use of wood wastes for energy in the forest products industry. The MiniCAM scenarios explicitly account for some current uses of biomass energy, such as that used in the pulp and paper industry, and separately consider the future potential for bio-fuels derived from wastes and residue along with energy crops grown explicitly for their energy content.

Apparent differences among the models need to be considered in light of this differential accounting. In the MiniCAM reference scenario, biomass production tends to be higher in early years because it is accounting waste and residue-derived bio-fuels explicitly. These waste and residue-derived bio-fuels account for all of the biomass production in the MiniCAM refer-

Figure 3.12. Global Net Emissions of CO_2 from Terrestrial Systems Including Net Deforestation Across Reference Scenarios (GtC/yr). Global net emissions of CO_2 from terrestrial systems, including net deforestation, serve as a slight net sink in 2000 that grows over time in the IGSM and MiniCAM reference scenarios, mainly because of reduced deforestation and CO_2 fertilization of plants. The MERGE scenarios assume a neutral terrestrial system.





ence scenario in the early part of the century and the majority of all biomass production at the end of the century. The IGSM reference scenario exhibits strong growth in bio-fuels production beginning after the year 2020. Deployment in the IGSM reference scenario is driven primarily by a world oil price that in the year 2100 is over 4.5 times the price in the year 2000. In contrast, the MiniCAM reference scenario, with its lower long-term world oil price, includes insufficient incentive to create a substantial market for biomass crops. However, the MiniCAM reference scenario does include 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 the IGSM scenarios. Thus, in the IGSM scenarios commercial biomass production must compete with other agricultural activities for cultivated land, but the extent of cultivated land does not change from scenario to scenario. Because the land-use pattern is fixed in the IGSM scenarios, changes in the net flux of carbon to the atmosphere reflect the behavior of the terrestrial ecosystem in response to changes in CO_2 and climatic effects that are considered within the IGSM's Earth system component. Taken together, these effects lead to the negative net emissions from the terrestrial ecosystem (Figure 3.12), which contrasts with the neutral biosphere assumed in the MERGE reference scenario. (Note that one tonne C is equivalent to 3.67 tonnes CO_2. See Box 3.2 for more on converting between units of carbon and units of CO_2.)

MiniCAM uses the terrestrial carbon cycle model of MAGICC (Wigley and Raper 2001, Wigley and Raper 2002) 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, the MiniCAM scenarios exhibit the same types of CO_2 fertilization effects as the IGSM scenarios, but they also represent interactions between the agriculture sector and the distribution of natural terrestrial carbon stocks.

EMISSIONS, CONCENTRATIONS, AND RADIATIVE FORCING

The growth in the global economy in the reference scenarios and the changes in the composition of the global energy system lead to growing emissions of GHGs over the century. Emissions from fossil fuel burning and cement production more than triple from 2000 to 2100 in all three reference scenarios. With growing emissions, GHG concentrations rise substantially over the twenty-first century, with CO_2 concentrations increasing by 2½ to over 3 times preindustrial levels. Increases in non-CO_2 GHG concentrations vary more widely across the reference scenarios. Radiative forcing from the GHGs considered in this research reaches 6.4 W/m^2 to 8.6 W/m^2 from preindustrial by 2100, with the non-CO_2 GHGs accounting for 20% to 25% of the instantaneous forcing in 2100.

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

Greenhouse Gas Emissions

Calculating Greenhouse Gas Emissions

Emissions of CO_2 from fossil fuels are the sum of emissions from each of the different fuel types, and for each type, emissions are the product of a fuel-specific emissions coefficient and the total combustion of that fuel. Exceptions to this treatment occur if a fossil fuel is used in a non-energy application (e.g., as a feedstock for plastic) or if the carbon is captured and stored in isolation from the atmosphere. All three of the modeling groups assumed the availability of CCS technologies and treated the leakage from such storage as zero over the time period considered in this research, although they assumed that carbon capture technologies capture and store less than 100% of the CO_2. CCS increases the costs of electricity production with no attendant benefits, absent actions to constrain carbon emissions, so CCS is not deployed in any of the reference scenarios.

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

The calculation of net emissions from terrestrial ecosystems, including land-use change, is more complicated, and each model employs its own technique. IGSM 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 scenarios, therefore, incorporate fluxes to the atmosphere as a dynamic response of managed and unmanaged terrestrial systems to the changes in the climate and atmospheric composition.

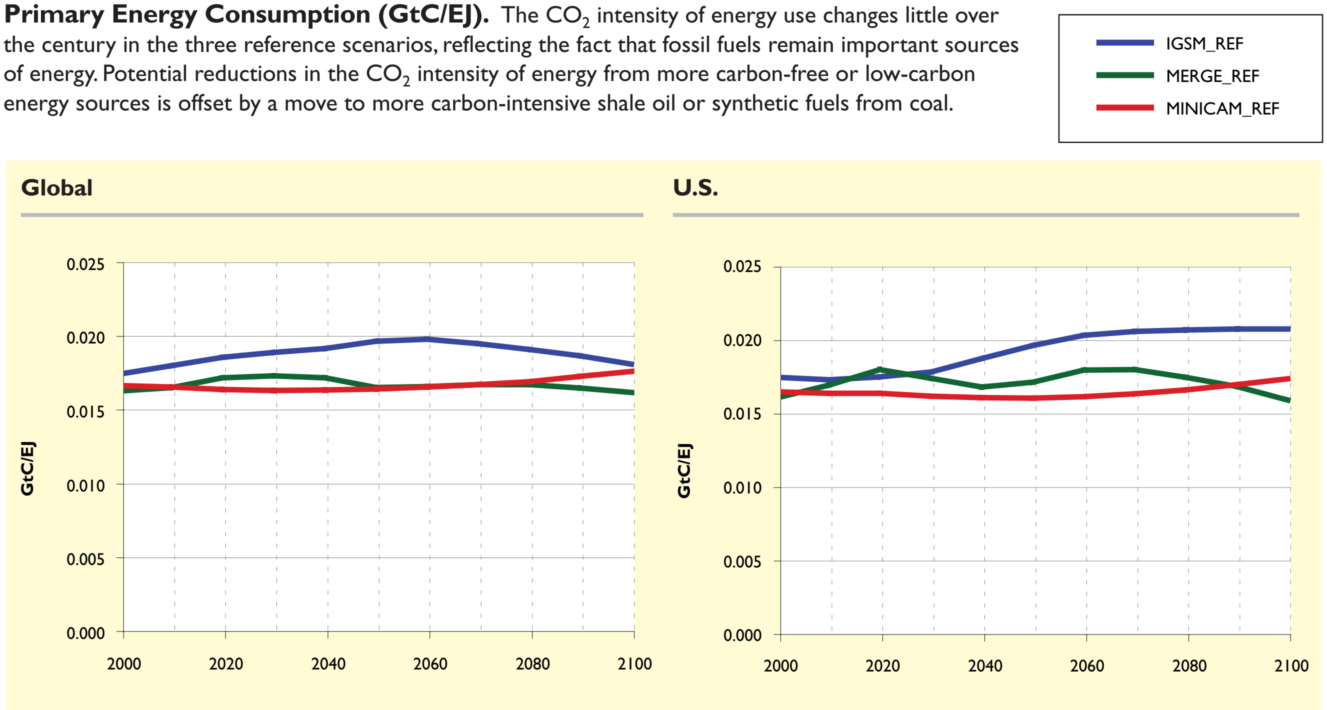
MiniCAM builds its net terrestrial carbon flux by summing both emissions from changes in the stocks of carbon from human-induced land-use change and the natural system response, represented in the reduced-form terrestrial carbon module of MAGICC. As noted above, MiniCAM employs a simpler reduced-form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

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

Reference Scenarios of Fossil Fuel CO_2 Emissions

All three reference scenarios include 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 (Figure 3.13). While the particulars of the reference scenarios differ, no reference scenario shows a dramatic reduction in carbon intensity over this century.

Figure 3.13. Global and U.S CO_2 Emissions from Fossil Fuel Combustion and Industrial Sources Relative to Primary Energy Consumption (GtC/EJ). The CO_2 intensity of energy use changes little over the century in the three reference scenarios, 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 synthetic fuels from coal.



Substantial increases in total energy use with no or little decline in carbon intensity lead to substantial increases in CO_2 emissions per capita (Figure 3.14) and in global totals (Figure 3.15). Emissions of CO_2 from fossil fuel use and industrial processes increase from less than 7 GtC/yr in 2000 to between 22.5 and 24.0 GtC/yr by 2100. These global emissions are higher than in many earlier studies such as IS92a, where emissions were 20 GtC/yr in 2100 (Leggett et al. 1992). Global emissions from these reference scenarios are closer to those from the higher scenarios in the IPCC SRES (Nakicenovic et al. 2000); particularly those included under the headings A1FI and A2. U.S. emissions trajectories are more varied than the global trajectories. By 2100, U.S. emissions are between 2 GtC/yr and 5 GtC/yr.

The three reference scenarios display a larger share of emissions growth outside of the Annex I nations – the developed nations of the OECD as well as Eastern Europe and the former Soviet Union[1] (Figure 3.16). Annex I emissions are highest and Non-Annex I emissions lowest in the IGSM reference scenarios. At least in part, this is because of two factors underlying the

BOX 3.2 Reporting Conventions for Carbon Emissions and Prices

Two different conventions have been used to report emissions and prices in past studies of CO_2 emissions and concentrations. One convention is based on the total mass of emitted CO_2. Emissions are commonly expressed in tonnes of CO_2 and prices in terms of dollars per tonne of CO_2. The second convention is based on the carbon component of the emitted CO_2. Emissions are expressed in tonnes of carbon and prices in terms of dollars per tonne of carbon. This report uses the second approach throughout. In contrast, emissions of non-CO_2 GHGs, such as CH_4 or N_2O, are reported in terms of their full mass.

It is important to be clear on which convention is used, but it is easy to convert between the two based on the molecular composition of CO_2. One molecule of CO_2 includes one carbon atom, with a molecular weight of 12, and two oxygen atoms, each with a molecular weight of 16. The total molecular weight of CO_2 is therefore 44, and carbon represents 12/44 of this weight. Emissions expressed in terms of CO_2 are therefore larger than when expressed in terms of the carbon component of CO2: one tonne of CO_2 is equivalent to 44/12, or 3.67, tonnes of carbon. Conversely, emissions prices are lower when reported in units of CO_2 because the price must be spread over a larger weight; $100 per tonne of carbon is equivalent to $27 per tonne of CO_2.

[1] Annex I is defined in the U.N. Framework Convention on Climate Change (FCCC [UN 1992]). 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 groups may not precisely align with the present partition of the world's nations. However, the quantitative implications of these differences are small.

Figure 3.14. Global and U.S. Emissions of CO_2 from Fossil and Other Industrial Sources per Capita Across Reference Scenarios (tonnes per capita). Global per capita fossil fuel and industrial CO_2 emissions grow in all three reference scenarios. However even after 100 years of growth, global per capita CO_2 emissions are slightly less than ½ of the 2000 U.S. level in the three scenarios. There is greater divergence in U.S. CO_2 emissions per capita over the century among the reference scenarios.

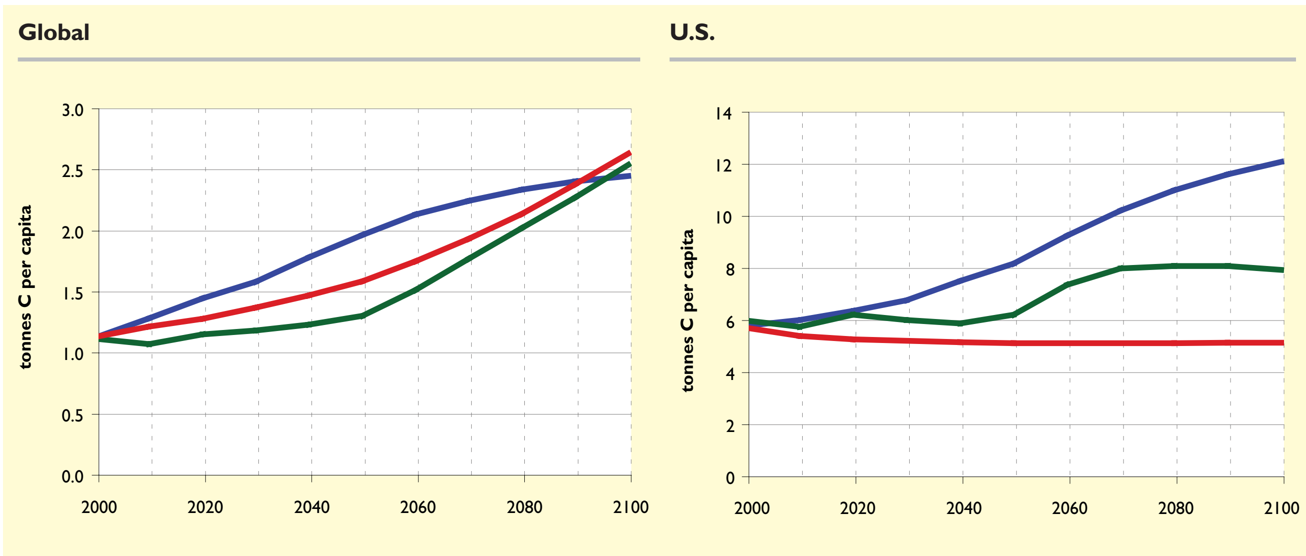
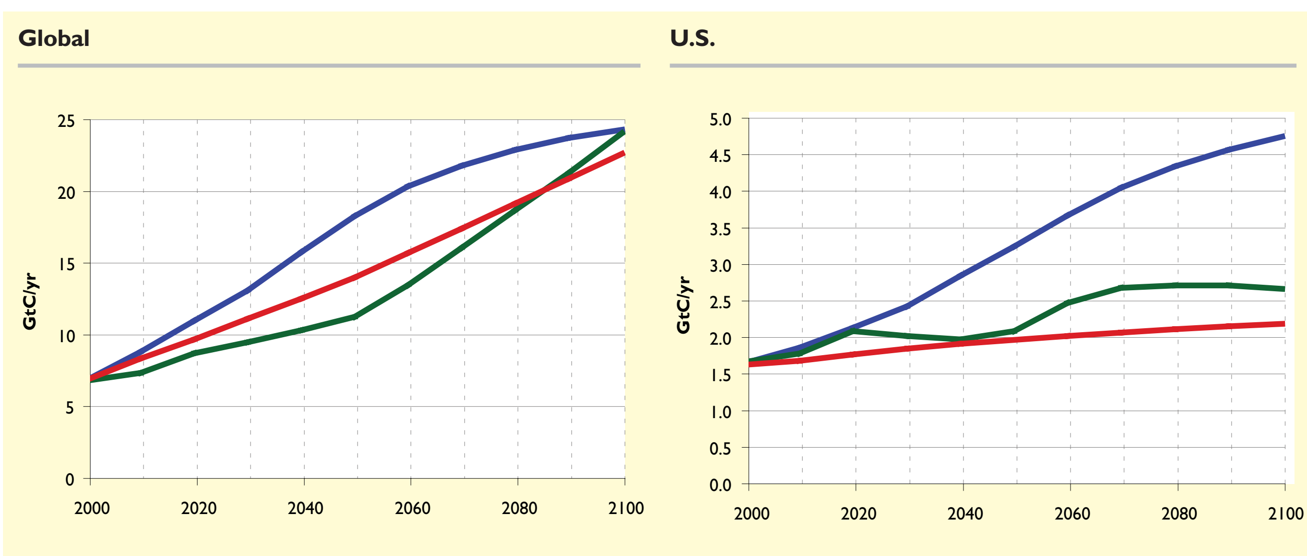


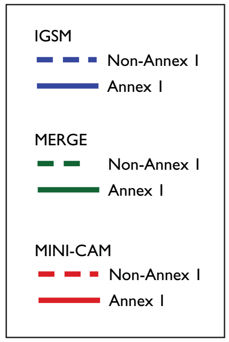
Figure 3.15. Global and U.S. Emissions of CO_2 from Fossil Fuels and Industrial Sources (CO_2 from land-use change excluded) Across Reference Scenarios (GtC/yr). Global emissions of CO_2 from fossil fuel combustion and other industrial sources, mainly cement production, grow throughout the century in all three reference scenarios. By 2100, global emissions are between 22.5 GtC/yr and 24.0 GtC/yr. U.S. emissions are more varied across the reference scenarios. By 2100, U.S. emissions are between 2 GtC/yr and 5 GtC/yr. Note that CO_2 from land-use change is excluded from this figure.

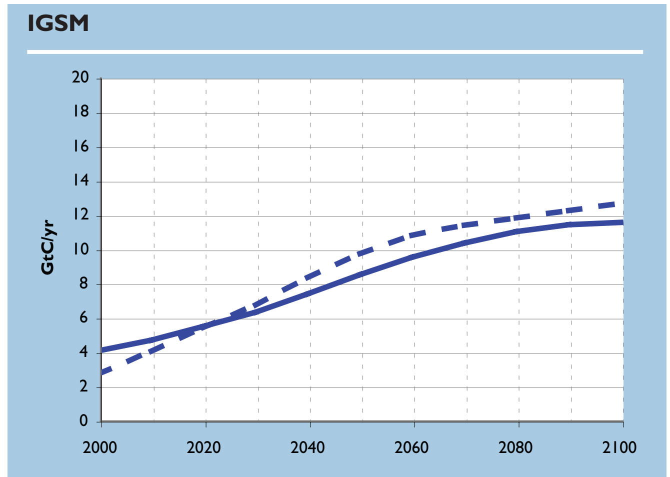


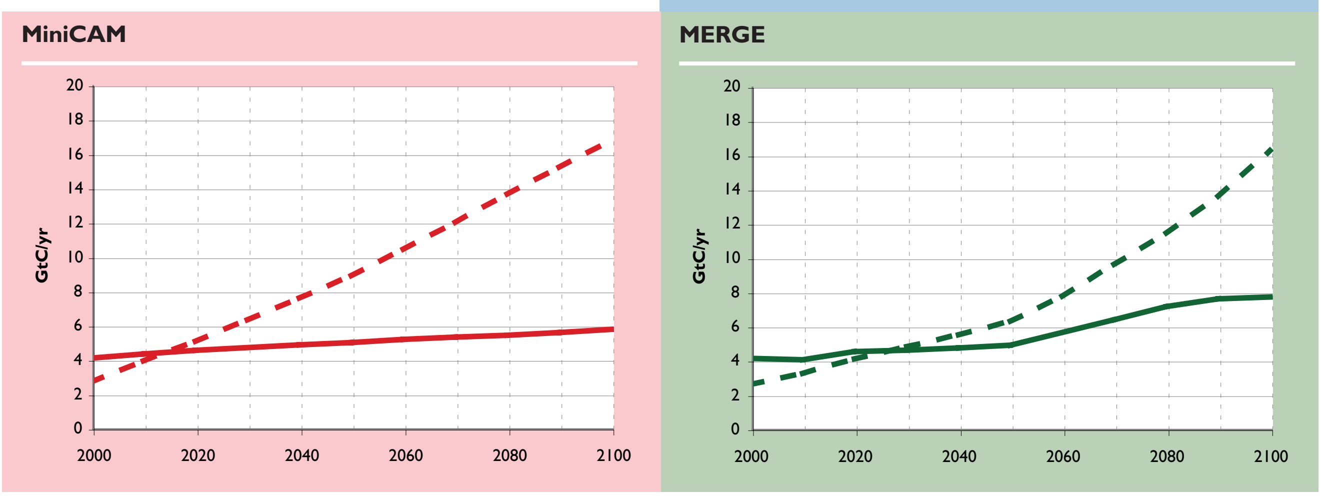
IGSM scenarios. First, the demand for liquids is satisfied by expanding production of unconventional oil, which has relatively high carbon emissions at the point of production. The U.S., with major resources of shale oil, switches from being an oil importer to an exporter but is responsible for CO_2 emissions associated with shale oil production. Second, assumed rates of productivity growth in Non-Annex I nations are lower in the IGSM scenarios than in those of the other two models.

In contrast, the MERGE reference scenario assumes that liquids come primarily from coal, a fuel that is more broadly distributed around the world than unconventional oils. The MERGE

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







scenarios also exhibit higher rates of labor productivity in the Non-Annex I nations than the IGSM scenarios. Finally, the MERGE reference scenario has a greater deployment of nuclear power, leading to a lower carbon-to-energy ratio. These three features combine to produce lower Annex I emissions and higher Non-Annex I emissions than in the IGSM reference scenario. The MiniCAM reference scenario has Annex I emissions similar to those of the MERGE reference scenario, but higher Non-Annex I emissions.

The range of global fossil fuel and industrial CO_2 emissions across the three reference scenarios is relatively narrow compared with the uncertainty inherent in these developments over a century. While it is beyond the scope of this research 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 to 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. 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 constructing the collection in the figure to weight scenarios for the quality of underlying analysis. Scenarios for which no underlying trajectories of population or GDP are available are mixed in with efforts that incorporate the combined wisdom of a large team of interdisciplinary researchers working over the course of years. Moreover, it is not clear that the observations are independent.

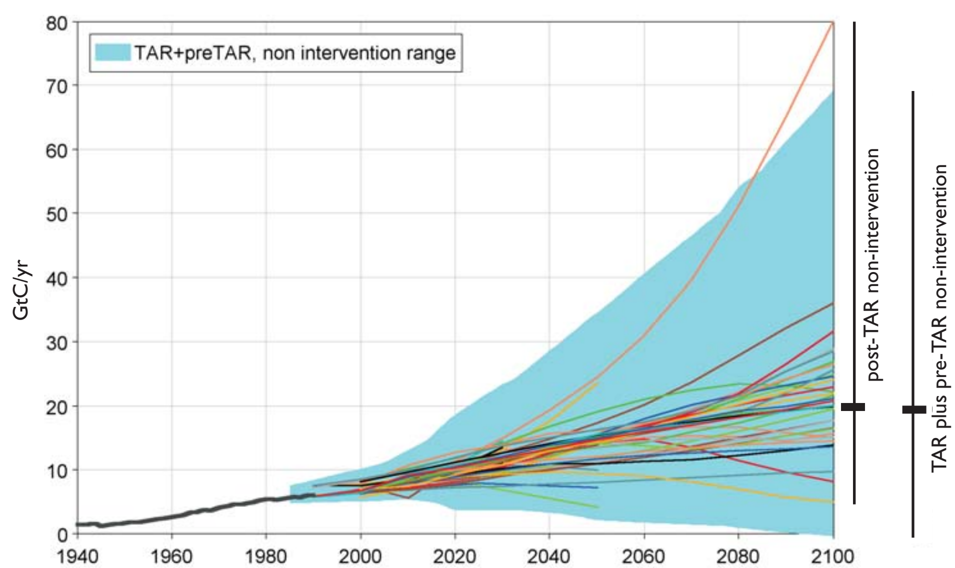


Figure 3.17. Global Emissions of CO_2 from Fossil Fuel and Industrial Sources: Historical Development and Scenarios (GtC/yr). The 284 non-intervention, or reference, scenarios published before 2001 are included in the figure as the blue-shaded range. The thin lines are an additional 55 non-intervention scenarios published since 2001. Two vertical bars on the right-hand side indicate the ranges for scenarios since 2001 (post-TAR non-intervention) and for those published up to 2001 (TAR plus pre-TAR non-intervention). *Source: Figure 4, Nakicenovic et al. 2006, with kind permission of Springer Science and Business Media.*

The clustering of year 2100 fossil fuel and industrial CO_2 emissions around 20 GtC/yr in both the pre- and post-IPCC TAR time frames coincides closely with the IPCC IS92a scenario. Many later scenarios were simply tuned to it, so are not independent assessments. For these reasons and others, looking to the open literature can provide some information, but caution in interpreting literature compilations is warranted.

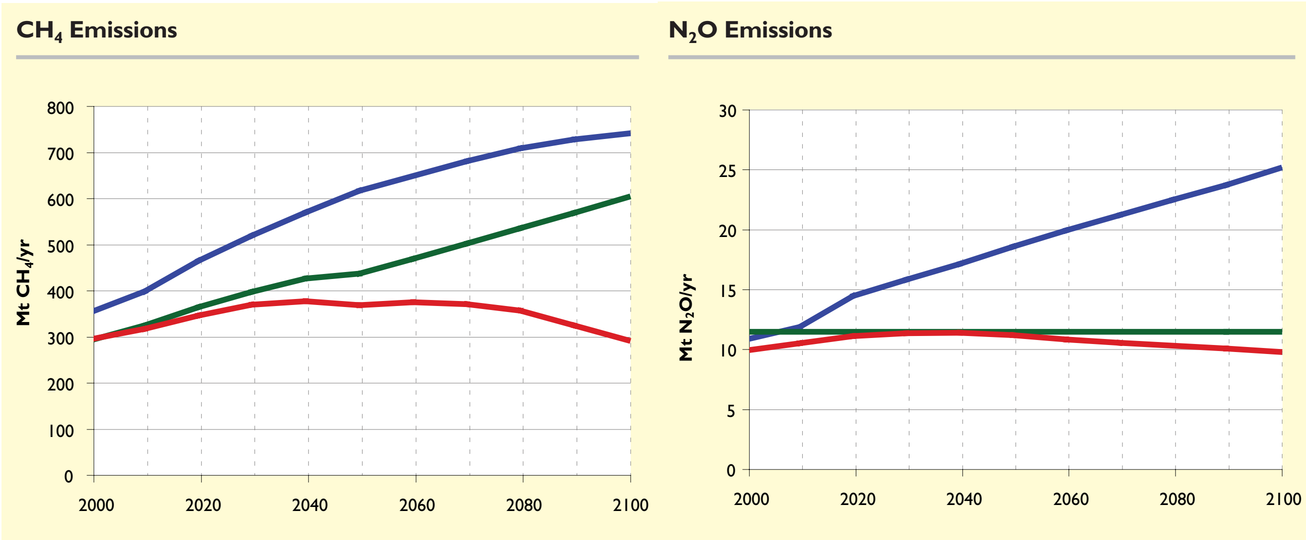
Another approach to provide a context is systematic uncertainty analysis. There have now been several such analyses, including efforts by Nordhaus and Yohe (1983), Reilly et al. (1987), Manne and Richels (1994), Scott et al. (2000), and Webster et al. (2002). These studies contain many valuable lessons and insights. For the purposes of this research, one useful product of these uncertainty studies is an impression of the position of any one scenario within the window of futures that might pass a test of plausibility. Also useful is the way that the distribution of outcomes is skewed upward – 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 (Webster 2003).

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 (Figure 3.18). Base-year emissions in the MERGE and MiniCAM reference scenarios are similar for N_2O but diverge for CH_4. In the IGSM reference scenario, CH_4 emissions are higher in the year 2000 than in the other scenarios, reflecting an independent assessment of historical emissions and uncertainty in the scientific literature regarding even historic emissions. Note that the IGSM reference scenario has a correspondingly lower natural CH_4 source (from wetlands and termites) that is not shown in Figure 3.18, balancing the observed concentration change, rate of oxidation, and natural and anthropogenic sources.

Both the IGSM and MERGE reference scenarios exhibit steadily growing CH_4 emissions throughout the twenty-first century as a consequence of the growth of CH_4-producing activities such as ruminant livestock herds, natural gas use, and landfills. Unlike CO_2, for which the combustion of fossil fuels without CCS leads inevitably to emissions, 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 CH_4 production, emissions control technologies will be deployed in response

Figure 3.18. Global CH_4 and N_2O Emissions Across Reference Scenarios (Mt CH_4/yr and Mt N_2O/yr). Global anthropogenic emissions of CH_4 and N_2O vary widely among the reference scenarios. There is uncertainty in year 2000 CH_4 emissions, with the IGSM reference scenario ascribing more of the emissions to human activity and less to natural sources. Differences in the scenarios 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.



to local environmental regulations and in response to the economic value of CH_4. For this reason, CH_4 emissions peak and decline in the MiniCAM reference scenario.

Future Scenarios of Anthropogenic F-Gas Emissions

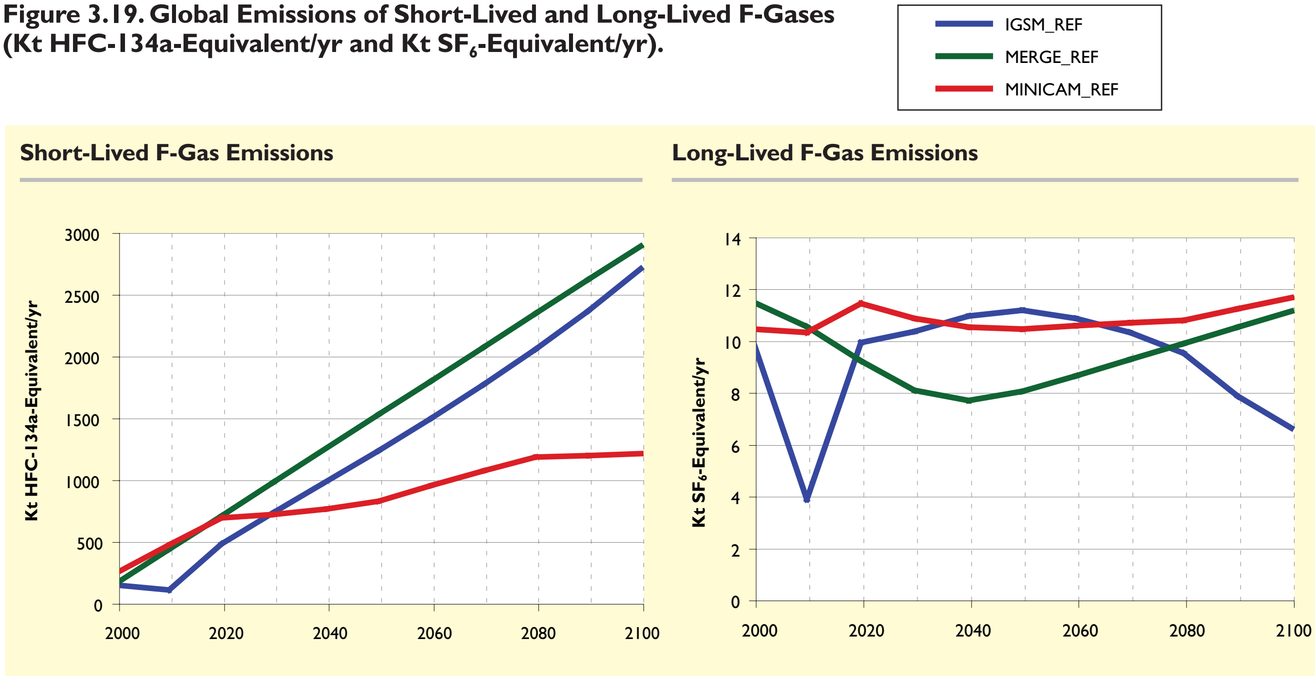
A set of industrial products that act as GHGs are combined under the term, F-gases, which refers to an element that is common to them, fluorine. Several are replacements for the CFCs that have been phased out under the Montreal Protocol. They are usefully divided into two groups: (1) a group of HFCs, most of which are short-lived, and (2) the long-lived PFCs and SF_6. Figure 3.19 presents the reference scenarios for these GHGs. The IGSM and MERGE reference scenarios exhibit strong growth in the short-lived species, while the MiniCAM reference scenario exhibits about half as much growth over the century. Emissions of the long-lived gases are very similar among the reference scenarios. PFCs are used in semiconductor production and are emitted as a byproduct of aluminum smelting; they can be avoided relatively cheaply. Emissions from the main use of SF_6 in electric switchgear can easily be abated by recycling to minimize venting to the atmosphere. Many of the abatement activities have already been undertaken, and the modeling groups assumed they will continue to be used.

The Carbon Cycle: Net Ocean and Terrestrial CO_2 Uptake

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

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

Figure 3.19. Global Emissions of Short-Lived and Long-Lived F-Gases (Kt HFC-134a-Equivalent/yr and Kt SF_6-Equivalent/yr).



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 regrowth, and the net effects of atmospheric CO_2 and climate conditions on vegetation. As noted earlier, MERGE employs a neutral biosphere: by assumption, its net uptake is zero with processes that store carbon assumed to just offset those that release it. Taken together with its more active ocean system in the reference scenario, the behavior of the carbon cycle in total is similar to the other two models, especially MiniCAM. IGSM and MiniCAM employ active terrestrial biospheres, which on balance remove carbon from the atmosphere (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 and MiniCAM reference scenarios also include feedback effects of a changing climate.

Greenhouse Gas Concentrations

Radiative forcing is related to the concentrations of GHGs in the atmosphere. The relationship between emissions and concentrations of GHGs is discussed in Box 2.2. The concentration of gases that reside in the atmosphere for long pe-

Figure 3.20. CO_2 Uptake from Oceans Across Reference Scenarios (GtC/yr, expressed in terms of net emissions). The IGSM reference scenario, which is based on the IGSM's three-dimensional ocean model, exhibits less CO_2 uptake than the other two reference scenarios and, after some point, little additional increase in uptake even though concentrations are rising. The MiniCAM reference scenario exhibits some slowing of ocean uptake, although not as pronounced as in the IGSM reference scenario. There is no slowing of uptake in the MERGE reference scenario. Although the MERGE reference scenario has higher ocean uptake in the latter half of the century, the effects of this increase are offset by the assumption of a neutral biosphere. Hence the aggregate behavior of its carbon cycle tends to be more similar to that in the other two reference scenarios, especially the MiniCAM reference scenario (Figure 3.22). The three ocean models produce more similar behavior in the stabilization scenarios.

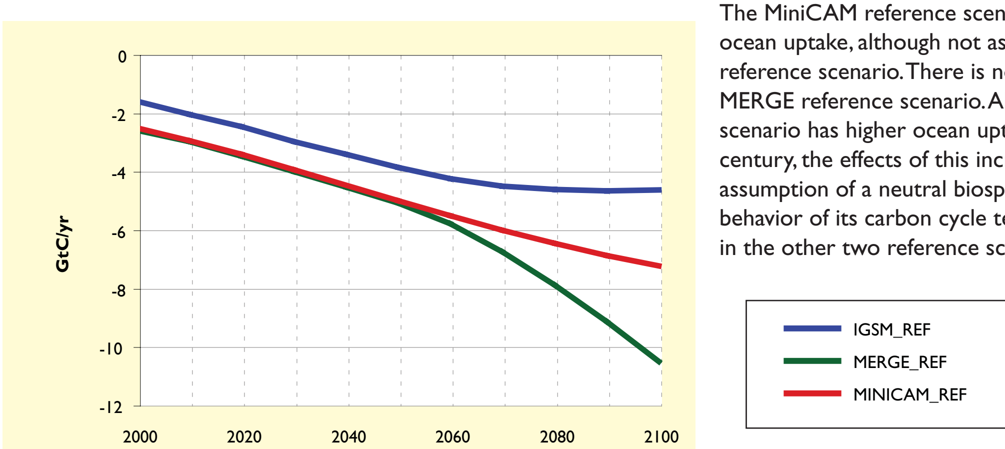
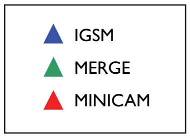
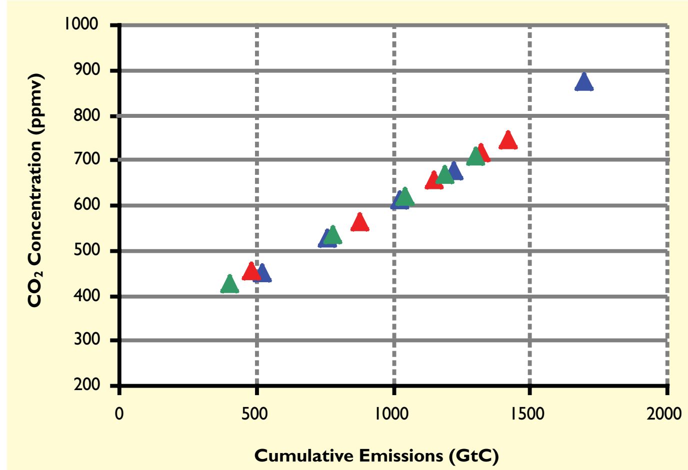


Figure 3.21. Relationship Between Cumulative CO_2 Emissions from Fossil Fuel Combustion and Industrial Sources, 2000-2100, and Atmospheric CO_2 Concentration in 2100 Across All Scenarios. Despite differences in how the carbon cycle is handled in each of the three models, the scenarios exhibit a very similar response in terms of concentration level for a given level of cumulative emissions. *[Note. The cumulative emissions do not include emissions from land use and land-use change].*





riods of time – decades to millennia – is 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 the three reference scenarios and the twelve stabilization scenarios, are plotted against the CO_2 concentration in the year 2100. The plots for all three models lie on essentially the same line, indicating that despite considerable differences in representation of the processes that govern CO_2 uptake, the aggregate response to increased emissions is very similar. This basic linear relationship also holds for other long-lived gases, such as N_2O, SF_6, and the other long-lived F-gases.

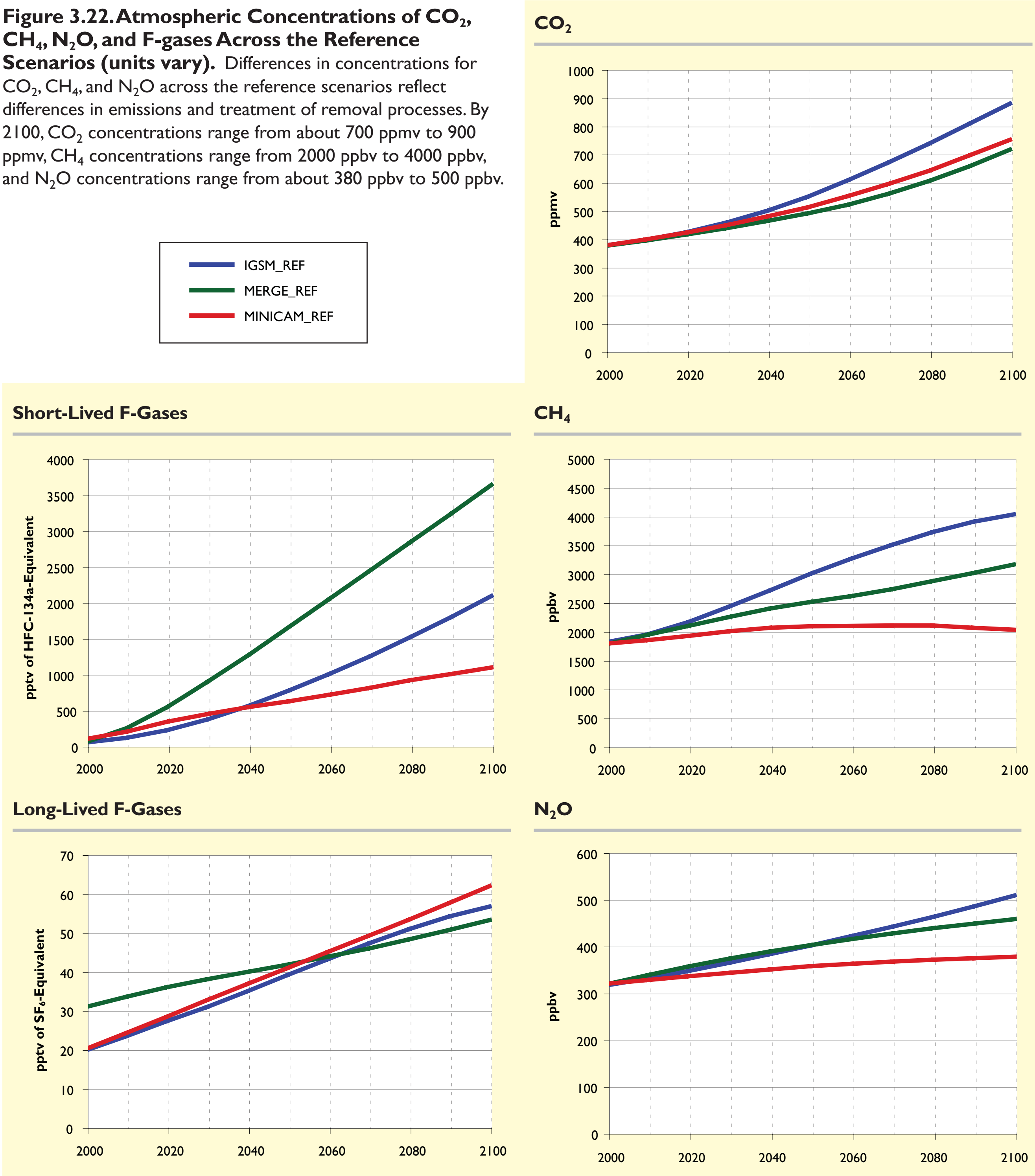
GHG concentrations rise in all three reference scenarios. CO_2 concentrations increase from 370 ppmv in year 2000 to somewhere in the range of 700 to 875 ppmv in 2100 (Figure 3.22). The preindustrial concentration of CO_2 was approximately 280 ppmv. While all three reference scenarios display the same 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).

Increases in the concentrations of the non-CO_2 GHGs vary across the reference scenarios. The concentrations of CH_4 and N_2O in the MiniCAM reference scenario are on the low end of the range, reflecting assumptions discussed above about use of CH_4 for energy and emissions control for non-climate reasons. The IGSM reference scenario has the highest concentrations for all of the substances. The differences mainly reflect differences in anthropogenic emissions, but they also are influenced by the way each model treats natural emissions and sinks for the gases. The IGSM scenarios include 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 the IGSM scenarios 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 among the reference scenarios. The concentrations of the short-lived and long-lived F-gases are also presented in Figure 3.22.

Radiative Forcing from Greenhouse Gases

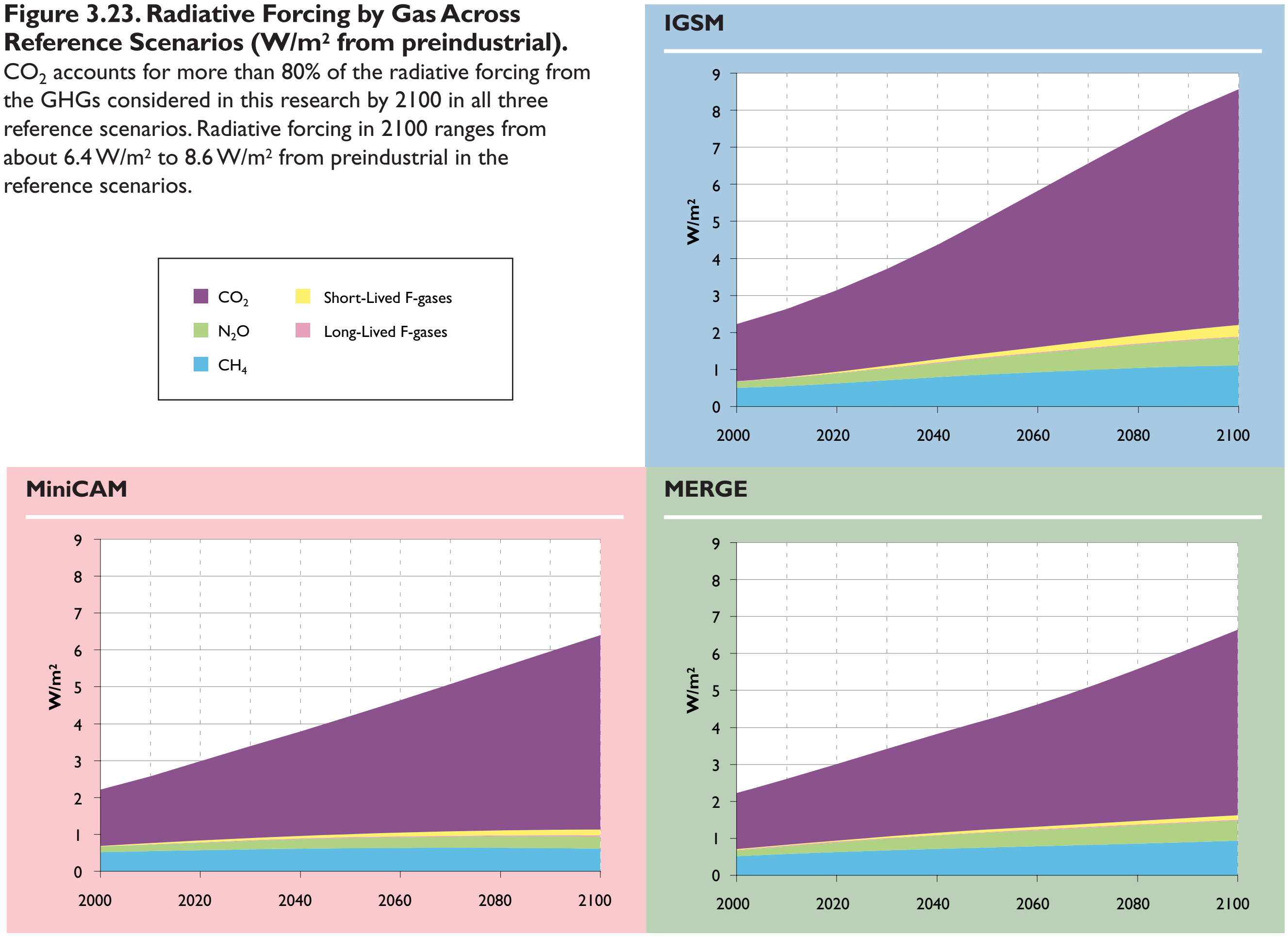
Contributions to radiative forcing are a combination of the abundance of the gas in the atmosphere and its heat-trapping potential (radiative efficiency). Of the directly released anthropogenic gases, CO_2 is the most abundant, measured in parts per million; the others are measured in parts per billion.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

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 reference scenarios reflect differences in emissions and treatment of removal processes. By 2100, CO_2 concentrations range from about 700 ppmv to 900 ppmv, CH_4 concentrations range from 2000 ppbv to 4000 ppbv, and N_2O concentrations range from about 380 ppbv to 500 ppbv.



The three models display essentially the same relationship between GHG concentrations and radiative forcing, so the three reference scenarios also all exhibit higher radiative forcing, growing from roughly 2.1 W/m² from preindustrial in 1998 to between 6.4 W/m² and 8.6 W/m² in 2100. The differences among radiative forcing in 2100 imply differences in the amount of emissions reductions required to stabilize as the four radiative forcing levels in this research. For example, the emissions reductions required for stabilization in the IGSM stabilization scenarios are larger than those required in the MiniCAM stabilization scenarios, because the

Figure 3.23. Radiative Forcing by Gas Across Reference Scenarios (W/m² from preindustrial). CO_2 accounts for more than 80% of the radiative forcing from the GHGs considered in this research by 2100 in all three reference scenarios. Radiative forcing in 2100 ranges from about 6.4 W/m² to 8.6 W/m² from preindustrial in the reference scenarios.



radiative forcing reaches 8.6 W/m² in 2100 in the IGSM reference scenario and 6.4 W/m² in the MiniCAM reference scenario.

The relative contribution of CO_2 to radiative forcing increases over the century in all three reference scenarios (Figure 3.23). In 2000, the non-CO_2 GHGs examined in this research contributed slightly above 30% of the estimated radiative forcing from preindustrial. In the IGSM reference scenario, the contribution of the non-CO_2 GHGs to radiative forcing falls slightly to about 26% by 2100. The MiniCAM reference scenario includes little additional increase in radiative forcing for non-CO_2 GHGs, largely as a result of assumptions regarding the control of CH_4 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 GHG contribution falling to about 24%.

From the discussion above, it can be seen that the three reference scenarios contain many large-scale similarities. All have expanding global energy systems, all remain dominated by fossil fuel use throughout the twenty-first century, all generate increasing concentrations of GHGs, and all produce substantial increases in radiative forcing. Yet the reference scenarios differ in many details, ranging from demographics to labor productivity growth rates to the composition of energy supply to treatment of the carbon cycle. These 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 efforts to limit radiative forcing.