Synthesis Assessment of Long-Term Climate Change Technology Scenarios

If the Climate Change Technology Program (CCTP) is to develop plans, carry out activities, and help shape an R&D portfolio that will advance its vision and mission and make progress toward achieving its strategic goals, the Program needs a long-term planning context, one that is informed by analyses from many sources using a variety of models and other decision support tools. Useful information to help shape the portfolio can come from assessments of the potential contributions that successful advancement of technologies could make to achieving CCTP's strategic goals. Analysis can also help determine the technology performance requirements needed to achieve greenhouse gas (GHG) emission reduction goals and the costs.

Such assessments are complex and must consider many uncertainties, and hence they must include a range of assumptions about the future. Specifically, a technology strategy aimed at influencing global GHG emissions over the course of the 21st century would need to consider population change, varying rates of regional economic development, differing regional technological needs and interests, and availability of natural resources. In addition, the long-term costs of GHG emission reductions will depend in part on future technological innovations, many of which are unknown, and on other factors that could either promote or discourage the use of various technologies in the future. Finally, the uncertainties inherent in climate science and the fact that value judgments are involved make it difficult to determine a level at which atmospheric GHG concentrations in the Earth's atmosphere would meet the stabilization objective of the United Nations Framework Convention on Climate Change noted in Chapter 1.

Scenario analysis using various types of models is one valuable tool that can be used to assist in planning under uncertainty. Scenarios can present alternative views about the rate of future GHG emissions growth to help gauge the scope of the potential challenge by methodically and consistently accounting for the complex interactions among economic and demographic factors, energy supply and demand, the advance of technology, and GHG emissions. Scenarios can also investigate various proposed pathways toward achieving different levels of GHG emissions reductions. The results can provide relative indications of the potential emissions reductions and economic benefits of particular classes of technology under a range of different assumptions, and a better understanding of the factors and constraints that might affect their market penetration.

The synthesis assessment of global climate-change technology scenarios examined anyalses based on a variety of models and tools.

Courtesy: DOE/PNNL

Many research organizations, university-based teams, government agencies, and other groups have engaged in scenario analyses to explore these topics. This chapter reviews and synthesizes the results of such efforts to gain insights, under a range of uncertainties, about the scale of the technological challenge, the potential contributions of various advanced technologies to GHG emissions reductions or avoidances, the timing of technology deployment, and associated economic benefits. These insights will be used to guide CCTP in developing an effective climate change technology strategy and associated portfolio of technology R&D.

3.1

The Greenhouse Gases

GHGs are gases that absorb infrared radiation. In the Earth's atmosphere, the GHGs cause what is commonly known as the "greenhouse effect." As shown in Figure 3-1, the GHGs include[1] carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and substances with very high global warming potential (GWP),[2] such as the halocarbons and other chlorine and bromine containing substances.[3] CO_2 emissions from the burning of fossil fuels, other industrial activity, and land-use changes and forestry, account for the majority of GHG emissions. In 2000, the combined emissions of methane, nitrous oxide, and high-GWP gases accounted for about one-quarter of all GHG emissions (after converting the non-CO_2 gases to a CO_2-equivalency basis, in terms of gigatons carbon equivalent, or GtC-eq.).

As a GHG resulting from human activities, methane's contribution is second only to CO_2. Methane, on a kilogram-for-kilogram basis, is 23 times more effective than CO_2 at trapping radiation in the atmosphere over a 100-year time period (although it has a shorter lifetime in the atmosphere). Methane is emitted from various energy-related activities (e.g., natural gas, oil and coal exploration, and coal mining), as well as from agricultural sources (e.g., emissions from cattle digestion and rice cultivation; and waste disposal facilities, landfills, and wastewater treatment plants). Methane emissions have declined in the United States since the 1990s, due to voluntary programs to reduce emissions and regulation requiring the largest landfills to collect and combust their landfill gas.[4]

Another important gas is nitrous oxide (N_2O), which is emitted primarily by the agricultural sector through direct emissions from agricultural soils and indirect emissions from nitrogen fertilizers used in agriculture, as well as from fossil fuel combustion, especially from fuel used in motor vehicles; adipic (nylon) and nitric acid production; wastewater treatment and waste combustion; and biomass burning (EPA 2005).

Global Emissions of GHGs in 2000 (% of total GtC-eq. using GWPs)

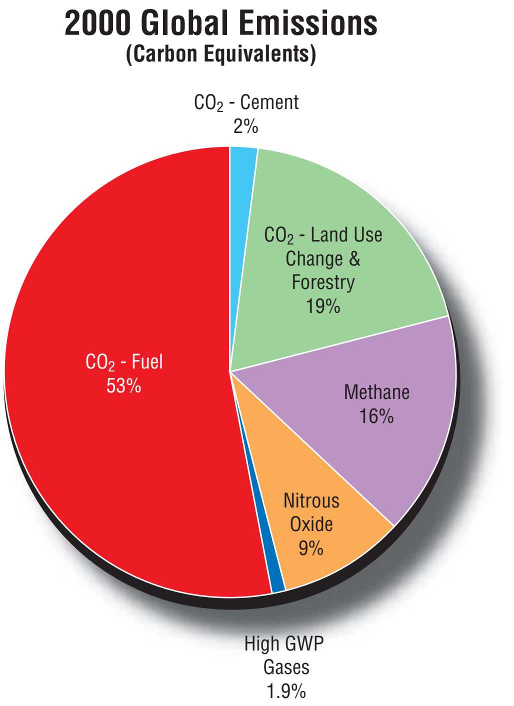

Figure 3-1. Global Emissions of GHGs in 2000 (percentage of total GtC-eq. using GWPs) (Sources: http://www.epa.gov/methanetomarkets/docs/methanemarkets-factsheet.pdf and http://www.mnp.nl/edgar/model/)

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[1] Water vapor and ozone are also GHGs.

[2] Global warming potentials (GWPs) are used to compare the abilities of different GHGs to trap infared radiation in the atmosphere. GWPs are based on the radiative efficiency (radiation-absorbing ability) of each gas relative to that of carbon dioxide (CO_2), as well as the decay rate of each gas (the amount removed from the atmosphere over a given number of years) relative to that of CO_2. The GWP provides a simplified construct for converting emissions of various gases into a common measure. However, it is important to note that GWPs are only an approximate metric for considering the relative impacts of different gases on the radiative balance of the Earth's atmosphere, because atmospheric lifetimes differ dramatically among gases. For example, methane's lifetime in the atmosphere is shorter than CO_2, so the radiative impact of a ton of methane emitted today will attenuate more quickly over time with respect to the radiative impact of a ton of CO_2 emitted today. Hence, the timeframe over which the GWP is developed critically affects the relative magnitude of the contributions of various gases (typically a 100-year timeframe is used), and GWPs serve as an indication of the relative importance of different gases, not as a precise measurement of the relative long-term impacts on the Earth's radiative balance.

[3] The ozone-depleting halocarbons and other chlorine- and bromine-containing substances are addressed by the Montreal Protocol and are not directly addressed by this Plan. Besides CO_2, N_2O, and CH_4, the Intergovernmental Panel on Climate Change (IPCC) definitions of GHGs include sulfur hexafluoride (SF_6), hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs), often collectively called the "F-gases."

[4] See http://www.epa.gov/methane/voluntary.html.

Other non-CO_2 GHGs, including certain fluorine-containing halogenated substances such as sulfur hexafluoride (SF_6), hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs), often collectively called the "F-gases," are used or produced by a variety of industrial processes. In most cases, emissions of these F-gases were relatively low in 1990 but have since grown rapidly. The sources of these non-CO_2 GHG emissions are discussed in more detail in Chapter 7.

The radiation-trapping capacities of GHGs vary considerably. GHGs also have different lifetimes in the atmosphere. In addition, some anthropogenic emissions (such as aerosols) can have cooling effects. Combining these effects, the Intergovernmental Panel on Climate Change (IPCC) estimated the key anthropogenic and natural factors causing changes in warming and cooling from year 1750 to year 2000,[5] as shown in Figure 3-2. The figure shows warming and cooling in terms of radiative forcing—the change in the balance of infrared radiation coming into and going out of the atmosphere. Positive radiative forcing leads to warming, and negative radiative forcing leads to cooling.

The differences in the characteristics of GHGs and other radiatively important substances, as well as the potential differences in rates of the growth of their emissions over time, influence the formulation of strategies to stabilize overall GHG concentrations through emissions mitigation. In addition to the climate implications of increasing atmospheric CO_2, there are also concerns about chemical and biological impacts to the ocean. As discussed in Chapter 6, an increase in ocean CO_2 concentrations and the potential effect on ocean chemistry and biology provide additional motivation, apart from climate change and considerations of global temperature, to mitigate emissions and stabilize atmospheric CO_2 concentrations.

3.2

Factors Affecting Future GHG Emissions

Most analyses of future GHG emissions indicate that, in the absence of actions taken to address climate change, increases will occur in both emissions of GHGs and their atmospheric concentrations. The

Global Mean Radiative Forcing of the Climate System for the Year 2000, Relative to 1750

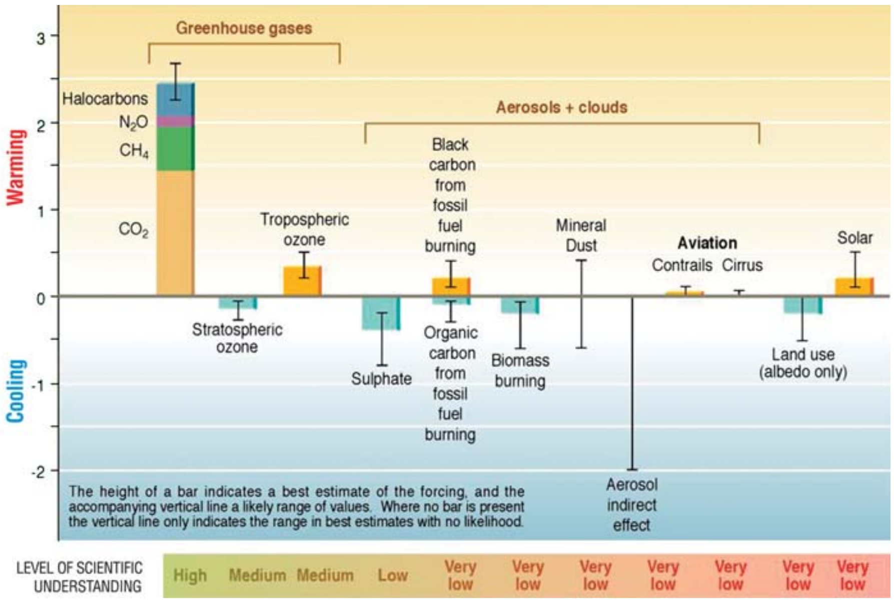

Figure 3-2. Global Mean Radiative Forcing of the Climate System for the Year 2000, Relative to 1750 (Source: IPCC[6])

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[5] A large body of work has been undertaken to understand the influence of external factors on climate using the concept of changes in radiative "forcing" due to changes in the atmospheric composition, alteration of surface reflectance by land use, and variations in solar input. Some of the radiative forcing agents, such as CO_2, are well mixed over the globe, thereby perturbing the global heat balance. Others, such as aerosols, represent perturbations with stronger regional signatures because of their spatial distribution. For this and other reasons, a simple sum of the positive and negative bars cannot be expected to yield the net effect on the climate system.

[6] Available at http://www.ipcc.ch/present/graphics/2001syr/large/06.01.jpg.

projected rate of emissions growth is dependent on many factors that cannot be predicted with certainty. Studies conducted by organizations, including the IPCC,[7] the Stanford Energy Modeling Forum (EMF),[8] and others,[9] indicate that among the more significant factors expected to drive future GHG emissions growth are demographic changes (e.g., regional population growth), social and economic development (e.g., gross world product and standard of living), fossil fuel use (i.e., coal, oil, and natural gas), and land use changes. The most important factors limiting increases in future GHG emissions include improvements in energy efficiency; increases in nuclear, renewable, and non-CO_2-emitting fossil energy supply; decreases in GHG emissions from industry, agriculture, and forestry; and rapid technological change that results in reducing GHG emissions.

CO_2 Emissions from Energy Consumption

The International Energy Agency estimates that 1.6 billion people lack access to electricity. The United Nations estimates that 2 billion people are without clean and safe cooking fuels, relying instead on traditional biomass (UNDP 2000). Over the course

Primary Energy Use Projections Using Various Energy-Economic Models and Assumptions

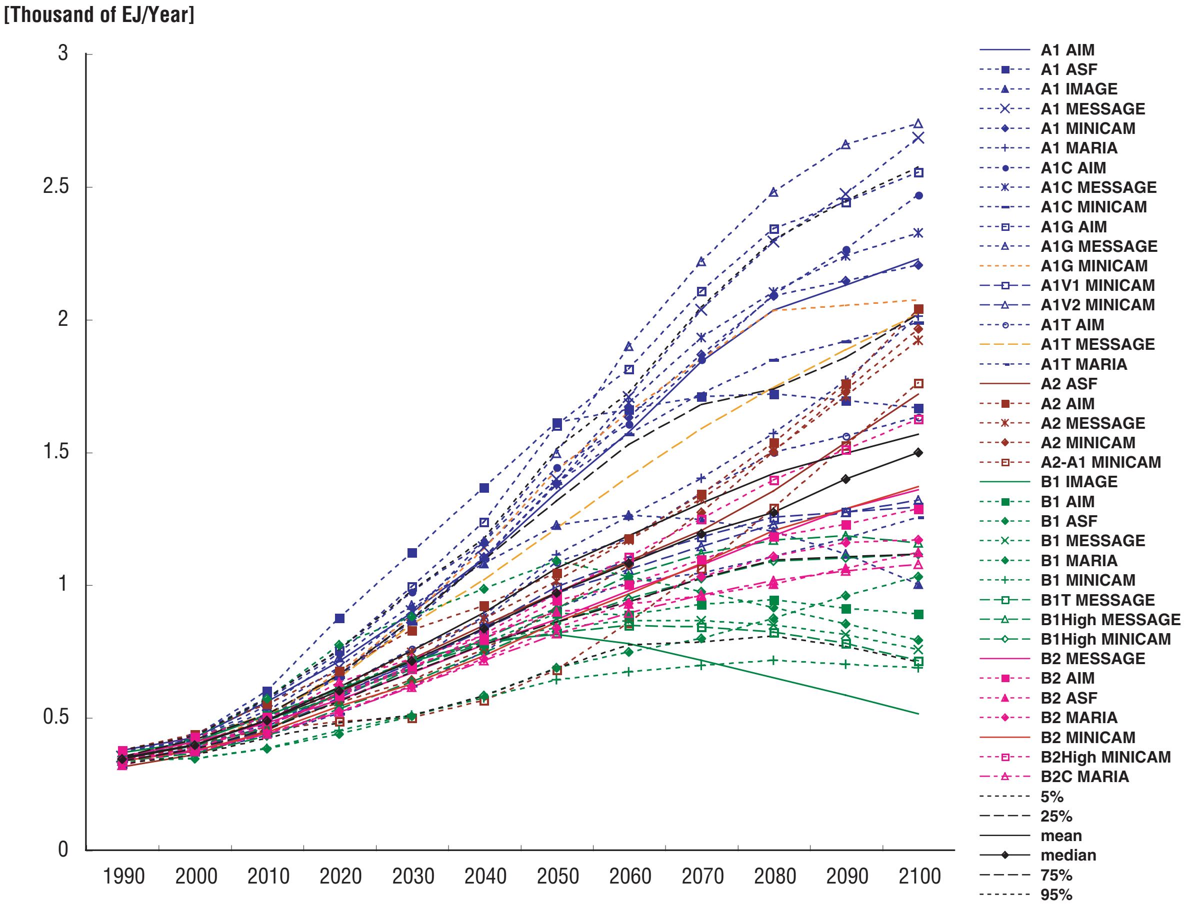

Figure 3-3. Primary Energy Use Projections Using Various Energy-Economic Models and Assumptions
Note: The mean, median, and percentile bands in the figure are based on the range of projections and do not represent probabilities of the projections. (Source: IPCC 2000)

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[7] One study that examined emissions growth in the absence of special initiatives directed at climate change is the *Special Report on Emissions Scenarios (SRES)* by the Intergovernmental Panel on Climate Change (IPCC 2000), in which six leading energy-economic models were used to explore a suite of scenarios that projected growth in global energy and GHG emissions.

[8] See http://www.stanford.edu/group/EMF/publications/index.htm.

[9] See for example, *Direct and Indirect Human Contributions to Terrestrial Carbon Fluxes: A Workshop Summary* (2004) and *Human Interactions with the Carbon Cycle: Summary of a Workshop* (2002), both available from the National Academies Press (Coppock and Johnson 2004 and Stern 2002).

of the 21st century, a greater percentage of the world's population is expected to gain access to electricity and commercial fuels, as well as experience major improvements to quality of life. These changes are expected to result in increased per capita energy use. In addition, world population is expected to grow, which will further increase overall demand for energy.

Estimates of projected energy demand vary considerably. The Energy Information Administration (EIA 2005) projects world primary energy demand will increase from about 411.5 exajoules (EJ) in 2002 to 680 EJ in 2025. Most of that increase will come in demand from developing countries. EIA forecasts primary energy use in the developed world will rise just 1.1 percent annually while that in the developing world will rise 3.2 percent annually. Energy use in the emerging economies of developing Asia, driven largely by demand in China and India, is projected to more than double over the course of the quarter century.

In the IPCC's *Special Report on Emissions Scenarios* (SRES) (IPCC 2000), projected world primary energy use in 2100 fell within a range of 600 to 2800 EJ for 90 percent of the scenarios explored (Figure 3-3). Among the scenarios surveyed in SRES, the average annual growth rates for global energy demand over the period from 2000 to 2100 ranged from 2.4 percent per year to -0.1percent per year, with a median value of 1.3 percent per year.[10]

As about four-fifths of GHG emissions are energy related, energy generation and consumption are key determinants of CO_2 emissions. The scenarios with the highest CO_2 emissions are those that assume the highest energy demand along with the highest

CO_2 Emissions Projections from Energy Use Using Various Energy-Economic Models and Assumptions

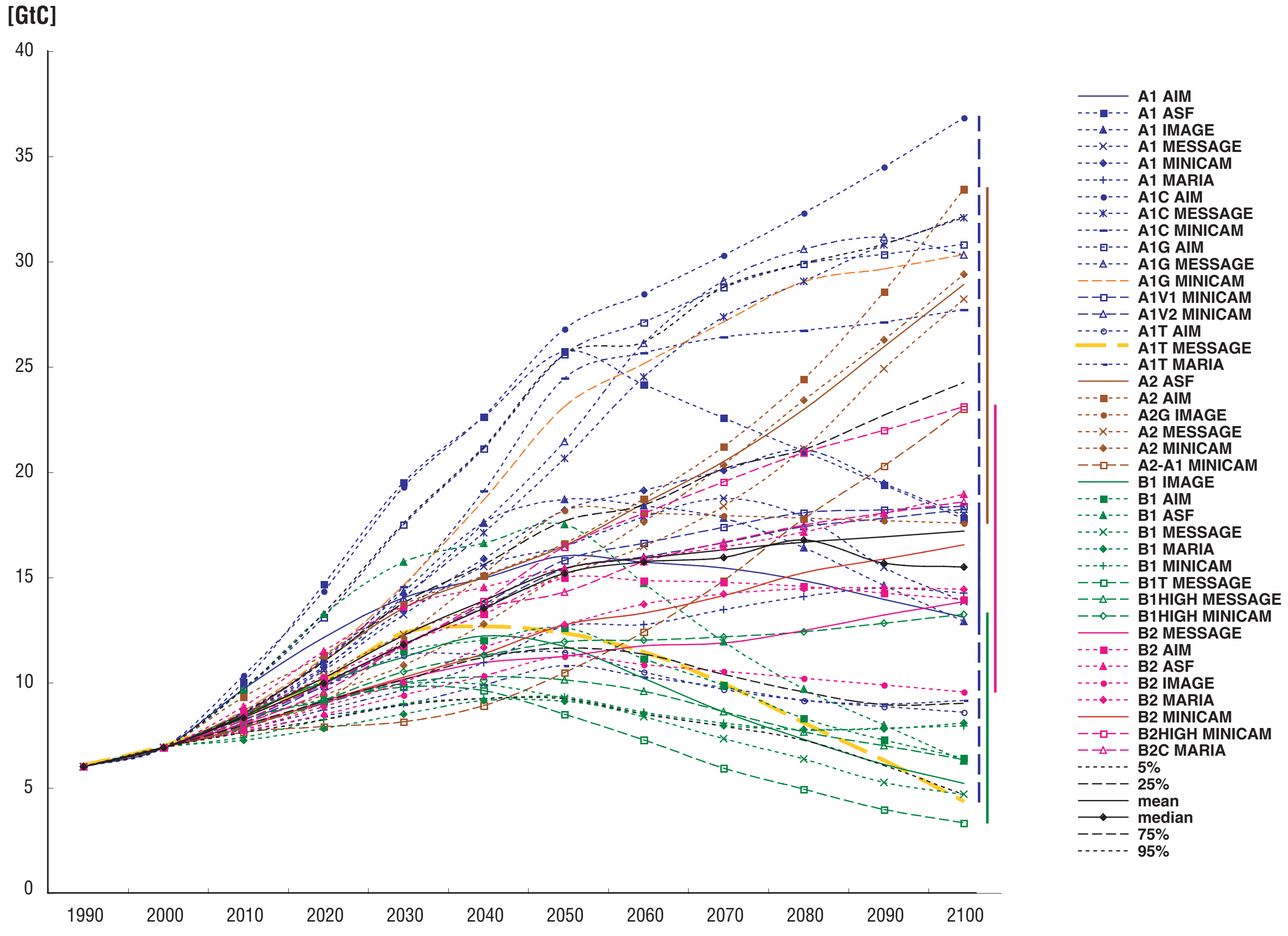

Figure 3-4. CO_2 Emissions Projections from Energy Use Using Various Energy-Economic Models and Assumptions
Note: The mean, median, and percentile bands in the figure are based on the range of projections, and do not represent probabilities of the projections. (Source: IPCC 2000)

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[10] Scenarios that show low or negative energy consumption growth rates over time represent cases where technological improvement is projected to be very rapid and where population and GDP growth rates lie at the lower bounds of the projections.

proportion of fossil fuel use unaccompanied by CO_2 capture and storage. Since 1900, global primary energy consumption has, on average, increased at more than two percent per year, similar to the 20-year trend from 1975 to 1995.

Without constraints, energy-related CO_2 emissions are expected to increase significantly over the next 100 years at rates similar to those for the growth in energy consumption. Specific projections vary depending on assumptions. According to EIA (2005), annual global CO_2 emissions may increase by about 60 percent between 2002 and 2025. Higher growth rates are expected in the developing regions of the world, where CO_2 emissions may increase by a factor of two or more by 2025.

In 2025, global use of petroleum products, primarily in the transportation sector, is expected to continue to account for the largest share of global emissions of CO_2. This is followed in importance by the use of coal, primarily for electricity generation, and natural gas. Natural gas is a versatile fuel, used for power generation, residential and commercial fuel, and many other uses. CO_2 emissions from fossil fuel combustion by end-use sector for 2002 can be broken down as follows: transportation, 24 percent; electricity and heat, 35 percent; and industrial and other end uses, 41 percent.

IPCC's SRES examined projections of CO_2 emissions from energy use based on multiple reference scenarios from six long-term modeling efforts. It found that different assumptions about the driving forces led to widely divergent emissions trajectories (Figure 3-4). Ninety percent of the CO_2 emissions projections fall within the upper and lower bounds shown in Figure 3-4. The mean, median, and percentage bands shown were calculated based on the range of projections across the full set of scenarios and do not represent probabilities associated with the projections.

The upper bounds in Figures 3-3 and 3-4 are formed by scenario results that assume very high world economic growth, high per-capita energy use, and continued dominance of fossil fuels. At this upper bound, world CO_2 emissions from energy use are projected to grow from about 6 GtC/year in 2000 to more than 30 GtC/year in 2100—a five-fold increase.

The lower bounds in Figures 3-3 and 3-4 are formed by scenarios that assume less population growth, changes in the composition of economic activity away from energy-intensive output, lower per-capita energy use, more energy efficiency, and considerably more use of carbon-neutral fuels, compared to the upper bound. At this lower bound, CO_2 emissions are projected to grow for the first half the century, but then to decline to levels about equal to those in 2000, representing no net growth by 2100. Assumptions for the various scenarios are described in Box 3-1.[11] The models used in this study include AIM,[12] ASF,[13] IMAGE,[14] MARIA,[15] MESSAGE,[16] and MiniCAM.[17]

Recent studies have explored the uncertainty in future emissions using a probabilistic approach (see for example, Webster et al. 2002).[18] While there are some differences in the upper and lower bounds of the emissions projections between the SRES scenarios and these more recent probabilistic-based analyses, the range of the SRES scenarios overlaps to a large degree with the range of emissions estimated using these probabilistic approaches.

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[11] The range of CO_2 emissions in the SRES has been compared to scenarios done later (post-SRES). In general, the ranges are not very different. The estimated CO_2 emissions in post-SRES scenarios have a higher lower bound, a similar median, and a higher upper bound of the distribution. The post-SRES scenarios use lower population estimates, both in range and median. The post-SRES economic development projections (based on market exchange rates) have approximately the same lower bound and median but a lower upper bound of the distribution. A comprehensive database of emissions scenarios is available at http://www-cger.nies.go.jp/cger-e/db/enterprise/scenario/scenario_index_e.html.

[12] Asian Pacific Integrated Model (AIM) from the National Institute of Environmental Studies in Japan (Morita et al. 1994).

[13] Atmospheric Stabilization Framework Model (ASF) from ICF Consulting in the USA (Lashof and Tirpak 1990; Pepper et al. 1992, 1998; Sankovski et al. 2000).

[14] Integrated Model to Assess the Greenhouse Effect (IMAGE) from the National Institute for Public Health and Environmental Hygiene (RIVM) (Alcamo et al. 1998; de Vries, Olivier et al. 1994, de Vries, Janssen et al. 1999; de Vries, Bollen et al. 2000), used in connection with the Dutch Bureau for Economic Policy Analysis (CPB) WorldScan model (de Jong and Zalm 1991), the Netherlands.

[15] Multiregional Approach for Resource and Industry Allocation (MARIA) from the Science University of Tokyo in Japan (Mori and Takahashi 1999; Mori 2000).

[16] Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE) from the International Institute of Applied Systems Analysis (IIASA) in Austria (Messner and Strubegger 1995; Riahi and Roehrl 2000).

[17] Mini Climate Assessment Model (MiniCAM) from the Pacific Northwest National Laboratory (PNNL) in the USA (Edmonds et al. 1994, 1996a, 1996b).

[18] Use of uncertainty analysis and probabilistic forecasting can help identify and quantify critical but uncertain parameters (such as demographic or technology trends over time). Multiple simulations are performed by sampling from those distributions to construct probability distributions of the outcomes (such as GHG emissions). Distributions for factors, such as labor productivity growth, energy efficiency improvement, agricultural and industrial emissions coefficients for various GHGs, etc., are quantified by expert elicitation or from a review of the literature. These distributions are then used in assessment models to generate a distribution of results, such as GHG emissions and/or climate impacts (e.g., temperature change or sea-level rise).

BOX 3-1 THE SRES SCENARIOS

The SRES scenarios are organized around four major storylines, which received the names A1, A2, B1, and B2. Each of these storylines represented different general conceptions of how the world might evolve over time, including the evolution of key drivers such as economic growth (including differences or convergence in regional economic activity), population growth, and technological change. Each driver was interpreted by the participating modeling teams in terms of quantitative assumptions about the evolution of specific model parameters. Some scenario drivers, such as economic growth, final energy, and population growth, were harmonized across many of the models, while others, such as the specific technology assumptions, were developed by the individual modeling teams to be generally consistent with the storylines. For the A1 Scenario, four basic assumptions about technology were also developed, so there are four categories of technology scenarios under the A1. The scenarios are described as follows:

A1. The A1 storyline and scenario family describe a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The four A1 groups are distinguished by their technological emphasis: fossil intensive (A1C – coal- and A1G – gas), non-fossil energy sources (A1T), or a balance across all sources (A1B), where balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end-use technologies.

A2. The A2 storyline and scenario family describe a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in a continuously increasing population. Economic development is primarily regionally oriented, and per capita economic growth and technological change more fragmented and slower than in other storylines.

B1. The B1 storyline and scenario family describe a convergent world with the same global population, which peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.

B2. The B2 storyline and scenario family describe a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population, at a rate lower than in A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels.

The set of harmonized drivers depended both on the scenario and the specific model. Key drivers that characterized the scenarios are summarized qualitatively in the table below. All scenarios assume energy intensity reductions over the coming century at or greater than the historical average over the past few decades. Comparison of the emissions trajectories in Figures 3-5 and 3-6 can be interpreted in terms of the relative evolution of these drivers and the discussion of these drivers above.

DRIVER	A1				A2	B1	B2
	A1C	A1G	A1B	A1T			
Population Growth	low	low	low	low	high	low	medium
GDP Growth	very high	very high	very high	very high	medium	high	medium
Energy Use	very high	very high	very high	high	high	low	medium
Energy Intensity Improvement	high	high	high	high	low	very high	medium
Land-use Changes	low-medium	low-medium	low	low	medium-high	high	medium
Availability of Conventional Oil & Gas	high	high	medium	medium	low	low	medium
Pace of Technological Change	rapid	rapid	rapid	rapid	slow	medium	medium

CO_2 Emissions and Sequestration from Changes in Land Use

CO_2 emissions in the future will be influenced not only by trends in CO_2 emissions from energy use and industrial sources, but also by trends in land use that result in either net CO_2 sequestration or release. CO_2 emissions and carbon sequestration associated with various land uses will be driven primarily by increasing demand for food. Other important factors include demand for wood products, land management changes, demand for biomass energy and bio-based products, and technological change.

The role of land-use change has received relatively limited consideration (compared to energy use) in prior modeling exercises aimed at developing long-run GHG emissions scenarios. To date, the most comprehensive treatment is contained in the scenarios developed for the IPCC SRES (IPCC 2000). In developing these scenarios, the IPCC assembled a data base of over 400 earlier emissions scenarios. Of these, 26 scenarios (all the work of three modeling groups) explicitly considered the role of land-use change on global CO_2 emissions. The projections vary considerably in the near term, with some scenarios showing increasing and some decreasing net global CO_2 emissions from land-use change (Figure 3-5). A key insight to emerge from the IPCC exercise was that the link between land-use change and global CO_2 emissions is more complex and uncertain than had been reflected in previous analyses.

Across and within the four storylines described in Box 3.1, the scenarios produced a wide range of land-use paths that included large increases and decreases in the global areas of cropland, grassland, and forest over the course of the century. Differences in land-use patterns resulted primarily from alternative assumptions about population and income growth. Hence, the scenarios indicate that land-use change could become either an important source or sink of global CO_2 emissions over the next 100 years, depending on the mix of goods and services the world's population demands from its land resources.

Further, future paths of technological change in today's land-intensive sectors—including agriculture, forestry, energy, construction, and environment quality—will help to define the contribution land-use change makes to net CO_2 emissions. Many of the IPCC scenarios show that CO_2 emissions from

Net CO_2 Emissions from Land-Use Change

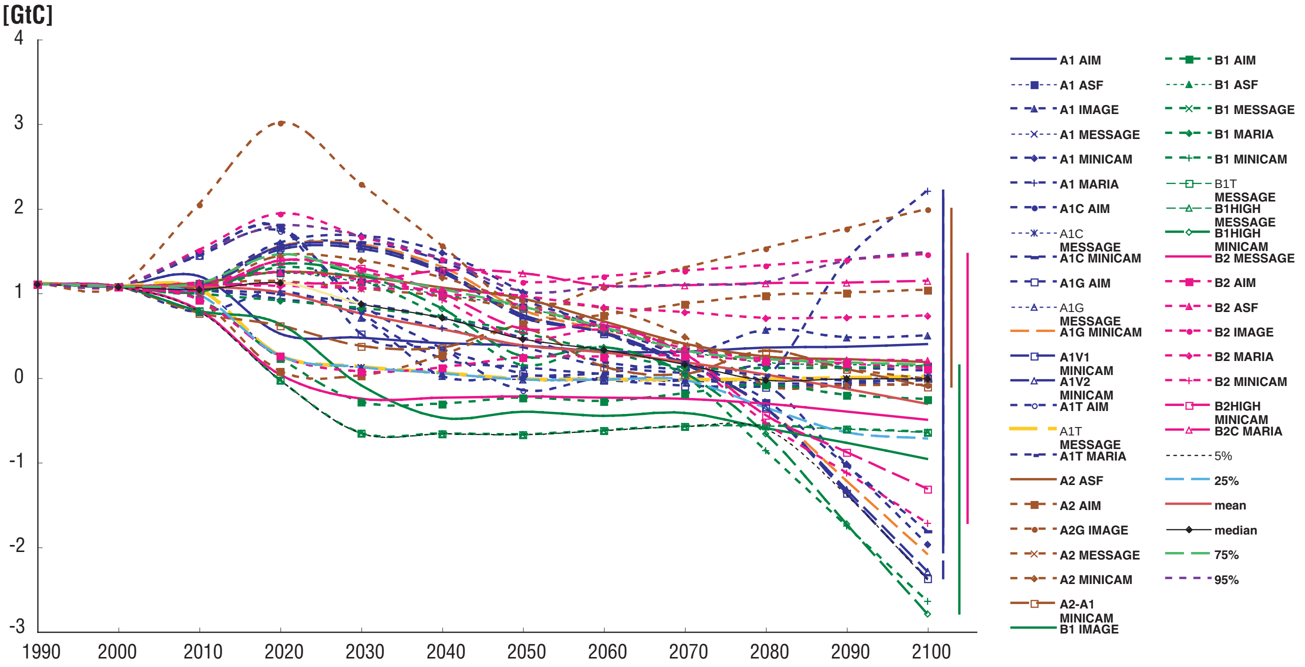

Figure 3-5. Net CO_2 Emissions from Land-Use Change
Note: The mean, median and percentile bands in the figure are based on the range of projections, and do not represent probabilities. (Source: IPCC 2000)[19]

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[19] The structure of the underlying modeling exercise required harmonization in 2000. Such harmonization in the context of a modeling exercise does not necessarily reflect agreement.

deforestation are likely to peak after several decades and then subsequently decline.[20] Despite the differences among the scenarios' assumptions, most of the scenarios show a net decrease to below current levels by the end of the century.

Sohngen and Mendelsohn (2003) linked a global forestry model with the global optimization model DICE to more explicitly explore the relationships between forestry management, land-use emissions, and global energy systems. They reported a net sequestration potential ranging from 32 to 102 GtC in the coming century, depending on carbon prices. Much of the sequestration occurs through avoided deforestation.

Other Greenhouse Gases

The non-CO_2 GHGs include a diverse group of gases such as methane, nitrous oxide, chlorofluorocarbons, and other gases with high global warming potential (see Chapter 7). Future growth in emissions of non-CO_2 GHGs will depend on the future level of the activities that emit these gases, as well as the amount of emissions control that occurs. The cost-effectiveness of emission controls for mitigating the various GHGs will depend on their relative estimated costs and anticipated climate-related benefits.

Integrated assessment models have only recently begun to project long-term trends in non-CO_2 GHGs. In a recent international modeling exercise conducted by the Stanford Energy Modeling Forum (EMF-21), non-CO_2 emissions and mitigation potential were projected by 18 models of various forms (Weyant and de la Chesnaye 2005).[21] Each model ran a "reference case" scenario, in which non-CO_2 GHGs were allowed to grow in the absence of any constraints or incentives for GHG emissions mitigation.

The results for methane and N_2O are shown in Figures 3-6 and 3-7, respectively. The projections vary considerably among models. On average, emissions of non-CO_2 GHGs were projected to increase from 2.7 gigatons of carbon equivalent emissions (GtC-eq.) in 2000 to 5.1 GtC-eq. in 2100. On average, methane emissions were projected to increase by 0.6 percent/year between 2000 and 2100; nitrous oxide by 0.4 percent/year; and the fluorinated gases by 1.9 percent/year. (By comparison, in these same scenarios, CO_2 emissions were projected to grow by 1.1 percent/year over the same time period.)

A recent modeling study conducted for CCTP projected the contributions of CO_2 and other GHGs to future radiative forcing (Clarke et al. 2006). In the reference case scenario (without actions specifically targeted toward lowering GHGs), radiative forcing from pre-industrial levels was projected to increase to 6.5 watts per square meter (W/m^2), compared to a level of about 2 W/m^2 in 2000 (Figure 3-8). In this projection, CO_2 contributed approximately 80 percent of the radiative forcing in 2100, with other GHGs (CH_4, N_2O, and the F-gases) contributing about 20 percent.

Some other models show larger contributions from non-CO_2 GHGs. The analysis for CCTP (which used MiniCAM) projects a considerable amount of control of methane in the absence of mandated controls.[22] In results from other models, radiative forcing was projected to increase to over 9 W/m^2, due in part to growth in non-CO_2 GHG emissions (van Vuuren et al. 2006). These studies indicate the importance of non-CO_2 GHGs, especially in the future, as their emissions rise as a result of increased industrial and agricultural activity and population growth.

3.3

Analytical Context for CCTP Planning

For the purposes of CCTP planning and analysis, it is useful to understand the potential contributions that advanced technologies could make to future GHG emissions reductions and to the potential stabilization of atmospheric GHG concentrations and its integrated multi-gas metric, radiative forcing, over a century-long planning horizon. No particular GHG stabilization level is assumed in this plan, nor is there an assumed "best path" for reaching stabilization. Accordingly, the synthesis assessment of various analyses of advanced technology scenarios explores two degrees of freedom (or uncertainty)—one is about the hypothesized levels of GHG concentrations

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[20] This pattern is tied to declines in the rate of population growth toward the latter half of the century and increases in agricultural productivity.

[21] The models included a variety of model types, including integrated assessment models and general equilibrium models.

[22] Note that certain models (such as MiniCAM) project that some GHG-reducing technologies penetrate the market without incentives or policies. For example, in MiniCAM, technologies for reducing methane emissions from coal and natural gas production would penetrate the market when it is cost-effective to do so, based on the value of the methane (natural gas) collected, which is marketable as a fuel.

Methane Emissions Projections from the EMF-21 Study, With No Explicit Initiatives to Reduce GHG Emissions

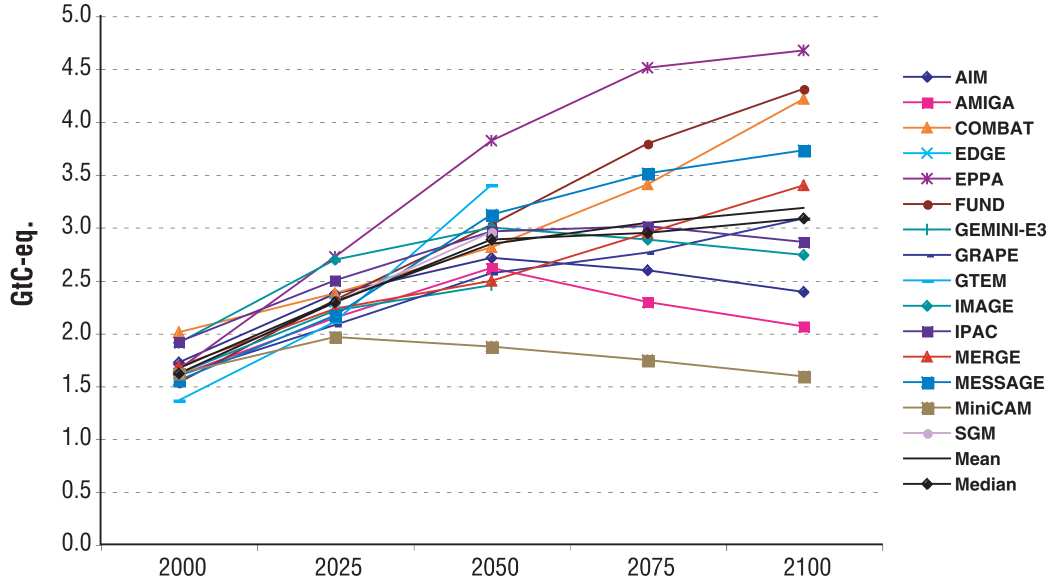

Figure 3-6. Methane Emissions Projections from the EMF-21 Study, With No Explicit Initiatives to Reduce GHG Emissions

Nitrous Oxide Emissions Projections from the EMF-21 Study, With No Explicit Initiatives to Reduce GHG Emissions

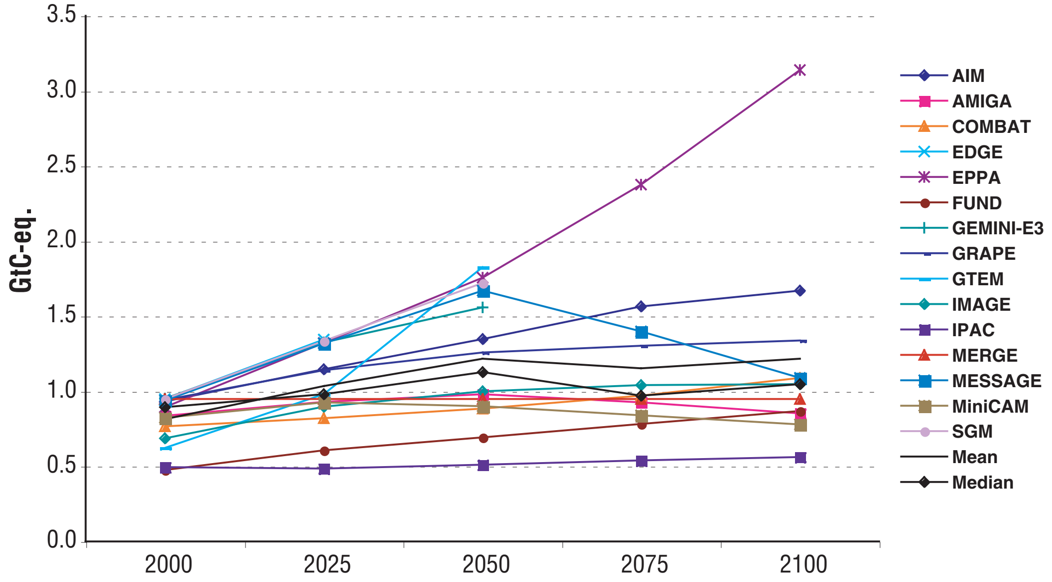

Figure 3-7. Nitrous Oxide Emissions Projections from the EMF-21 Study, With No Explicit Initiatives to Reduce GHG Emissions

Radiative Forcing in a Reference Case Scenario

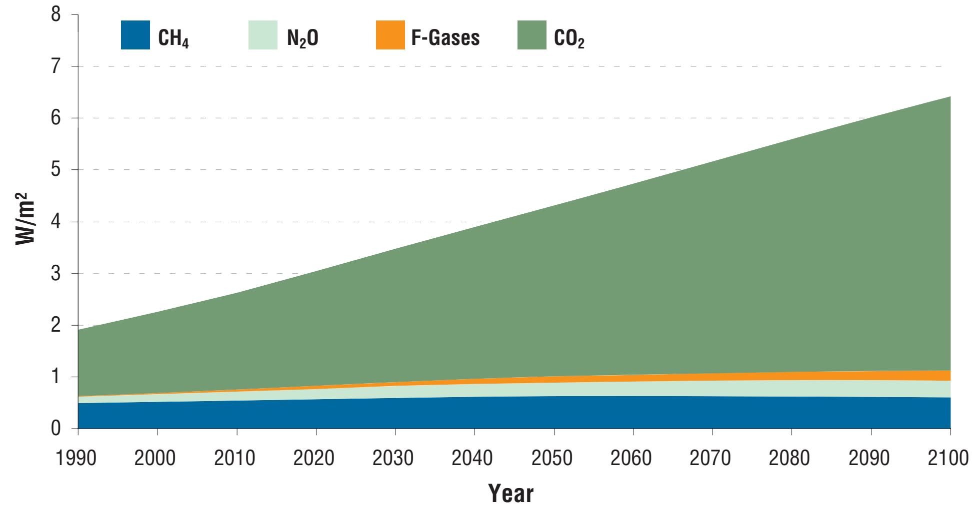

Figure 3-8. Radiative Forcing in a Reference Case Scenario (Source: Clarke et al. 2006)

and the other is about the technologies. Useful insights may be gained by modeling the hypothesized levels across a range of assumptions about, and mixes of, advanced technologies.

Cost-effective means to stabilize radiative forcing would include reductions in emissions of both CO_2 and other GHGs. A recent analysis by Pacific Northwest National Laboratory (PNNL) examined various GHG emissions reduction options associated with a range of radiative forcing levels in the year 2100, each leading to long-run stabilization of radiative forcing (Clarke et al. 20006). The results are presented in Figure 3-9, which compares the estimated radiative forcing in 2000 to projected radiative forcing in 2100 under an unconstrained emissions scenario (Reference Case) and four emissions-constrained scenarios that lead to lower radiative forcing in 2100.

Other studies also examined integrated multi-gas strategies for reducing radiative forcing, considering possible tradeoffs among CO_2 and other GHG emissions. For example, using results from a variety of different models, an analysis by Weyant and de la Chesnaye (2005) showed that a multi-gas approach results, on average, in CH_4 emissions reductions of almost 50 percent, N_2O reductions of about 40 percent, and a reduction in F-gases of almost 75 percent (on a GtC-eq. basis) by 2100, compared to reference case levels.

Radiative Forcing Levels under Different Degrees of Constraint

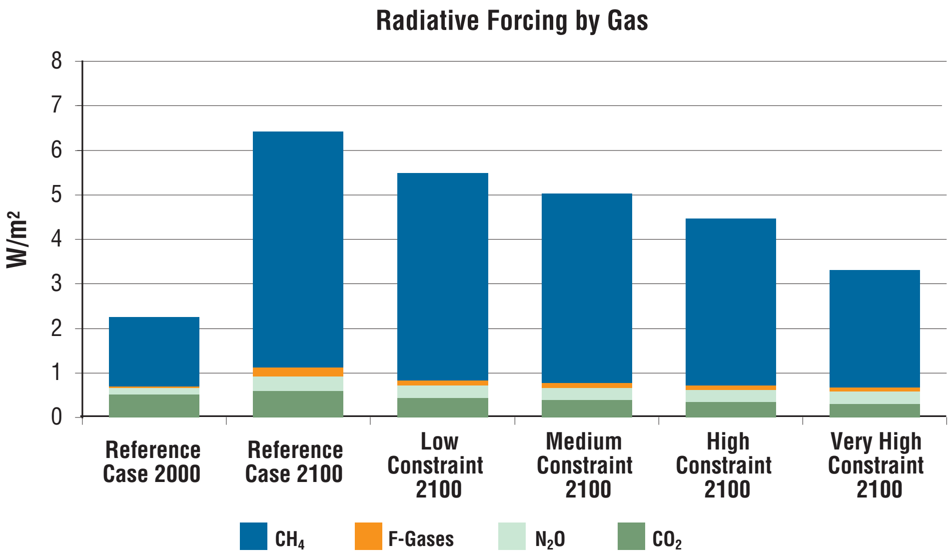

Figure 3-9. Radiative Forcing Levels under Different Degrees of Constraint (Source: Clarke et al. 2006)

For any assumed constrained radiative forcing scenario, reductions in the non-CO_2 gases lead to the need for smaller reductions in CO_2 emissions. Nevertheless, CO_2 remains by far the most important GHG. Accordingly, a range of potential CO_2 stabilization levels have been explored, using different models and assumptions. Figure 3-10 shows one set of relationships between CO_2 emissions and CO_2 concentrations over time, across a range of CO_2 stabilization levels commonly found among the literature on scenarios.[23]

The set of hypothetical CO_2 emissions scenarios (Figure 3.10-A), shown here across a range of five corresponding CO_2 concentration stabilization levels (Figure 3.10-B), illustrates a general pattern found consistently across the analyses. Emissions scenarios leading to CO_2 stabilization typically show growth of emissions in the near term, but with that growth slowing; the emissions eventually peak and then gradually decline; and ultimately they approach levels that are low or near zero. In almost all stabilization scenarios, emissions must continue to decline beyond 2100 and into the 22nd century and beyond. Over the same time period, as discussed earlier, the world's energy needs can be expected to continue to grow.

An illustration of the scale of the overall emissions reductions needed to achieve stabilization of CO_2 concentrations is shown in Figure 3-11. To meet the CO_2 stabilization level in this hypothetical example, by 2100 annual CO_2 emissions would need to be reduced by almost 15 GtC-eq/year below the level in an otherwise "unconstrained" emissions scenario case.[24] For the example shown, the cumulative emissions reduction would be approximately 600 GtC-eq over the course of the 21st century. For other scenarios (PNNL), the 100-year cumulative CO_2 emissions reductions ranged from about 300 to about 1,000 GtC-eq.[25]

Illustrative CO_2 Emissions Profiles and Corresponding Concentrations

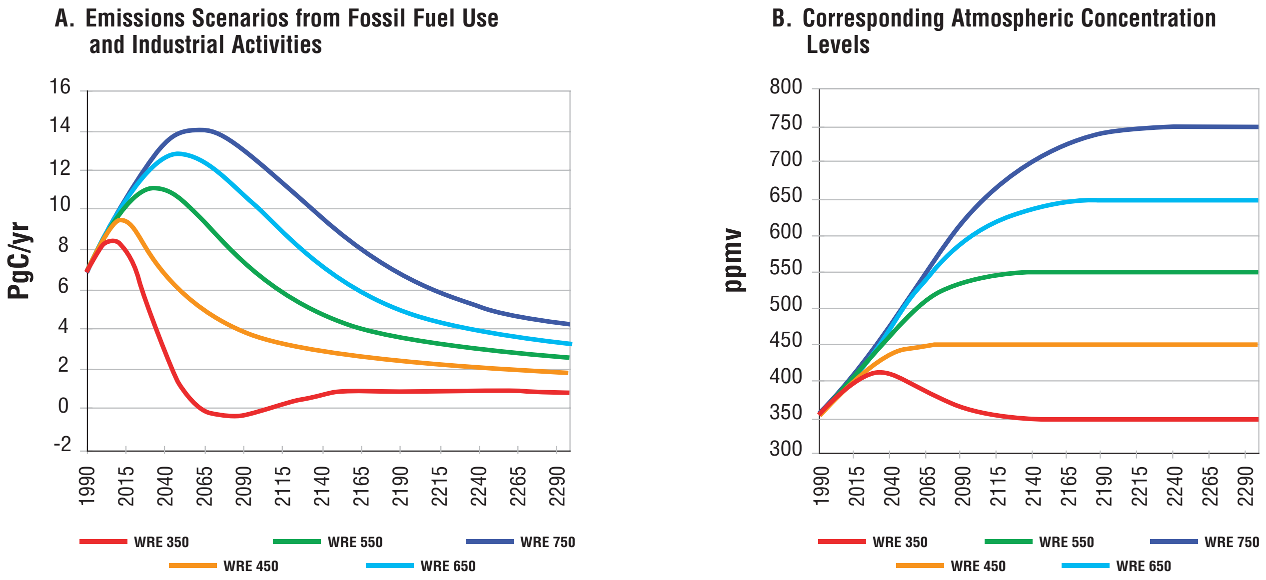

Figure 3-10. Illustrative CO_2 Emissions Profiles and Corresponding Concentrations

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[23] Derived from Wigley et al. 1996. The emissions scenarios represent net emissions from fossil fuels (i.e., including emissions reductions from carbon dioxide capture and storage) and industrial sources. They do not include emissions from land use and land-use change. The concentration levels are based on a range of specific assumptions regarding net emissions from land use and land-use change, and about the carbon cycle more generally, including assumptions regarding the rate of ocean uptake. Note that significant uncertainties remain about many aspects of the carbon cycle; reducing these carbon cycle uncertainties is one of the goals of the U.S. Climate Change Science Program (CCSP). Other estimated scenarios showing relationships between emissions and concentrations can be found in the literature on scenarios.

[24] The "unconstrained" case in this illustrative example is based on the reference scenario developed for CCTP by PNNL; see Clarke et al. (2006). Note that this reference scenario includes a considerable amount of energy efficiency as well as increased use of renewable and nuclear energy resulting from improvements in these technologies over time, increased prices for fossil fuels, and hence increased ability of renewable and nuclear technologies to compete in the market. The lower curve represents a reduced-emissions scenario leading to stabilization; it is a slightly modified version of the 550 ppmv trajectory shown in Figure 3-10A.

[25] See Clarke et al. 2006 and IPCC 2001. Estimates of the emissions reductions required to stabilize concentrations are uncertain and vary based on assumptions. Key assumptions include: (1) estimates of future emissions to 2100 in the absence of actions aimed at GHG mitigation (i.e., the "reference" scenario); (2) selection of the stabilization level or levels of atmospheric GHG concentrations; and (3) the nature of baseline and advanced technology scenarios and their associated time-specific emissions trajectories. Results for CCTP are shown as "mitigated emissions" on Figure 3-14.

Potential Scale of CO_2 Emissions Reductions to Stabilize GHG Concentrations: Hypothetical Unconstrained and Constrained Emissions Scenarios

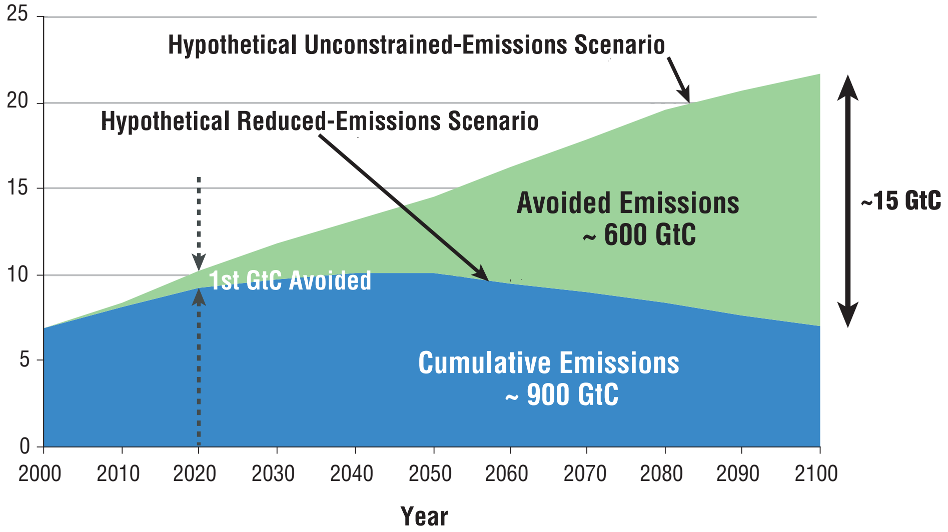

Figure 3-11. Potential Scale of CO_2 Emissions Reductions to Stabilize GHG Concentrations: Hypothetical Unconstrained and Constrained Emissions Scenarios (Source: Clarke et al. 2006)

Box 3-2 provides illustrations of technological measures that could achieve an annual reduction of one GtC-eq./yr. As these illustrations suggest, GHG-reducing technologies would need to be implemented on a significant scale. The costs of achieving such reductions using today's technology options could be high. Developing and deploying advanced technology with significantly improved performance and cost characteristics could substantially lower these costs, thereby facilitating their entry into the marketplace or their expanded adoption. The implication for CCTP and its associated science and technology R&D programs is that advanced technologies, including novel or breakthrough technologies, are important, if not essential, to the CCTP goals of significantly reducing or avoiding GHG emissions, while maintaining economic growth and ensuring safety and overall environmental quality.

3.4

Exploring the Role for Advanced Technology

Reducing or avoiding GHG emissions on the scale hypothesized in Section 3.3 could be facilitated by a variety of advanced scenarios, each characterized by a different mix of technologies, estimated cost, and timing of the emission reductions. Given the diversity of activities and processes that emit GHGs, achieving emissions reductions on such a scale will likely require significant contributions from a combination of existing, improved or transitional, and advanced technologies. At present, the "best" combination of technologies (and other means) is unknown, but insights about the role for technology can be gained through analysis.

Estimating the potential contribution to CCTP strategic goals of any technology is difficult and depends in large part on assumptions about the success of scientific and technical advancements and other factors. These assumptions may be explored in scenario analyses featuring advanced technology. For example, several studies have projected that lower carbon fuels (e.g., natural gas) and lower GHG-intensity technologies (e.g., coal gasification) could bridge the transition to zero- or very low-carbon technologies.[26] Two other themes common among many GHG mitigation technology scenarios are steady improvement in energy efficiency (e.g., lowering of GHG-intensity) and the emergence of bio-based products as an important energy source throughout the 21st century.

In addition to technological considerations, cost considerations are major elements in the mitigation

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[26] See, for example, studies by van Vuuren et al. (2004) and Manne and Richels (2004), and the the mitigation scenarios studied in the IPCC Working Group III (see http://www.grida.no/climate/ipcc_tar/wg3/084.htm).

BOX 3-2

HOW BIG IS ONE GIGATON PER YEAR OF GHG REDUCTION?

Actions that provide 1 gigaton per year of carbon-equivalent mitigation for the duration of their existence:

- **Coal-Fired Power Plants.** Build 1,000 "zero-emission" 500-MW coal-fired power plants to supplant coal-fired power plants without CO_2 capture and storage. (Current global installed generating capacity is about 2 million MW.)
- **Geologic Storage.** Install 3,700 carbon storage sites like Norway's Sleipner project (0.27 MtC/year).
- **Nuclear.** Build 500 new nuclear power plants, each 1 GW in size, to supplant an equal capacity of coal-fired power plants without CO_2 capture and storage. This would more than double the current number of nuclear plants worldwide.
- **Electricity from Landfill Gas Projects.** Install 7,874 "typical" landfill gas electricity projects (typical size being 3 MW projects at non-regulated landfills) that collect landfill methane emissions and use them as fuel for electric generation.
- **Efficiency.** Deploy 1 billion new cars at 40 miles per gallon (mpg), instead of new cars at 20 mpg.
- **Wind Energy.** Install 650,000 wind turbines (1.5 MW each, operating at 0.45 capacity factor) to supplant coal-fired power plants without CO_2 capture and storage.
- **Solar Photovoltaics.** Install 6 million acres of solar photovoltaics to supplant coal-fired power plants without CO_2 capture and storage (assuming 10% cell DC efficiency, 1700 kWhr/m^2 solar radiance, and 90% DC-AC conversion efficiency).
- **Biomass Fuels from Plantations.** Convert a barren area about 15 times the size of Iowa's farmland (about 33 million acres) to biomass crop production.
- **CO_2 Storage in New Forest.** Convert a barren area about 40 times the size of Iowa's farmland to new forest.

Note: SRES (IPCC 2000) scenarios assume that all of these technologies will be used extensively prior to 2100.

scenarios. When projected declines in the costs of low-carbon-emitting technologies make them attractive economically, they play major roles in many scenarios. Different technologies may mature and become cost-competitive at different times over the course of a 100-year planning horizon. For example, increased energy efficiency (using today's technologies), mitigation of non-CO_2 GHGs such as methane, and terrestrial sequestration may be cost-effective options in the near term. Transformative supply-side and end-use technologies with greatly reduced GHG emissions profiles could become more cost-effective later, as these technologies advance.

Several landmark multi-model studies,[27] as well as various scenario analysis efforts based on individual models, have explored a range of emission reduction scenarios. In most of these analyses, advanced technology scenarios are modeled under a range of hypothetical GHG emissions constraints (e.g., low, medium, high, and very high). These advanced technology scenarios, in turn, can be compared against baseline scenarios, where the given GHG emissions constraints are met, but with less optimistic assumptions about the advancement of technology. The results can suggest what roles various technologies may play, if assumptions about their advancement could be realized. The results can also, by inference, provide insights about various R&D programmatic goals, suggesting what technological progress would be needed, and by when, in order to achieve the hypothesized results.

Reference Case, Baseline, and Advanced Technology Scenarios

A number of analytical approaches have been pursued to explore the potential contributions of advanced

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[27] For example, the IPCC "Post-SRES" report on mitigation (IPCC 2001) and the EMF studies (Weyant 2004).

[28] The low- or no-cost suite of technologies generally includes improvements to current systems and various cost-effective energy conservation strategies. These are usually modeled as a general rate of energy-efficiency (or intensity) improvement, and are often included in the business-as-usual (or "reference case") emissions projections.

technologies. One approach is to focus on a particular technology or genre of technology, one at a time, and estimate what could be achieved if it were to be fully adopted by a certain time in the future. For example, Brown et al. (1996) estimated the amount of mitigation that could be achieved through use of a variety of individual technologies. More recently, Pacala and Socolow (2004) discussed technology "wedges," each of which represents the mitigation of one gigaton of carbon emissions in the year 2050 (Box 3-2), some of the examples of which were inspired by Pacala and Socolow). Hoffert et al. (2002) examined technologies needed to deliver a certain amount of carbon-free energy by the end of the 21st century. Such approaches are useful for understanding the technical potential of various technologies.

Other analytical approaches address important underlying factors that may influence a technology's ability, within a larger competitive context, to achieve its technical potential. In this context, advanced technologies would need to meet an array of conditions before they could be successfully adopted. They would need to be cost-competitive, in the context of the future global economy and the world energy market, compared to other available technologies. Other considerations include ease of use, reliability, public safety, and acceptance; and still others include policy, environmental, or regulatory factors. Taking these considerations into account requires an integrated assessment approach using models, which typically require competition among technologies to meet certain exogenously imposed emissions constraints, in conjunction with other emissions-related factors and considerations.

Such models simulate, for each step in time, the competitive deployment of technologies and approaches that would be needed to achieve a given amount of emissions reductions at the lowest cost in that time period. Depending on the level of emissions constraint assumed, low- or no-cost approaches may supply a large portion of the emissions reduction.[28] More costly advanced technologies may be adopted more widely in scenarios that require moderate to high levels of emissions reduction. Expensive, undeveloped, or undemonstrated technologies, or technologies that face difficult challenges to wide-scale deployment, may enter the market later in the mitigation period. Hence, the mix of technologies in any given scenario depends on assumptions about technical readiness, costs, and barriers to adoption for each technology, as well as the level of emissions constraint assumed.

In a recent model-based integrated assessment, sponsored by CCTP and conducted by PNNL, a set of 17 scenarios was developed to explore and compare advanced technology options for achieving significant GHG emission reductions. The 17 scenarios include a Reference Case and four sets of GHG-emissions-constrained scenarios (each set has four different levels of emission constraint). One set of emissions-constrained scenarios (the Baseline Scenarios) assumes reference case technologies are available to meet the emissions constraints, and three sets of emissions-constrained scenarios assume advanced technologies become available.[29] The scenarios are summarized as follows:

- A Reference Case scenario represents a hypothetical technological future, where GHG emissions are not constrained, but where significant technical improvements are achieved in a broad spectrum of currently known or available technologies for supplying and using energy.[30] This scenario results in improvements in global GHG-intensity over time, but not in lower GHG emissions. It provides reference level energy and emissions projections to which the energy and emissions in the emissions-constrained scenarios can be compared.
- A set of four Baseline Scenarios use the same Reference Case technology assumptions described above but applies four hypothesized GHG emissions constraints. Because these scenarios require emission reductions from the Reference Case, low- or zero-emission technologies and other means to reduce GHG gases are deployed at higher rates in these baseline emission-constrained scenarios than in the Reference Case. These baseline scenarios provide energy and mitigation cost projections to which the energy mix and costs in the advanced technology scenarios can be compared.
- Each of the three advanced technology scenarios includes a distinct set of technology advancements, beyond those in the Reference Case.[31] Each of

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[29] The four hypothesized GHG emissions constraints (i.e., Very High, High, Medium, and Low) were designed to stabilize, over the long term, the aggregated radiative forcing of the following GHGs: CO_2, CH_4, N_2O, and the so-called "F-gases" (hydrofluorocarbons [HFCs], perfluorocarbons [PFCs], and sulfur hexafluoride [SF_6]). A range of additional substances, such as aerosols, also have important effects on radiative forcing. These substances are not included in this analysis.

[30] The reference case assumes energy efficiency improvements occur, as well as cost decreases in renewable and nuclear technologies that bring their costs to below today's levels.

[31] In the PNNL analysis, Scenarios 1, 2, and 3 are given representative labels of "Closing the Loop on Carbon," "A New Energy Backbone," and "Beyond the Standard Suite," respectively.

these, in turn, is also applied under the four GHG emissions constraints (for a total of twelve advanced technology cases). The advanced technology scenarios include:

Scenario 1, which assumes successful development of carbon capture and storage technologies for use in electricity, as well as in applications such as hydrogen and cement production.

Scenario 2, which assumes additional technological improvement and cost reduction for carbon-free energy sources, such as wind power, solar energy systems, and nuclear power.[32]

Scenario 3, which assumes major advances in fusion energy and/or novel energy applications for solar energy and biotechnology such that they can provide zero-carbon energy at competitive costs in the second half of this century.[33]

A number of common features cut across all three of the advanced technology scenarios:

- Additional gains in energy efficiency beyond the reference case occur.
- Additional technologies for managing non-CO_2 GHGs become available.
- Terrestrial carbon sequestration increases.
- The full potential of conventional oil and gas is realized.
- Hydrogen production technology advances.

None of the advanced technology scenarios is intended to represent a preferred "path" to the future. Rather, each is designed with unique features, distinct from the others, so as to explore orthogonally a wide range of technology options. The current CCTP portfolio of technology R&D is diversified and includes elements of all three of the advanced technology scenarios. The scenarios are not necessarily intended to represent every component of the CCTP portfolio, however. Instead, they illustrate several possible pathways to lower emissions that could be the outcome of successful technology R&D.

Figures 3-12 and 3-13 provide illustrative results across the three advanced technology scenarios for a high emissions constraint case. Figure 3-12 shows the mix of technologies and their associated contributions to total global energy demand for the three advanced energy scenarios. Figure 3-13 shows the CO_2 emissions reduction contributions from the various energy sources and technologies, under the same set of assumptions.

Although each scenario assumes advances in particular classes of technology, all scenarios result in a mix of energy efficiency and energy supply technologies. The overall results show the extent of the variation possible in the mix of emissions-reducing technologies under a variety of assumptions and planning uncertainties.

Economic Benefits of Advanced Technologies

The purpose of CCTP is to accelerate the development of promising technologies that can reduce, avoid, capture, or sequester emissions of GHGs at greatly reduced cost compared to current technologies. Providing advanced technology options can enable progress toward CCTP's strategic goals through greater choice and competition. Stated in other terms, the same amount of GHG emissions could be reduced with advanced technology options at costs significantly lower than would otherwise be the case had they not been developed or made available.

In the PNNL analysis (Clarke et al. 2006), the estimated costs of achieving a range of emission reductions were compared for cases with and without the use of advanced technology.[34] The scenarios described above were supplemented by an additional scenario in which the advanced technologies in all three scenarios were combined in one model run. The resulting cost estimates (Figure 3-14) show that the cumulative cost for meeting the hypothetical carbon constraints is significantly lower in all three advanced technology scenarios than in the Baseline Scenarios that use reference case technology

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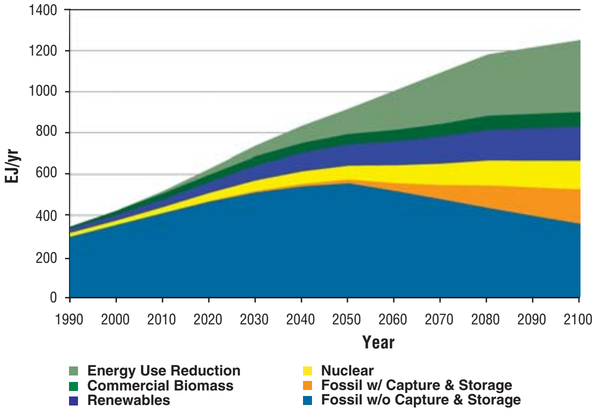
[32] Note that renewables and nuclear energy increase over time in the reference case scenario, but increase more in Scenario 2 due to more significant decreases in cost and performance.

[33] Advanced biotechnologies (sometimes called "Bio-X") are those that combine the biosciences with fields such as nanotechnology, chemistry, computers, medicine, and others to create novel solutions for technology challenges. This could lead to innovative concepts such as the use of "enzyme machines" or even new materials (e.g., bio-nano hybrids) that could replace traditional technology altogether.

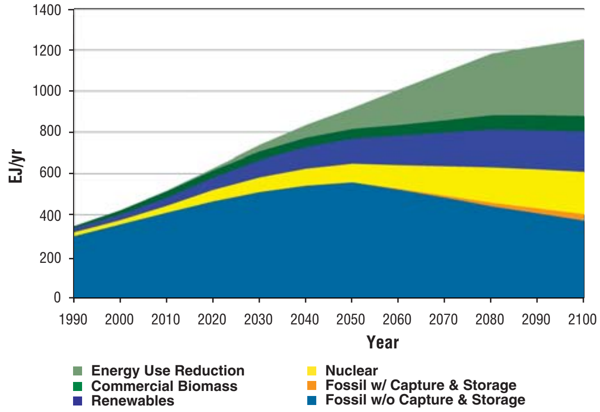
[34] The term "advanced technologies" is used to represent major improvement in current technologies, as well as novel technologies currently not in use. In this study, technology advancement was assumed to lead to more efficient energy technologies with lower capital and operating costs. Details on the assumptions can be found in Clarke et al. (2006). The resulting cost reductions do not consider the cost associated with performing any R&D that might be necessary to achieve the improved technology performance.

World Primary Energy Demand for Three Advanced Technology Scenarios Under a High GHG-Emissions-Constraint Case

SCENARIO 1



SCENARIO 2



SCENARIO 3

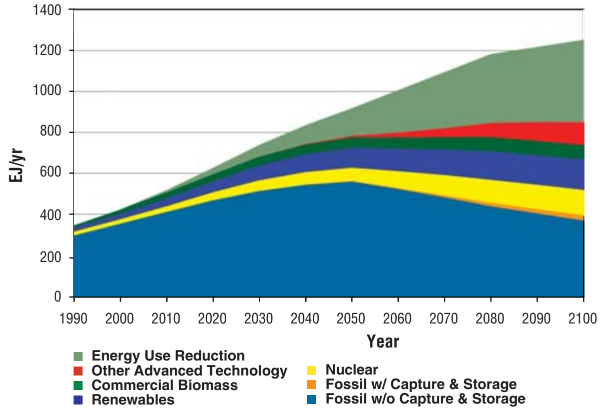
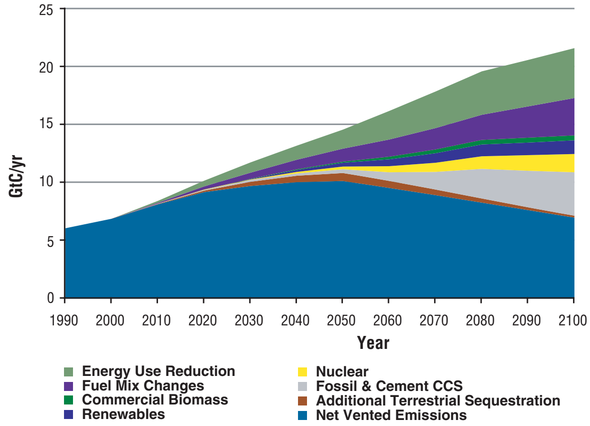


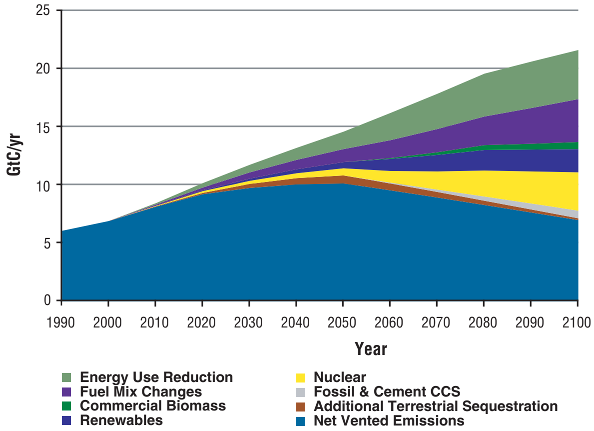
Figure 3-12. World Primary Energy Demand for Three Advanced Technology Scenarios Under a High GHG-Emissions-Constraint Case Note: "Energy Use Reduction" is the amount of energy conserved or saved through advanced energy-efficient end-use technologies compared to a Reference Case, which also includes a considerable increase in energy efficiency compared to today's level. (Source: Clarke et al. 2006)

World Carbon Dioxide Emissions for Three Advanced Technology Scenarios Under a High GHG-Emissions-Constraint Case

SCENARIO 1



SCENARIO 2



SCENARIO 3

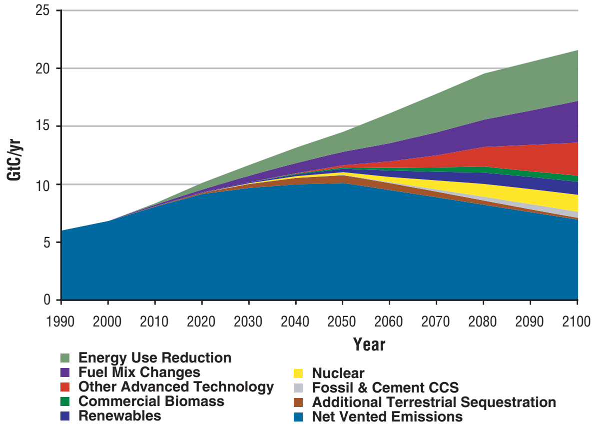


Figure 3-13. World Carbon Dioxide Emissions for Three Advanced Technology Scenarios Under a High GHG-Emissions-Constraint Case Note: "Energy Use Reduction" is the amount of energy conserved or saved through advanced energy-efficient end-use technologies compared to a Reference Case, which also includes a considerable increase in energy efficiency compared to today's level. (Source: Clarke et al. 2006)

Cost Reductions Associated with Advanced Technology Scenarios, Compared to a Baseline Case without Advanced Technologies

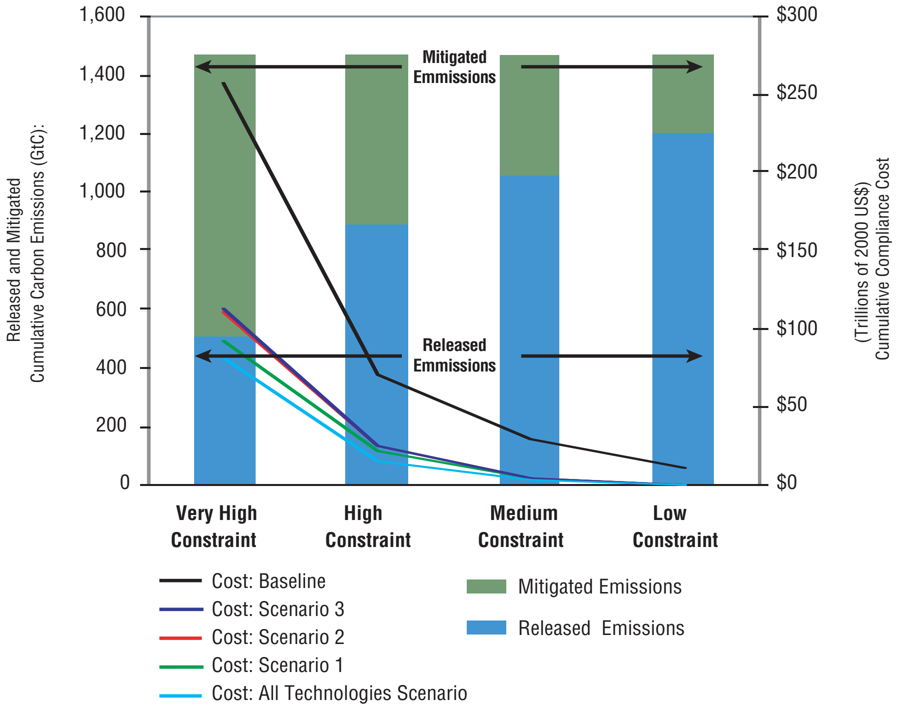


Figure 3-14. Cost Reductions Associated with Advanced Technology Scenarios, Compared to a Baseline Case without Advanced Technologies (Source: Clarke et al. 2006)

Note: Cumulative released emissions (shown in the bar graphs) are highest and mitigated emissions are lowest when the emissions constraint is least stringent (Low Constraint). Costs (line graphs) are highest when the emissions constraint is most stringent (Very High Constraint). Costs are lower when advanced technology was assumed to be available (purple, red, green, and blue lines), than when technology was assumed to advance only incrementally (black line).

assumptions. Accumulated over the course of the 21st century, the potential economic benefits of an advanced technology strategy are likely to be significant, independent of which technologies eventually emerge as most successful. Furthermore, the cumulative cost for meeting the carbon constraints was even lower in the case in which all technology advances were combined, implying that benefits will be greatest if many types of advanced technologies achieve success.

Numerous other studies reach similar conclusions. For example, Manne and Richels (2004) examined limiting global temperature rise using scenarios with “optimistic” technological assumptions. They assumed advanced technologies, such as fuel cells and integrated gasification combined cycle with CO_2 capture and storage, are available in the future. They compared these to more “pessimistic” scenarios without such advanced technologies. The costs[35] were estimated to be 2.5 times lower in the advanced technology cases than in the scenarios without advanced technologies. In another study, Edmonds et al. (2004) report that when a suite of advanced technologies (such as carbon capture and storage, biotechnology, and hydrogen energy systems) are available to be deployed at a large scale, the inferred added dollar value to GHG emissions that would be required to achieve the assumed reduction was 60 percent lower than when the advanced technologies were not available.

The economic benefits of accelerated technical advances are also identified by a class of studies that explore the dynamics of technical change (e.g., Edenhofer et al. (2005), Manne and Richels (2004), van Vuuren et al. (2004), Löschel (2002), Gerlagh and van der Zwaan (2003) and Goulder and Mathai (2000)). These analyses model technical change through mechanisms such as “technology learning” or “learning by doing,” where costs of technologies decline with experience as a function of investment in R&D or other mechanisms. The mechanisms are then used to examine the effects of the technological change on the costs of complying with various climate policy and emissions constraints.

Although these studies vary in design, model platform, and methodology, a common conclusion can be drawn from all of them. That is, technological change can significantly reduce the costs of emissions reduction policies. In these studies, the costs were typically reduced by over 50 percent when technological change was introduced in a portfolio of mitigation options. One of the major conclusions drawn at the recent IPCC Expert Meeting on

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[35] In the study, costs included those associated with fuel switching (to fuels or technologies with lower emissions), changes in domestic and international fuel prices, and price-induced conservation activities.

Emission Scenarios was that technological change can have a significant impact on reducing costs of GHG stabilization.[36]

In addition, the studies indicate that the benefits are greatest when technology advancement is pervasive. A study conducted using the MESSAGE model (Roehrl and Riahi 2000) concluded that mitigation costs are highest in scenarios with static technologies and lowest in scenarios where technology improvements span both supply and end-use sectors.

A multi-gas, rather than a CO_2-only, approach is another important dimension to lowering the costs of stabilizing radiative forcing from GHGs. Weyant and de la Chesnaye (2005) showed that using a multi-gas approach results in a cost reduction of 30 to 50 percent, compared to CO_2-only approaches.

Timing of Advanced Technology Market Penetration

CCTP's planning activities must also consider the timing of the commercial readiness of the advanced technologies included in its R&D portfolio. However, the time at which certain technologies would need to be ready for large-scale deployment in the marketplace is uncertain and would vary, depending on the level of the GHG reductions to be achieved. Understanding how timing varies with varying GHG concentration levels and with varying assumptions about the technology mix provides insights for R&D planning and related technology development strategies. Clearly, R&D programs must complete their contributions well before the time when large-scale deployment of the technologies is expected.

As an illustration, in the PNNL scenario analysis under a "high" emissions constraint, advanced technologies for reducing emissions for energy end use and infrastructure begin achieving emissions reductions at a significant level (one GtC/year) between 2030 and 2040. Under a similar constraint, technologies effecting capture, storage, and sequestration of CO_2 begin making significant contributions (one GtC/year) around 2040 or later. Variations among these dates result from varying assumptions about technologies. A summary of the insights about timing, shown for each CCTP strategic goal, is presented in Table 3-1, across a wide range of hypothesized GHG emissions constraints. In general, the higher the emissions constraint, the sooner the advanced technologies are needed and deployed.

Estimated Timing of the First GtC-eq./Year of Reduced or Avoided Emissions (Compared to the Reference Case) for Advanced Technology Scenarios

CCTP STRATEGIC GOAL	VERY HIGH CONSTRAINT	HIGH CONSTRAINT	MEDIUM CONSTRAINT	LOW CONSTRAINT
Goal #1. Reduce Emissions from Energy End Use & Infrastructure	2010 - 2020	2030 - 2040	2030 - 2050	2040 - 2060
Goal #2. Reduce Emissions from Energy Supply	2020 - 2040	2040 - 2060	2050 - 2070	2060 - 2100
Goal #3. Capture and Store or Sequester Carbon Dioxide	2020 - 2050	2040 or Later	2060 or Later	Beyond 2100
Goal #4. Reduce Emissions of Non-CO_2 GHGs	2020 - 2030	2050 - 2060	2050 - 2060	2070 - 2080

Note: The years shown in the table represent the period in which the first GtC (or GtC-eq.) of incremental emissions reduction (compared to the Reference Case) is projected to occur due to penetration of each class of advanced technology in any one of the advanced technology scenarios. The Reference Class includes significant penetration of energy-efficient end use technologies, nuclear, renewable, and biomass energy, terrestrial sequestration, and non-CO_2 emission reductions.

Table 3-1. Estimated Timing of the First GtC-eq./Year of Reduced or Avoided Emissions (Compared to the Reference Case) for Advanced Technology Scenarios (Source: Clarke et al. 2006)

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[36] Meeting Report of the IPCC Expert Meeting on Emission Scenarios, 12-14 January 2005, Washington D.C. http://www.ipcc.ch/meet/washington.pdf.

3.5

CCTP Goals for Advanced Technology

Review of scenario analyses indicates that, given the scale of the challenge, no single technology or class of technology would be likely to provide, by itself, the quantity of GHG emissions reductions needed to achieve stabilization of GHG concentrations, or its integrated multi-gas metric, radiative forcing, at most of the levels typically hypothesized and examined in the technology literature on scenarios. Instead, these studies show that, under a wide range of differing assumptions and planning uncertainties, technological advances aimed at the following four broad areas are likely to be needed in combination in order to contribute to the needed GHG emissions reductions:[37]

1. Energy End-Use Efficiency and Infrastructure
2. Low- and Zero-CO_2 Emissions Energy Supply
3. CO_2 Capture/Storage and Sequestration
4. Non-CO_2 GHGs

Energy End-Use Efficiency and Infrastructure

Ultimately, global GHG emissions are driven by the demand for services (heating, cooling, transportation, agriculture, industrial process activities, etc.) that require energy or other services and consumables with embodied GHG emissions. Technological advances that can reduce the energy and services required to meet these needs are one of the key means for reducing GHG emissions from energy end-use and infrastructure. Scenario analyses suggest that increased use of highly energy-efficient technologies and other means of reducing energy end use could play a major role in contributing to cost-effective emissions reduction.

In published scenarios, increasing demand for energy services, driven by population and economic growth, drives growth in GHG emissions over the 21st century. If gross world product were to grow by 2.0 percent per year over the span of the 21st century, and the demand for energy services were to grow at a commensurate 2.0 percent per year, then energy demand would grow seven-fold by 2100. Many published scenarios assume gross world product growth above these rates. For example, at the top of the range of the IPCC's *Special Report on Emissions Scenarios* (SRES) scenarios, gross world product grows at more than 3.0 percent per year from 1990 through 2100.

In virtually all published scenarios, however, the demand for final energy[38] and associated emissions of CO_2 grows at rates lower than the growth rates of gross world product. This is because improvements in end-use efficiency, along with structural changes in economic activity, tend to drive up economic value-added and drive down energy inputs associated with increasing global prosperity.[39] In 1990, global final energy intensity (energy used per constant dollar of gross world product) was roughly 17 million joules per dollar. In the IPCC's SRES scenarios, final energy intensities in 2100 ranged from 1.4 million to 5.9 million joules per dollar of gross world product.[40] Without these reductions in energy intensity, which are significant, energy demand growth and associated GHG emissions would be significantly higher. This point is illustrated in Figure 3-15, which shows the relationship between global CO_2 emissions and energy intensities in 2100 in various published scenarios. Although Figure 3-15 shows variation across multiple scenarios due to differences in energy mix and the levels of deployment of low or zero-emitting technologies, the general pattern indicates that lower energy use per unit of economic output leads to lower CO_2 emissions per unit of economic output.

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[37] CCTP also includes two supporting technology areas. These are measuring and monitoring technologies, and application of basic science to applied technology R&D. These supporting areas are not discussed in this chapter, although they are integral elements of the overall CCTP technology strategic plan.

[38] Final energy refers to energy delivered to the point of end use (e.g., to buildings or gas stations) as opposed to energy used as an input to, for example, electricity generation. However, final energy does not represent the actual energy ultimately delivered in the way of services to end-users (e.g., building cooling or vehicle miles traveled) because final energy must be converted to these final services by equipment such as air conditioners and automobiles. Hence, changes in final energy should be interpreted as combining changes both in the level of services demanded and in the efficiency at which final energy is used to supply those services.

[39] See the GHG Emissions Scenario Database at http://www-cger.nies.go.jp/cgere/db/enterprise/scenario/scenario_index_e.html.

[40] Range based on the illustrative scenarios from IPCC (2000). Changes in final energy intensity incorporate both changes in end-use efficiency and changes in the relationship between economic output and the demand for services such as transportation and air conditioning (see footnote 39). Hence, improvements in energy intensity should not be interpreted strictly as improvements in end-use efficiency.

Global CO_2 Emissions Intensity versus Global Energy Intensity

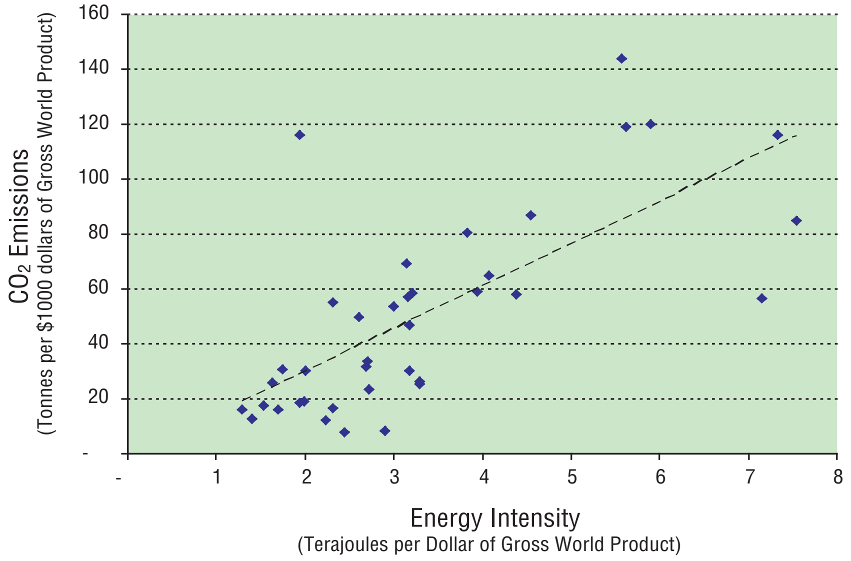

Figure 3-15. Global CO_2 Emissions Intensity versus Global Energy Intensity

(Source: Data from the Greenhouse Gas Emissions Scenario Database[41])

This relationship suggests the significance of the emissions reduction benefits that would accrue from increasing the efficiency of end-use technologies. If R&D efforts were to increase the rate of final energy intensity improvement by one-quarter of one percent per year over the span of the 21st century (leading to an increase in energy efficiency by the end of the century of roughly 25 percent), scenario analyses indicate that CO_2 emissions would be reduced by 3.5 GtC/year by 2100. For perspective, this is roughly half of the total global CO_2 emissions in 2006.[42]

This point is further illustrated by the advanced technology scenarios in the PNNL report on climate change technology strategies (Clarke et al. 2006). In this study, advanced energy-efficiency technologies were assumed to lower final energy requirements by 17 to 32 percent globally in 2100. These reductions were responsible for a cumulative decrease of between 130 to 270 GtC of CO_2 emissions over the course of the 21st century. Energy-efficiency improvements also contributed to the lowering of the costs for achieving stabilization of GHG concentrations across a range of varied assumptions.

Similarly, one of the IPCC's SRES scenarios featuring advanced end-use technologies (A1T) indicates that reductions from end-use efficiency (through reduced final energy intensity) could be responsible for roughly 4.0 GtC/yr by 2100.[43] In addition, Hanson and Laitner (2004) developed an advanced technology scenario and projected that approximately one-third of the U.S. carbon emissions reductions in 2050—roughly one GtC/yr—were attributable to the deployment of more efficient end-use technologies.[44]

Providing technological options to improve energy end-use efficiency can provide a fundamental way to achieve GHG emissions reductions and lower the need for CO_2-free energy supply. This insight is robust across a full spectrum of varied technology futures—whether these futures emphasize fossil fuels combined with CO_2 capture and storage, renewable or nuclear power, or novel technologies such as fusion and advanced bio-technology.

Low- and Zero-CO_2-Emissions Energy Supply Technologies

Supplying the world's energy needs while achieving substantial reductions in GHG emissions may also

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[41] See http://www-cger.nies.go.jp/cger-e/db/enterprise/scenario/scenario_index_e.html.

[42] This calculation is based on the illustrative B2 scenario from IPCC (2000). It assumes that lower final energy requirements would not alter the relative proportions of energy provided from different sources.

[43] Result based on the illustrative scenarios for the A1 set. It was calculated based on a comparison of the illustrative A1T scenario with the illustrative A1B scenario, assuming no change in the primary energy mix between the two. While not identical to A1T, A1B is similar in terms of the emissions per unit of primary energy and therefore serves as an effective reference. The particular scenario cited above used the AIM (model).

[44] Note that many of the assumptions in this study followed from the study, *Scenarios for a Clean Energy Future* (Brown et al. 2000).

Global CO_2 Emissions Intensity versus Percentage of Renewable and Nuclear Energy in the Energy Supply Mix

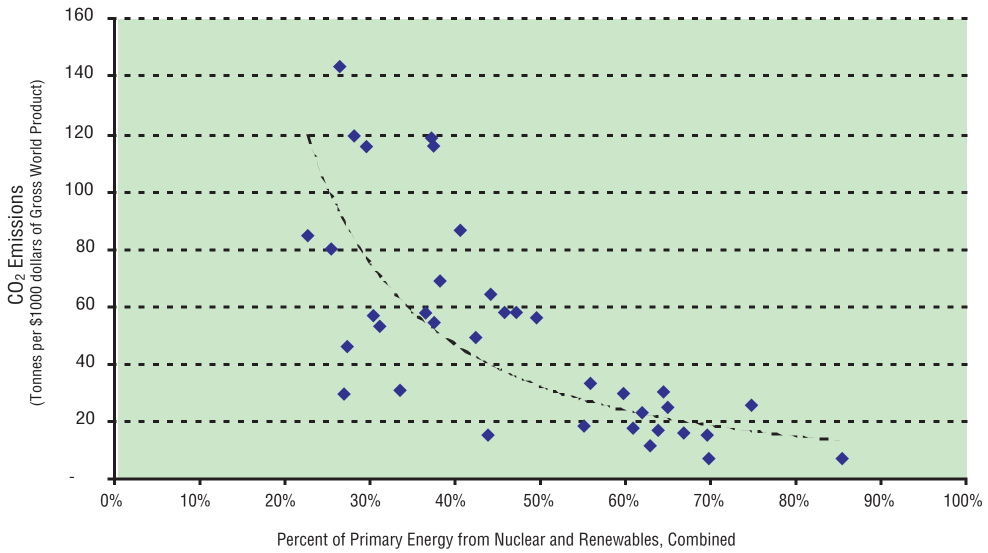

Figure 3-16. Global CO_2 Emissions Intensity versus Percentage of Renewable and Nuclear Energy in the Energy Supply Mix

(Source: Data from the Greenhouse Gas Emissions Scenario Database[45])

require large contributions from energy supply technologies with low or near-zero emissions profiles. These include renewable energy sources for electricity, such as wind, solar, and hydroelectric power; biomass-based energy systems; nuclear power; and the use of these and other technologies to produce the energy carrier, hydrogen. These could also include other advanced technologies such as fusion energy, solar energy from space or remote desert locations, and novel biotechnologies.

In integrated assessment models, low- and near-zero-emissions energy supply technologies are modeled at varying levels of technological detail. While some models explicitly model various low- and near-zero-emissions energy supply technologies, others use one or more generic technology classes to represent these technologies. In either case, the low- and near-zero-emissions technologies prove to be important components to technology strategies aimed at stabilizing GHG concentrations. Figure 3-16 shows the strong correlation between the CO_2 emissions intensity (tonnes of CO_2 emissions per constant dollar of GWP) of the global economy and the percentage of renewable and nuclear energy found in the energy supply mix, as projected in a wide number of scenarios.

A number of scenario analyses give quantitative significance to the importance of low- and near-zero-emissions energy supply technologies in reducing emissions. For example, Akimoto et al. (2004)[46] show that for a hypothetical climate policy where emissions are constrained, the share of the world's primary energy in 2100 met by biomass and wind energy increased by more than 70 percent from their reference case contributions of 10 percent and 4 percent, respectively. In addition, solar power supplied almost 5 percent of the world's primary energy demand by 2100.[47] Growth in nuclear energy (fission), biomass, and renewable energy accounted for about 30 percent of the emissions reduction in 2100, in about equal shares. Similarly, Edmonds et al. (2004) reported that contributions from solar and nuclear energy grew under CO_2 emissions constraints, especially when no technological advancement was assumed for fossil-based generation technologies and CO_2 capture and storage (CCS) technologies.[48]

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[45] See http://www-cger.nies.go.jp/cger-e/db/enterprise/scenario/scenario_index_e.html.

[46] The study used an updated version of the DNE21 model, an integrated assessment model which hard-links macroeconomic, energy systems, and climate change models, and seeks optimal development of the world's energy system for a given climate policy based on maximizing macroeconomic consumption.

[47] The upper limit of the world total nuclear production assumed in this scenario was 920 GW in 2050 and 1450 GW in 2100, so nuclear energy was not a major contributor in this analysis.

[48] This study used the MiniCAM model and the IPCC SRES B2 Scenario to examine the role of advanced technologies under a climate policy aimed at stabilizing atmospheric CO_2 concentrations at 550 ppmv.

As discussed in previous sections, Clarke et al. (2006) examined several advanced technology scenarios to achieve a range of emissions reductions. Low- and near-zero-emissions energy technologies (including solar, wind, biomass, nuclear fission, and advanced concepts such as nuclear fusion and novel biotechnology) contribute between 23 percent and 34 percent of world primary energy demand by 2100. These technologies were projected to contribute between 30 and 340 GtC of CO_2 emissions reductions (cumulative) over the course of the 21st century, under a variety of scenarios aimed at stabilizing GHG concentrations (Clarke et al. 2006).

Finally, in several scenarios that explored the use of hydrogen as a fuel or energy carrier, renewable energy sources were found to be important means for generating hydrogen and other fuels. Edmonds et al. (2004) showed that, under a medium carbon constraint, the preferred feedstock for hydrogen production shifts from fossil fuels to biomass, because the application of CCS to biomass-based H_2 production can result favorably in net negative emissions. Alternatively, Mori and Saito (2004) report that H_2 production from fast breeder reactors can, under certain emissions constraints, cost-effectively supply nearly all of the final energy demand for hydrogen.[49]

Carbon Capture/Storage and Sequestration

Several physical, chemical, geochemical, and biological mechanisms can remove CO_2 from the atmosphere or from point sources, and store or use the resulting CO_2 or chemical derivatives (see e.g., Halmann 1993, Kojima 1997, Inui et al. 1998, Lackner 2002). The CCTP technology thrusts related to capturing/storing and sequestering CO_2 (see Chapter 6) include: (1) engineered capture and storage of CO_2 from power plants and other industrial sources of CO_2 emissions; (2) terrestrial sequestration of CO_2 in trees, soils, and other terrestrial systems; and (3) ocean sequestration via direct injection or other means.

Capture and Storage of Carbon Dioxide

Carbon capture and storage (CCS) refers to the capture, purification, and concentration of molecular carbon dioxide resulting from combustion or other industrial processes, and the subsequent transport to and storage of CO_2 in suitable geologic or ocean reservoirs. CCS has the potential to lower the carbon emissions intensity of fossil energy systems. CCS could also be applied to bio-based electricity-generation systems or to other non-fossil-fuel waste streams, such as those from calcining operations (cement or lime production, for example).

Figure 3-17 shows the amount of carbon dioxide captured and stored, as a function of the amount of primary energy supplied by fossil fuels for various scenarios from the Center for Global Environmental Research data base[50] in the years 2050 and 2100. Both parts of the figure show a relationship between the amount of carbon sequestered and the amount of fossil fuel used. The plots show that by the middle of the century, the deployment of CCS technologies in conjunction with fossil fuel use is occurring in many scenarios, even though lower-carbon fuels (such as natural gas) are still available. By the end of the century, when such fuels are less abundant and/or expensive, CCS is almost always deployed in scenarios with high fossil fuel consumption.

A number of recent studies using integrated assessment models have examined the potential of CCS to lower future CO_2 emissions. Edmonds et al. (2004) report that fossil energy technologies with CCS can supply approximately 55 percent of the global electricity generation by the end of the century in an advanced technology scenario with high emissions reductions.[51] This was more than twice the contribution than in a case where CCS (and other advanced energy technologies) was not assumed to advance. McFarland et al. (2004) find that fossil-based power systems with CCS account for approximately 70 percent of global electricity production by 2100 under a high GHG emissions constraint, where CCS systems and other advanced fossil energy systems are allowed to deploy to their full market potential.[52] Clarke et al. (2006) show fossil systems with CCS contributing up to 50 percent

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[49] This study used the MARIA integrated assessment model to examine the role of nuclear technology and hydrogen use under different climate policies, and different technology advancement assumptions.

[50] Center for Global Environmental Research, National Institute for Environmental Studies, Tsukuba, Japan. See http://www-cger.nies.go.jp/cger-e/db/enterprise/scenario/scenario_index_e.html.

[51] This analysis employed the PNNL MiniCAM model, using the IPCC SRES B2 scenario as the reference case, and compared that case to an advanced technology case that incorporates more efficient and economical CCS, higher efficiency fossil generation, and hydrogen energy systems.

[52] This study used the MIT EPPA model, a recursive dynamic multi-regional general equilibrium model of the world economy. Bottom-up information about coal- and natural gas-based generation systems with CCS were used in a top-down energy economics model to examine the effect of CCS on different climate policies.

Carbon Dioxide Captured and Stored, as a Function of Primary Energy Supplied from Fossil Fuels for Various IPCC Scenarios

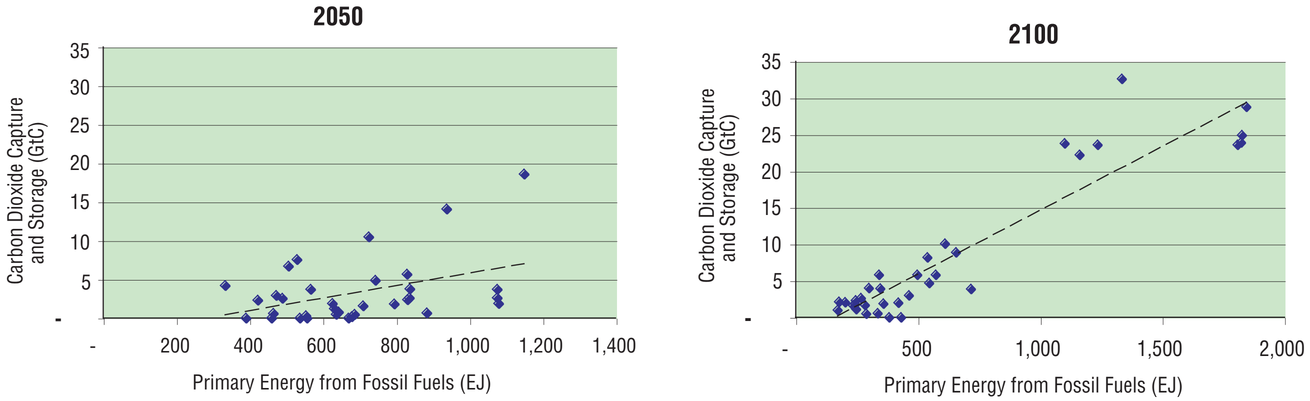

Figure 3-17. Carbon Dioxide Captured and Stored, as a Function of Primary Energy Supplied from Fossil Fuels for Various IPCC Scenarios. Note: The dashed lines in the figures reflect the correlation between fossil energy and CCS deployment. (Source: Various scenario results were extracted from the database maintained by the Center for Global Environmental Research, National Institute for Environmental Studies, Tsukuba, Japan. See http://www-cger.nies.go.jp/cger-e/db/enterprise/scenario/scenario_index_e.html.)

more of the world's total primary energy consumption in 2100 in scenarios featuring technology advancement in CCS, compared to other advanced technology scenarios.[53]

Recent studies have also examined the economic benefits of using CCS in isolation or along with other technological advancements. By allowing fossil energy resources to be used while simultaneously delivering reductions in CO_2 emissions, CCS technologies help to constrain the rate of increase and ultimate peak of carbon prices (an indication of the overall cost of achieving the emission reductions).[54] For example, Edmonds et al. (2004) show that through the large-scale adoption of CCS and other advanced fossil energy technologies, peak carbon permit prices were 62 percent lower than if those technologies were not deployed to their full market potential. In the study by McFarland et al. (2004), CCS reduces carbon prices by 33 percent at the end of the century.

While many studies employ different modeling approaches, technology representations, and assumed climate policies, the synthesis assessment of scenarios shows that CCS has the potential to play a significant role in emissions mitigation during the 21st century. The advancement of CCS-related technologies magnifies this contribution, delivering substantial economic savings. Early technical resolution of the viability of various CCS options could have significant implications for subsequent R&D investment strategies.

Terrestrial Sequestration

Land-use change that results in net CO_2 release to the atmosphere accounts for about 22 percent of today's global CO_2 emissions (IPCC 1996). At the same time, terrestrial systems in many parts of the world are being managed in ways that remove CO_2 (also referred to here simply as "carbon") from the atmosphere and sequester it in soils and biomass. Over the next several decades, the potential exists to offset a significant portion of global CO_2 emissions by managing the world's terrestrial systems to accumulate and store additional carbon. How much of this potential can be realized is uncertain, however, and will depend on the development and diffusion of advanced technologies in a variety of economic sectors.

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[53] This study used the PNNL MiniCAM model to examine energy and economic implications of different technology futures and different levels of emissions reductions. One future assumes that CCS technologies meet aggressive technical, economic, and environmental goals for application on fossil and biomass-based energy systems, along with higher-efficiency fossil generation and greater end-use efficiency gains.

[54] Since the cost of compliance is the total area under the marginal abatement curve, the last two metrics are strongly correlated, i.e., the greater the reduction in the carbon price, the greater the reduction in the cost of compliance.

Globally, the goods and services derived from land resources—including food, water, shelter, energy, and recreation—are basic to human existence and quality of life. Future changes in cropland, grassland, and forest land areas—regionally and globally—will be driven by the ability of land resources to provide these basic goods and services. Hence, the potential to use terrestrial systems to sequester carbon and mitigate global GHG emissions will be directly affected by the development of advanced technologies that reduce human pressures on land by increasing land productivity across a range of economic sectors—including (but not limited to) agriculture, forestry, and energy.

In agriculture, advanced technologies could enhance terrestrial carbon sequestration by enabling the development of new food and fiber products, production processes, and distribution systems that reduce the amount of land needed to feed and clothe the world's population. In forestry, advanced technologies could accelerate the processes of reforestation and afforestation, as well as increase the quantity of wood products that could be obtained from a unit of forest land. Advanced energy technologies could increase terrestrial sequestration by reducing deforestation pressures in developing countries and shifting cropland to bioenergy crop systems that not only increase soil carbon levels but also shift energy production toward technologies that recycle atmospheric CO_2.

Sohngen and Mendelsohn (2003) suggest that global forests have a net sequestration potential ranging from 32 to 102 GtC in the coming century, depending on carbon prices (see Section 3.2.1.2). In a more recent study performed as part of EMF-21, the net sequestration was projected to increase from today's level by 48 to 148 GtC by 2100 under different climate policies (Sohngen and Sedjo, 2006). The cost of land-use and forest sequestration has been estimated to range between $10 and $200 per ton of carbon stored (Richards and Stokes 2004).

Non-CO_2 GHG Emissions

Non-CO_2 GHGs play an important role in the CCTP analytical framework because of their high potential to reduce overall radiative forcing, both in the near term and over the next 100 years, and to reduce the overall cost of GHG stabilization. As shown in Figure 3-1, combined emissions from non-CO_2 gases accounted for about one-quarter of all GHG emissions (in terms of global warming potential) in the year 2000. These gases are particularly important because a variety of scenario analyses show that a significant level of reduction is achievable in the first half of the 21st century.

Potential reductions and cost savings are illustrated in the Energy Modeling Forum multi-gas scenario study—EMF-21 (Weyant and de la Chesnaye 2005)—and other long-term multi-gas studies (e.g., Manne and Richels 2000, 2001; Reilly et al. 2002). The various models exercised in the EMF-21 study used a range of assumptions about technology development, leading to a range of reductions of non-CO_2 GHGs. The studies suggest that, between 2000 and 2100, emissions of non-CO_2 "well mixed" gases (methane, nitrous oxide, and the F-gases) in a moderately constrained emissions case[55] could be reduced by as much as 48 percent, and the cost of GHG stabilization could be lowered by 30 to 60 percent compared to a CO_2-only scenario.

In addition to the long-term EMF-21 multi-gas scenarios, two other studies illustrate maximum technology potential of non-CO_2 mitigation options over the medium term. Delhotal and Gallaher (2005) projected the reduction potential of technological improvements out to 2030 in the three major methane emitting sectors—landfills, natural gas, and coal—for selected countries. By 2030, cost-effective technologies could reduce methane emission to less than 50 percent of current levels in the United States, and could potentially reduce emissions by a factor of two in countries such as China, Mexico, and Russia in the same time frame. Another study by the International Institute for Applied Systems Analysis (IIASA) (Cofala et al. 2005) shows the "maximum potential reductions" to 2030. This study concluded that if all currently available technologies were applied to landfills, agriculture, the natural gas sector, the coal sector, and oil and gas extraction, without consideration of cost, global CH_4 emissions would stop increasing and remain constant through 2030.

The scenarios described above do not explicitly include new or highly advanced mitigation technologies for non-CO_2 GHGs. An analysis conducted by PNNL in cooperation with the U.S. Environmental Protection Agency assumed the development of advanced technologies in areas such as methane emissions from waste and energy sectors, methane and nitrous oxide emissions from agriculture, and high-GWP emissions from the industrial sector (Clarke et al. 2006). Compared to a reference scenario with no emissions constraints and no new non-CO_2 mitigation technologies, the

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[55] The constrained case was defined as 4.5 W/m^2 stabilization target by 2100.

advanced technology scenarios showed that reductions in emissions of non-CO_2 GHGs could potentially contribute 91 to 165 GtC-eq. in cumulative emissions reductions over the 21st century. The assumptions underlying the advanced technology scenario are based on the currently known methods to achieve emissions reduction, as well as detailed "bottom-up" analyses of the technical potential to reduce non-CO_2 GHGs further. Results from this analysis for a high GHG-constrained case are shown in Figure 3-18.

Summary of Relative Contributions of Four CCTP Goals

As described in the sections above, a variety of scenario analyses conducted by different research groups show the importance of technology advancement consistent with each of the four core CCTP emissions-reduction goals:

1. Reduce emissions from energy end-use and infrastructure.
2. Reduce emissions from energy supply.
3. Capture and sequester CO_2.
4. Reduce emissions of non-CO_2 GHGs.

In general, scenario analyses indicate that no single technology option, as presently envisioned, is able to provide sufficient emissions reductions to meet stabilization objectives. Rather, even when assumptions vary, the analyses strongly indicate that a portfolio of technologies is required, with each technology contributing significantly to the GHG emission reductions required.

This point is illustrated by the results of a recent PNNL study (Clarke et al. 2006) in which each of the four technology areas was shown to make contributions toward stabilizing concentrations. Based on the assumptions used in this set of scenarios, no one area was markedly more or less important than others. Figure 3-19 shows the contributions of four technology categories (directly linked to the four CCTP goals stated above) to cumulative GHG emissions reductions between 2000 and 2100. The figure represents one set of possible outcomes from scenarios that are based on a particular set of assumptions about advanced technologies over the next century. It offers a glimpse of the range of emissions reductions new technologies might make possible through reduced energy end use; low- or zero-emission energy supply; carbon capture, storage, and sequestration; and reduction of other GHGs—on a 100-year scale and across a range of uncertainties. Given the magnitude of the CO_2 challenge and the uncertainties in cost, efficacy, impacts, and ultimate design of the mitigation technologies being considered, pursuit of new technological advances and alternative approaches may prove beneficial to the formulation of GHG stabilization strategies.

World Non-CO_2 GHG Emissions Under High Emissions Constraints[56]

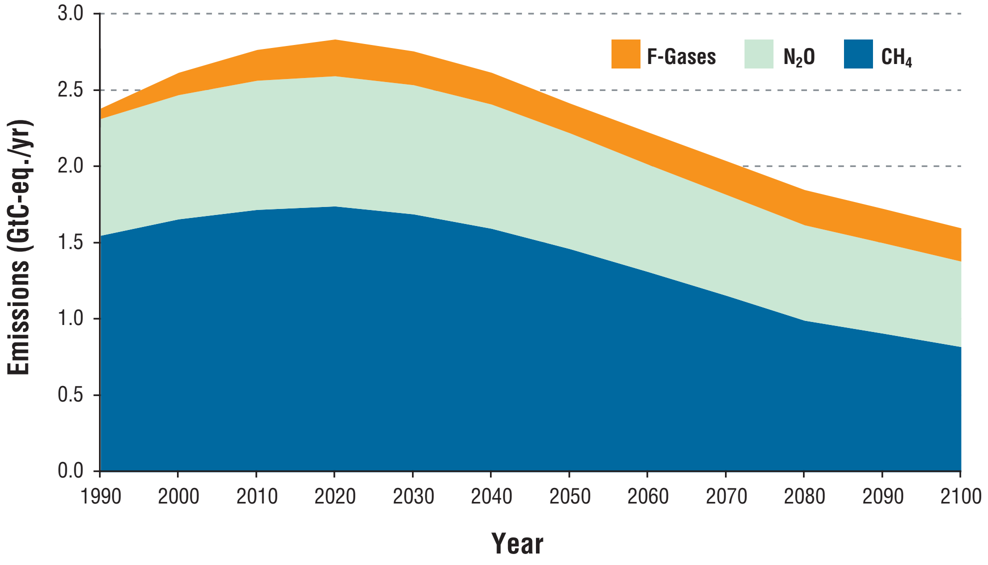

Figure 3-18. World Non-CO_2 GHG Emissions Under High Emissions Constraints[56] *(Source: Clarke et al. 2006)*

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[56] This figure was based on the A New Energy Backbone scenario (Scenario 2).

Cumulative Contributions Between 2000 and 2100 to the Reduction, Avoidance, Capture, and Sequestration of Greenhouse Gas Emissions for the Three Advanced Technology Scenarios, Under Varying Carbon Constraints[57]

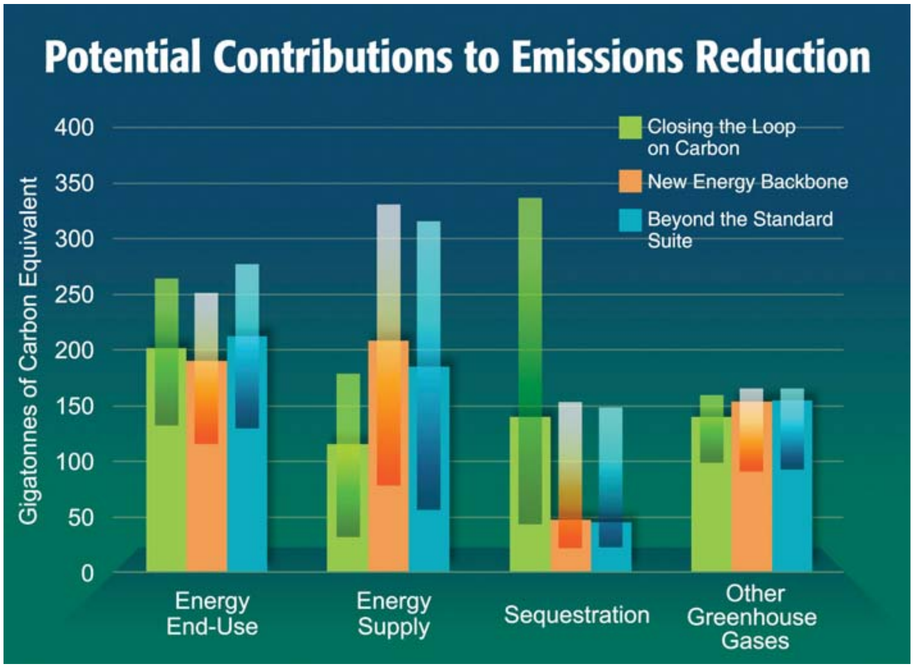

Figure 3-19. Cumulative Contributions Between 2000 and 2100 to the Reduction, Avoidance, Capture, and Sequestration of Greenhouse Gas Emissions for the Three Advanced Technology Scenarios, Under Varying Carbon Constraints[57]

Note: The thick bars show the contribution in the high emission reduction case and the thinner bars show the variation in the contribution between the very high emission reduction case and the low emission reduction case.

3.6 Summary of Insights

Many studies have examined long-term GHG emissions trends under a range of assumptions about the rate of change of population, economic growth, and technology change; and the potential role for advanced technology in mitigating emissions growth. Although the rate of GHG emissions growth over the 21st century is uncertain and dependent on many variables, the scenarios presented in this chapter suggest that significant increases in GHG emissions are projected through the end of the 21st century if there are no constraints on emissions.

Further scientific study is required to understand the quantities and timing of GHG emissions reductions that would be needed to stabilize GHG concentrations at a level that would prevent dangerous anthropogenic interference (DAI) with the climate system. In the approach adopted by CCTP to explore the potential roles for and benefits of advanced technologies, four levels of GHG concentrations were assumed, with results presented for each.

Regarding the scale of the challenge, the scenarios analysis conducted for CCTP suggests that mid-range estimates of the cumulative global emissions reductions needed to result in progress over the course of the 21st century toward eventual stabilization, across a range of GHG concentrations, would be on the order of 300 to 1,000 GtC-eq.[58] Analyses using different assumptions may result in different values, but a number of mid-range analyses indicate 100-year cumulative reductions of similar magnitude.[59] These reductions (or avoidances) would be in addition to the GHG emissions avoided by the substantial energy-efficiency improvements and CO_2-emission-free energy sources already assumed (embedded) in their respective reference case scenarios. Technology advancements could make such reductions much more feasible in the context of economic growth.

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[57] The figure shows the cumulative contributions between 2000 and 2100 to the reduction, avoidance, capture/storage, and sequestration of GHG emissions under the three Advanced Technology Scenarios, based on varying emissions constrained cases. The thick bars show the contribution under the high emission constraint and the thinner, semi-transparent bars show the variation in the contribution between the very high emissions constraint and the low emissions constraint. "Energy End-Use" includes emission reductions due to energy-efficiency measures. "Energy Supply" includes emissions reductions from the substitution of non-fossil energy supply technologies with low or zero CO_2 emissions for fossil-based power generation without capture and storage of CO_2. "Sequestration" includes carbon capture and storage from fossil-based technologies, as well as terrestrial sequestration.

The synthesis assessment of a large number of scenario analyses conducted by different research groups indicates that emissions reductions of the scale needed to achieve stabilization of GHG concentrations can be achieved through various combinations of many different technologies. An important insight that can be drawn from these studies is that, under a wide range of differing assumptions, advanced technologies associated with CCTP Strategic Goals 1 through 4 could all contribute significantly to overall GHG emission reductions.

While many technologies may reduce or avoid GHG emissions, scenario analyses can suggest roles for advanced technologies that could result in potentially large relative economic benefits. When the costs of achieving different levels of emissions reductions were compared for cases with and without advanced technologies, the cumulative cost savings of the former were projected to be 60 percent or more over the course of the 21st century. Further, by including the non-CO_2 gases in a multi-gas GHG reduction strategy aimed at stabilizing at various DAI levels of radiative forcing, overall costs of goal attainment were reduced, potentially by 30 to 50 percent when compared to CO_2-only approaches.

Finally, scenario analyses indicate that the timing of the commercial readiness of advanced technology options is an important R&D planning consideration, and particularly so for R&D planning under scenarios with the higher GHG emissions constraints. Table 3-1 is one set of representative results in this regard, showing when the first GtC/year of reduced or avoided emissions would be needed, depending on the range of GHG emissions constraints. Looking over a 100-year planning horizon, and allowing for capital stock turnover and other inertias, inherent in the global energy system and infrastructure, technologies with low or near-zero net emissions characteristics would need to be available and moving into the marketplace years before the periods shown on Table 3-1.

The following chapters focus in depth on various technological means for making progress toward, and eventually achieving, each CCTP strategic goal. Guided in part by the insights gained through the review and synthesis of the scenario analyses, each chapter's discussion addresses the rationale and technology strategy that would guide investments in the current technology portfolio, explains potential R&D progress, and identifies candidate areas for future research directions that could enrich and broaden the overall portfolio.

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[58] Estimates of emissions reductions required to stabilize GHG concentrations are uncertain and vary based on assumptions. See Section 3.3 and footnote 25. See also "mitigated emissions" in Figure 3-14.

[59] Manne and Richels 2004, Weyant 2004, and Roehrl and Riahi 2000.

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