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CO_2 Emissions Mitigation and Technological Advance: An Updated Analysis of Advanced Technology Scenarios

(Scenarios Updated January 2009)

L. Clarke
M. Wise
J. Edmonds
M. Placet
P. Kyle
K. Calvin
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December, 2008

Pacific Northwest
NATIONAL LABORATORY

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Pacific Northwest National Laboratory
Richland, Washington 99352

Abstract

This report documents a scenario analysis exploring the role of advanced technology in stabilizing atmospheric greenhouse gas concentrations. The analysis was conducted by staff members of Pacific Northwest National Laboratory (PNNL), working primarily at the Joint Global Change Research Institute, in support of the U.S. Climate Change Technology Program's (CCTP's) strategic planning process.

The conceptual framework for the analysis is a set of technology futures implemented in the MiniCAM integrated assessment model. Each future describes a set of technological developments over the 21st century, with a focus on the energy system. A range of futures were produced for this analysis, based on combinations of technological advances among technologies and technology sets.

The assumptions underlying each future were then used as a basis for exploring stabilization of atmospheric CO_2 concentrations at 450 parts per million by volume (ppmv) and 550 ppmv in MiniCAM. Each of the stabilization scenarios, under differing futures of technological evolution, captures a distinct possibility for the global energy system under stabilization, and comparison between them provides strategic insights into the role and character of technology in addressing climate change. These scenarios focus exclusively on the energy system. Future research will include scenarios of soil carbon sequestration and non-CO_2 greenhouse gases.

Several important observations regarding the role of advanced technology in climate change mitigation emerge from the analysis. First, no single technology or class of technology is likely to provide, by itself, the scope or quantity of greenhouse gas emissions reductions needed to achieve stabilization of greenhouse gas concentrations at the levels examined in this study. Because of the magnitude and complexity of the climate challenge, all of the stabilization scenarios in this study include a mix of energy efficiency and energy supply technologies. Second, accelerated technology development offers the potential to dramatically reduce the costs of stabilization. Global mitigation costs over the century were decreased by as much as 80 percent when all of the advanced technologies were available, relative to the stabilization scenarios with reference technologies assumptions, leading to economic benefits of hundreds of billions to trillions of dollars globally. Further, the economic benefits of deploying advanced technology are greater with more ambitious emissions limitation constraints, because near-term emissions mitigation requirements increase dramatically as CO_2 concentration targets are lowered. The 450 ppmv atmospheric CO_2 concentration limit requires deeper and nearer-term emissions reductions than does the 550 ppmv limit; however, both limits considered in this study imply the need for near-term actions to research, demonstrate, and deploy climate technologies.

An exhaustive set of scenario results is provided in a companion appendix to this report.

Contents

1.0 Introduction

Human activities, including the burning of fossil fuels, deforestation and other changes in land use, and agricultural and industrial processes, are leading to increasing atmospheric concentrations of substances that affect the radiative balance of the Earth and, consequently, its temperature and other aspects of its climate. Prominent among these substances are the greenhouse gases, which include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases such as halocarbons and aerosols, such as sulfur, black carbon (BC) and organic carbon (OC). CO_2 is the most important anthropogenic greenhouse gas, and the most important source of anthropogenic CO_2 is fossil fuel use—the oxidation of oil, natural gas, and coal. The full climatic implications of increasing concentrations of these substances are not completely understood, nor are the possible implications of climatic changes on human and natural systems. Uncertainty also surrounds the future emissions of these substances, which are influenced by forces such as population growth, economic growth, and technological changes that cannot be predicted with certainty. Moreover, climate change is a multi-century challenge due to the long lifetimes of many greenhouse gases in the atmosphere, which magnifies all of these uncertainties.

Despite these uncertainties, the possibility of dangerous anthropogenic impacts resulting from accumulations of greenhouse gases in the Earth's atmosphere has heightened attention on current and future anthropogenic sources of greenhouse gas emissions and various means for reducing these emissions. Illustrative of this concern, the United Nations Framework Convention on Climate Change, to which the United States is a party, states as its ultimate objective: "…stabilization of greenhouse gas concentrations in Earth's atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system…within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened, and to enable economic development to proceed in a sustainable manner" (UN 1992). Stabilizing atmospheric greenhouse gas concentrations requires that emissions be equally balanced by the processes that remove greenhouse gases from the atmosphere. For CO_2, this means that anthropogenic emissions must eventually decline toward zero as the ocean and atmosphere come into equilibrium. In contrast, CO_2 emissions are rising today and, absent actions designed to alter this situation, are projected to continue to rise for many decades into the future.

Meeting the objective of stabilizing greenhouse gas concentrations will, therefore, require fundamental changes in the way the world produces and uses energy, as well as in many other greenhouse gas-emitting activities within the industrial, agricultural, and land-use sectors of the global economy. It is widely acknowledged that new and improved technologies could substantially reduce the economic burden of such changes (GTSP 2000, Weyant 2004, Clarke et al., 2006). Modern-day industrial economies are dependent on fossil fuels with their associated greenhouse gas emissions. Not surprisingly, many governments view measures to foster technological change as integral to their policies toward climate change.

This report documents an analysis exploring the role that advanced technology could play in stabilizing greenhouse gas concentrations.[1] The analysis was conducted by staff members of Pacific Northwest National Laboratory (PNNL), working primarily at the Joint Global Change Research Institute, a

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[1] Note that reductions in greenhouse gas emissions are not the only role for technology. Technology may also be important, for example, in adapting to a changing climate.

collaboration between PNNL and the University of Maryland at College Park. The work was conducted in support of the U.S. Climate Change Technology Program's (CCTP's) strategic planning process. The CCTP, led by the U.S. Department of Energy, coordinates the Federal government's investment in climate-related technology research, development, demonstration, and deployment (R&D), which is carried out by twelve Federal agencies. The work in this report builds on previous scenario analyses for the CCTP found in Placet et al. (2004) and Clarke et al. (2006) (henceforth referred to as the 2004 CCTP Scenarios and the 2006 CCTP Scenarios).

For over two decades, PNNL has been developing and using a set of integrated assessment models to analyze the role that technology plays in determining future emissions of greenhouse gases and the economic implications of reducing these emissions. The CCTP asked PNNL to support its planning process by producing advanced technology scenarios using the MiniCAM integrated assessment model, developed and maintained by PNNL. PNNL constructed sets of future technology assumptions for a range of technologies and technology classes as inputs to MiniCAM. PNNL then produced various combinations of these technology assumptions and analyzed the energy, emissions and economic implications of these combinations under the constraint of stabilizing long-term atmospheric CO_2 concentrations. Two long-term concentrations were explored for this analysis: 450 ppmv and 550 ppmv. This report describes the scenarios, documents the assumptions used in scenarios, and provides an analysis of the results.

Scenario analysis is a well-established analytical approach for exploring complex interrelationships of large numbers of variables and for making decisions under uncertainty. Scenarios are not predictions; they are "what-ifs"—sketches of future conditions, or alternative sets of future conditions, for use in decision-making exercises or analysis. Scenario analysis has been used extensively in the climate change context (e.g., the CCSP Scenarios by Clarke et al. 2007, the *Special Report on Emissions Scenarios* by Nakicenovic and Swart 2000). Hence, the scenarios in this report should be viewed as an exploratory exercise to better understand the potential benefits of technology in addressing climate change. They are not meant to mirror any specific CCTP program goals or to provide the single best estimate of the benefits of advanced technology.

The scenarios in this report are fundamentally *technology* scenarios. They are intended to illuminate the benefits of advanced technology in addressing climate change across a range of different possible stabilization levels for greenhouse gas concentrations. The analysis does not focus on identifying or promoting any particular level of greenhouse gas emissions reduction or stabilization, nor does it explore different policy approaches to achieve such reductions.

The remainder of the report is organized as follows. Section 2 provides an overview of the approach to the development of the scenarios. Section 3 introduces the MiniCAM model and discusses key assumptions underlying the different technology scenarios. Section 4 presents the Reference Scenario, a scenario in which technology continues to improve beyond today's levels (according to reference technology assumptions), and governments take no explicit actions to mitigate climate change. The Reference Scenario is not a prediction of what might happen absent actions to address climate change; it is a scenario based on specific assumptions about the future, and it serves as a point of departure for assessing the potential impacts of stabilization and the associated benefits of advanced technologies. Section 5 discusses the stabilization scenarios, including the advanced technology stabilization scenarios. Section 6 provides a brief summary of the report and concluding thoughts. An exhaustive set of scenario results is provided in a companion appendix to this report.

2.0 Overview of Technical Approach

The scenarios in this report were designed to illuminate the role of advanced technology in making progress over a century-long planning horizon toward eventual stabilization of atmospheric CO_2 concentrations. Structuring the scenarios for this purpose required the resolution of a number of study design issues. This section discusses these issues and provides an overview of the technical approach underlying the scenarios.

Study design issues fall into three categories. The first involves the characterization of what is meant by stabilization. This includes issues such as the greenhouse gases included in the analysis, how these greenhouse gases are combined or weighted, the metric by which stabilization is measured, and the stabilization levels themselves. These issues are discussed in Section 2.1. The second category involves the development of emissions trajectories leading to stabilization. This includes issues such as the emissions-reduction scheme by which stabilization is achieved (e.g., the degree of global participation in reducing emissions) and the manner in which emissions reductions are spread over time. These issues are discussed in Section 2.2. The final category involves the development of the technology scenarios from MiniCAM input sets and the overall approach to implementing these scenarios in MiniCAM. This is discussed in Section 2.3. Model inputs are discussed in detail in Section 3.

2.1 Defining Stabilization

Given the prominent role of CO_2, many past studies of stabilization have focused exclusively on the actions and issues involved in stabilizing CO_2 concentrations, which are defined in terms of the parts per million by volume (ppmv) of CO_2 in the atmosphere. Stabilization levels commonly discussed in previous literature include, among others, 450 ppmv, 550 ppmv (which corresponds roughly to a doubling of CO_2 in the atmosphere relative to preindustrial levels), 650 ppmv, and 750 ppmv. This study follows in this tradition and focuses exclusively on CO_2 stabilization.

Although CO_2 is the most important greenhouse gas involved in climate change, non-CO_2 greenhouse gases and aerosols are also important. For this reason, a range of studies, including the 2006 CCTP Scenarios have applied a broader definition of stabilization that includes the significant non-CO_2 greenhouse gases. Extensions to this current scenario effort will include non-CO_2 greenhouse gases.

Because climate stabilization is discussed in the research and policy literatures in both in terms of CO_2 stabilization and in terms of multi-gas stabilization, it is useful to put the CO_2-only results from this analysis in the context of multi-gas stabilization. That is, how might the results of this analysis compare to those from analyses that include multiple greenhouse gases?

In multi-gas analyses, an aggregate metric is needed that can represent the combined effects of the multiple gases. It is not feasible to simply add the concentrations of different gases together, because the different gases have substantially different warming effects at similar concentrations. For example, one part per million of CO_2 has a different impact than one part per million of CH_4.

The most common metric for combining the radiative influences of different substances is radiative forcing (NRC 2005). When the Earth system is in radiative equilibrium, the average energy flowing into the Earth's atmosphere from the Sun is equally balanced by energy flowing out, largely through infrared (heat) radiation. An increase in the concentration of greenhouse gases reduces the outgoing energy flow, upsetting the balance between incoming and outgoing radiation. Over time, the climate system will respond to this radiative imbalance and adjust to bring energy flows back into balance. One of the principal responses to an increase in radiative forcing is an increase in the average surface temperature of the Earth, although other changes such as altered precipitation patterns will also occur. Radiative forcing measures the amount of change in the Earth's energy balance. It is a global average metric, measured in watts per square meter (Wm^{-2}).

A second, related metric is CO_2-equivalent concentrations. For a given multi-gas radiative forcing level, the CO_2-equivalent concentration is the CO_2-only concentration that would lead to the equivalent radiative forcing. That is, it is the CO_2 concentration that would lead to that forcing level if no other atmospheric constituents were changed from pre-industrial times. Hence, multi-gas radiative forcing and CO_2-equivalent concentrations are essentially the same metric, but expressed in different terms.[2]

The 2006 CCTP scenarios were constructed based on multi-gas radiative forcing, but in such a way as to be consistent with CO_2-only scenarios. The multi-gas radiative forcing levels were constructed so that resulting CO_2-only concentrations would correspond to 450 ppmv, 550 ppmv, 650 ppmv, and 750 ppmv. The Climate Change Science Program (CCSP) Scenarios (Clarke et al. 2007) were constructed using a similar approach. In that study, each of the three participating modeling teams developed different assumptions about the role of non-CO_2 greenhouse gases, leading to different forcing levels from these substances associated with any given CO_2 stabilization level. The non-CO_2 greenhouse gas forcings from the CCSP Scenarios can therefore be used to approximate the total radiative forcing that would be obtained if the current scenarios were constructed from a multi-gas perspective (IPCC 2007c). Table 2.1 shows the link between the CO_2-equivalent concentrations in this study and multi-gas metrics. A 450 ppmv CO_2 stabilization level, using the non-CO_2 forcings from the CCSP scenarios, would result in a CO_2-equivalent concentration of roughly 520 ppmv CO_2-eq to 560 ppmv CO_2-eq. Hence, when this study considers a 450 ppmv CO_2 stabilization level, the CO_2-eq level that accounts for all the greenhouse gases is closer to 550 ppmv. Table 2.1 shows the corresponding crosswalk for the 550 ppmv CO_2.

Table 2.1. CO_2 concentrations levels and associated RF from CO_2 and non-CO_2 GHGs (ppmv)

CO2-Only		Non-CO2 GHG RF from CCSP Scenarios (W/m2)*	Total RF from Greenhouse Gases (W/m2)**	CO2-Equivalent Concentration (ppmv)**
Concentration (ppmv)	Radiative Forcing (W/m2)			
450	2.58	0.76 to 1.15	3.34 to 3.73	519 to 558
550	3.65	0.79 to 1.22	4.44 to 4.87	638 to 691

* From the CCSP Scenarios (Clarke et al., 2007)

** Including RF from CO2 only with RF from non-CO2 GHGs from the CCSP Scenarios (Clarke et al., 2007).

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[2] Sometimes a "CO_2 equivalent" calculation is created by weighing each of the greenhouse gases with a number called a "global warming potential" or GWP The GWP is an approximation, of the CO_2 equivalent calculation based on radiative forcing. The calculation based on radiative forcing is always preferred.

Greenhouse gases are not the only atmospheric constituents that affect the global climate. Figure 2.1 shows an estimate of the radiative forcing impacts of a range of radiatively important substances and other effects as of 2000. As the figure shows, greenhouse gases are among the largest and best understood anthropogenic factors. Other substances, particularly aerosols, are likely to have substantial effects as well, although these effects are less well understood than those of the greenhouse gases. In addition, the atmospheric lifetimes of many of these substances in the atmosphere are very short relative to those of the greenhouse gases; hence, many of their effects are regionally heterogeneous.

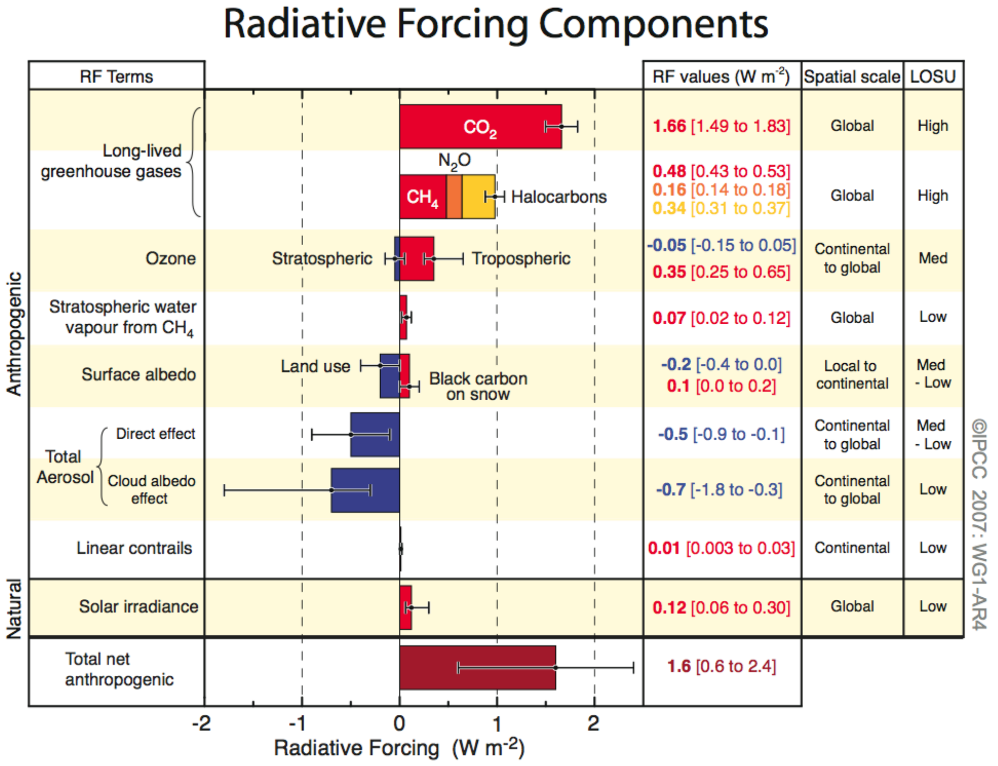

Figure 2.1. Radiative forcing of various atmospheric constituents and relative uncertainties (IPCC 2007)

2.2 Emissions Pathways to Stabilization

Stabilization of radiative forcing from greenhouse gases requires that the concentrations of these gases be stabilized and, consequently, that the net emissions of these gases be reduced to levels at which emissions are identically balanced either by uptake or destruction in natural systems. There are multiple ways that these emissions reductions might be achieved. There is potential flexibility in where reductions occur, when they occur, and the distribution of emissions reductions among greenhouse gases. All of these flexibilities must be addressed in defining an approach to stabilization.

The CO_2 emissions reductions pathways constructed for these scenarios are designed with the goal of minimizing the present value of global emissions reduction costs over the century. One characteristic of such cost-minimizing pathways is that emissions reductions at any point in time are distributed among the world's nations according to where they are least expensive. This means not only that all countries of the world are active participants in global CO_2 emissions reductions, but also that some countries will reduce emissions more than others because there are greater opportunities for cost-effective reductions in those countries. This approach is often referred to as "where" flexibility.[3] It is assumed in the construction of these scenarios. Several recent studies have explored non-optimal policy structures, along with the combined implications of these structures and advanced technology (see, for example, Edmonds et al., 2008, Richels et al, 2007).

An important extension of "where" flexibility is the degree to which different sectors of the economy are covered by the climate policy. These scenarios assume that all sectors of the energy and industrial (e.g., electricity and transportation) system see the same price for carbon, so that the marginal costs of mitigation across sectors is equal. Recent literature has demonstrated that terrestrial systems are also critical for stabilization. For example, production of bioenergy crops has the potential to lead to land-use change emissions from deforestation. Conversely, the desire to hold carbon in terrestrial systems, such as forests, can lead to an incentive to reforest or afforest when stabilization of CO_2 concentrations is the societal goal. Hence, these scenarios assume that carbon in terrestrial systems is fully incorporated into the global climate regime so that emissions from land-use change are treated comparably with emissions from energy and industrial systems.

A second characteristic of cost-minimizing pathways is that emissions reductions gradually increase over time, balancing competing goals, such as minimizing early retirement of existing capital stock, taking advantage of new technological advances that won't be available for decades, allowing for early and continued investment in other portions of the economy as a foundation for economic growth, and minimizing dramatic changes in reductions from year to year. This is often referred to as "when" flexibility (e.g., Manne and Richels 1997, Wigley et al. 1996). As a result of the gradually increasing emissions mitigation requirements, emissions peak and then decline toward levels at which they are balanced by removal or destruction in natural systems.

This study uses an approach to when flexibility that follows this principle of economic efficiency over time. Stabilization regimes can be split into two distinct time periods: (1) the time period before the final CO_2 concentration limit is reached and (2) the time period, stretching out into the far future, after the stabilization target has been reached. In the first period, the price of carbon rises exponentially at the discount rate, which is 5 percent in this study. This is known generally as a Hotelling price path, based on the seminal resource extraction work of Hotelling (1931).[4] Hence, there is an initial price in the first year of emissions mitigation, roughly assumed to be after 2012, which rises exponentially thereafter. The price of carbon is initially low, but doubles at a regular rate until the concentration of CO_2 reaches the concentration limit. Along this carbon price pathway, a decision maker in any period sees the discounted marginal cost of removing a ton of carbon from the atmosphere in the present and future as equal.

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[3] It is important to note that the net cost to an economy can be dramatically affected by the international policy environment. For example, in a "cap-and-trade" international policy regime, the allocation of permits ultimately determines the distribution of net costs or benefits to participants.

[4] A more accurate approach for climate analysis is a modification of the Hotelling approach articulated by Peck and Wan (1996). In this approach, the price of carbon rises at the rate of interest, plus the in-year average rate of removal of carbon from the atmosphere by ocean and terrestrial carbon sinks. This will tend to lead to a discount rate slightly above 5 percent, and one that will vary over time and with the CO_2 concentration. This study has used the simplified approach of a constant exponential rate without the adjustment for the rate of carbon removal from the atmosphere.

Therefore, if the initial price of carbon is known, then all subsequent carbon prices are uniquely determined until the concentration of CO_2 reaches the limit.

When the concentration of CO_2 reaches the limit, the price is no longer set by the exponential growth path. At this point, there is a transition to a price path determined by the physical characteristics of the carbon cycle. The physical uptake of terrestrial and ocean carbon reservoirs govern allowable emissions. Global emissions are thereafter controlled so that the concentration of CO_2 is held constant at the limit. The price of carbon is set so that allowable emissions are exactly equal to carbon uptake by terrestrial and ocean reservoirs.

For any concentration limit and assumptions regarding technology, population growth, economic growth, and other drivers of emissions and emissions mitigation potential, there is a unique starting point for both emissions reductions and the global carbon price that minimizes the discounted costs of mitigation over time. This path has the characteristics that the exponentially rising price path and the physically constrained price path are continuous at the point of transition. That is, there are no ways of reducing total costs by shifting emissions mitigation between the exponentially growing price regime and concentration maintenance regime by arbitraging at the transition point.

The economically efficient carbon price today is irrevocably linked to expectations about future technology availability and emissions mitigation. For any CO_2 concentration, pessimistic expectations about humanity's ability to mitigate carbon emissions in the far future would be reflected in a higher price of carbon and larger emissions reductions today. Conversely, optimistic expectations about humanity's ability to mitigate carbon emissions in the far future would be reflected in lower carbon prices and less aggressive emissions reductions today.[5]

The emissions pathways in this report are based on this concept of when flexibility. This means that every scenario is characterized by a unique emission and cost pathway over time that captures the two-part optimizing character described above. However, there remain some important consistencies between the scenarios in this regard; most notably that atmospheric CO_2 concentrations are stabilized around mid-century for the 450 ppmv scenarios, and atmospheric CO_2 concentrations are stabilized around the end of the century for the 550 ppmv scenarios.[6]

2.3 Constructing the Technology Scenarios

The technology scenarios in this report are based on combinations of future technology developments in the energy sector. Adjustments in the way that energy is produced and used will play a prominent role in

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[5] A third characteristic of economically optimal emissions trajectories is efficient tradeoffs between CO_2 and non-CO_2 substances. This is commonly referred to as "what" flexibility. In multi-gas scenarios, such as the 2006 CCTP Scenarios and the CCSP Scenarios used different means to obtain economically-efficient allocations. The CCSP Scenarios provide a discussion of methods for obtaining economically efficient tradeoffs over time between greenhouse gases. The contributions to forcing from non-CO_2 greenhouse gases in Table 2.1 are from the CCSP Scenarios and therefore reflect the approaches to what flexibility used by the authors of that report.

[6] Note that the 550 ppmv scenarios were based on the requirement that 550 ppmv must be reached by 2095. It was not possible to precisely determine the appropriate stabilization point for the 550 scenarios because MiniCAM does not extend beyond 2095. Hence, the requirement that stabilization must occur no later than 2095 is meant as a proxy for the appropriate timing of stabilization. Note that a number of studies have corroborated the assumption that stabilization at 550 ppmv tends to take place near the end of the century (see, for example, the CCSP Scenarios: Clarke et al, 2007). Although the majority of the 550 ppmv scenarios in this study exactly met the end-of-century requirement, several did reach stabilization prior to 2095.

efforts to stabilize greenhouse gas concentrations because of the energy system's increasingly dominant role in anthropogenic CO_2 emissions

Twelve aggregate technology areas were defined for the purposes of this study. For each of the 12 technology areas, advanced and reference technology assumptions were generated. The scenarios themselves are combinations of these assumptions along with the climate stabilization levels. The Reference Scenario assumes no climate policy and reference technology.

The choice of advanced and reference technology assumptions play a pivotal role in all of the key metrics that emerge from these scenarios, including deployment levels and economic impacts. The mechanisms by which these assumptions were chosen therefore deserve some discussion. The most important role of the reference technology assumptions is to serve as a plausible point of departure for analysis of stabilization and the role of advanced technology. Some reference technology assumptions represent a stylistic continuation of business-as-usual in technological advance, whereas others are explicitly chosen to be a counterfactual for large scale deployment. For example, the reference technology assumptions are based on no new nuclear builds over the century globally. This is an unlikely future, but is useful for understanding the role of nuclear power and the value of technological advances in safety, waste management, and proliferation resistance that would enhance the potential for large-scale deployment. The advanced technology assumptions then serve the complementary role of both representing levels of advance near the edge of what might be plausible (although here there is also a great deal of latitude in choosing what is plausible) and serving as a well-described deviation from the reference technology assumptions.

It is very important that the results of these scenarios not be seen as predictions of how much different technology areas might be worth. Instead, the appropriate interpretation is to consider the scenarios as demonstrating the sorts of implications that could arise, including economic benefits, if the assumptions in this report were to come true. Readers can use their own judgment as to whether those assumptions are likely or unlikely.

3.0 Modeling Framework and Technology Assumptions

3.1 Introduction

This section discusses the model assumptions used to create the scenarios within the modeling framework developed by Pacific Northwest National Laboratory (PNNL), called MiniCAM. Section 2 discussed the overall approach to scenario development, but the implementation of the scenarios requires detailed assumptions about technology, economic growth and many other factors. This section describes the model and the technology assumptions used in this analysis. The resulting scenarios are discussed in Section 4 (for the Reference Scenario) and Section 5 (for the reference and advanced technology stabilization scenarios).

Assumptions within any formal modeling framework include not just the values of model parameters, but also the formulaic and logical structure of the model itself. For example, a model that represents coal-fired electric generation with a single, representative technology delivering electricity at a constant cost per kWh requires a single parameter to represent this cost. In contrast, MiniCAM specifies a number of coal-fired electricity technologies, and for each it considers both the efficiency of the technology and the aggregate non-energy costs. This requires a larger and different set of parameters. More technologically detailed models will require still more, and perhaps different, parameters. This section describes both the modeling approach and the model parameters, to provide a more complete perspective on the assumptions that underlie the scenarios.

The remainder of this section is organized as follows. Section 3.2 provides an overview of MiniCAM. Section 3.3 provides an overview of the components of the model that differ among technology scenarios. Section 3.4 describes the assumptions and model structure, as appropriate, in the energy system. Section 3.5 discusses agriculture, land use, and bioenergy production in MiniCAM.

3.2 MiniCAM

MiniCAM is an integrated assessment model. Integrated assessment models are tools for exploring the complex interrelationships among economic activity, the energy and industrial system, managed and unmanaged ecosystems, the associated greenhouse gas emissions, and the resulting impacts on climate. Consistent with the nature of the greenhouse gas management challenge, many integrated assessment models generate results over a century-long time scale. MiniCAM was first developed decades ago and has been continually refined and updated since its creation. It has been used as the basis for numerous peer-reviewed publications, and it has been exercised in a range of model inter-comparison or scenario development exercises, including those run by the Energy Modeling Forum at Stanford University and the CCSP Scenarios. MiniCAM was also one of the six models included in the Intergovernmental Panel on Climate Change *Special Report on Emissions Scenarios* and is currently one of four international models being used to produce Representative Concentration Pathway (RCP) Scenarios that will be used by climate models in the development of ensemble calculations to be assessed in the IPCC Fifth Assessment Report. MiniCAM has been constructed to allow for substantial focus on technology and the implications of technology for emissions mitigation while still maintaining a global, long-term focus along with integration of energy systems, agriculture and land use systems, the carbon and other natural cycles, and the climate.

MiniCAM models the energy and industrial system, including land use, in an economically consistent global framework. MiniCAM is referred to as a partial equilibrium model because it explicitly models specific markets and solves for equilibrium prices only in its areas of focus: energy, agriculture and other land uses, and emissions. Population, economic growth rates, and the operation of other sectors of the economy are assumptions to the model.

MiniCAM operates over a projected time horizon from today through 2095 by solving, in each modeled time step (currently 15 years), for supply-demand equilibria in energy, agriculture, and greenhouse gas markets. The supply and demand behaviors for these markets are modeled as a function of market prices, technology characteristics, and demand sector preferences. Market prices are an output of the model. Prices are adjusted in the model solution algorithm until supply and demand for each market good are equal.

A key benefit of integrated assessment models is that they can be used to explore interactions between different sectors that would otherwise be difficult to discern. For example, an increase in the price of oil will reduce the quantity of oil demanded by the energy system, and increase demands for energy from competing sources. In equilibrium, these market-clearing prices (e.g., the prices of natural gas, crude oil, coal, electricity, and emissions) are, by definition, internally consistent with all other prices. A range of model parameters influence the nature of the resulting economic conditions, including (1) energy technology characteristics (from production to end-use), (2) fossil fuel resource bases (cost-graded resources of coal, oil, and natural gas), (3) renewable and land resources (e.g., hydroelectric potential and cropland), (4) population and economic growth (drivers of demand growth), and (5) policies (e.g., policies about energy and emissions).

MiniCAM uses a logistic choice methodology to determine market shares of different fuels and technologies based on a probabilistic model of the relative prices of the competing fuels or technologies (Clarke and Edmonds 1993, McFadden 1974, McFadden 1981). This methodology is based on the idea that every market includes a range of different suppliers and purchasers, and each supplier and purchaser may have different needs and may experience different local prices. Therefore, not all purchasers will choose the same technology because the average price of that technology is lower than the average price of a competing technology. The logistic choice methodology allocates market shares based on prices, but ensures that higher priced goods can gain some share of the market, which is consistent with real observations and economic fundamentals. Hence, the logistic choice approach captures the observed heterogeneity of real markets.

The MiniCAM includes regional detail for 14 regions: the United States, Canada, Western Europe, Japan, Australia & New Zealand, Former Soviet Union, Eastern Europe, Latin America, Africa, Middle East, China and the Asian Reforming Economies, India, South Korea, and Rest of South & East Asia. MiniCAM includes three final energy demand sectors in each region: buildings, industry, and transportation. A range of competing energy sources provides energy to meet these demands, including fossil fuels, bioenergy, electricity, hydrogen, and synthetic fuels. Intermediate energy carriers can be produced from multiple competing technologies. For example, electricity can be generated from multiple coal, oil, natural gas, and biomass technologies as well as from hydroelectric power, fuel cells, nuclear, wind, and solar power. Hydrogen can be produced from coal, oil, natural gas, biomass, and electrolysis. Synthetic fuels can be derived from coal, oil, natural gas, and bioenergy crops. MiniCAM also includes capture and geologic storage of CO_2 from burning fossil fuels and bioenergy. MiniCAM is based on a flexible, object-oriented computer structure that allows for easy adjustment to all elements of the energy system. Hence, there is no single version of MiniCAM; the model is continually evolving, and a range of model variations exist for a wide range of applications.

Because of the importance of land use in the emissions and sequestration of greenhouse gases, as well as the interaction between land use and biofuels, MiniCAM includes a detailed land-use module. This module captures the competition between the use of land to support production of dedicated bioenergy crops, the use of land for agriculture and other needs (e.g., managed forests), and the pressure to maintain carbon in terrestrial stocks when the societal goal is stabilization of CO_2 concentrations. The land-use model calculates net carbon emissions from land-use changes as land is switched among different uses. For example, as more and more land is used for dedicated bioenergy crops, the natural consequence is less land for other purposes and this can lead to land-use change CO_2 emissions. At the same time, if CO_2 in terrestrial systems is valued comparably to that in the energy and industrial systems, as is the case in these scenarios, there is pressure to convert from crops, including bioenergy crops, to land uses, such as forests, with higher carbon contents. MiniCAM can produce scenarios with and without incorporation of deforestation policies, and the implications for fossil and industrial emissions can be substantial. The stabilization scenarios in this report assume that there exists a policy to address CO_2 in terrestrial systems that is comparable to that applied to the energy and industrial systems.

In addition to CO_2, MiniCAM calculates emissions of the greenhouse gases, CH_4, N_2O, and seven categories of industrial sources for HFCFCs, HFCs, PFCs, and SF_6. MiniCAM also calculates emissions of other substances, including SO_2, NO_x, and black and organic carbon. Emissions of greenhouse gases are determined for over 30 sectors, including fossil fuel production, transformation, and combustion; industrial processes; land use and land-use change; and urban processes such as waste management. Again, these scenarios focus exclusively on the CO_2 portion of the climate challenge. Future work will incorporate these non-CO_2 substances in the same way that they were included in the 2006 CCTP Scenarios.

3.3 Overview of the Technology Scenarios

Ten different sets of technology assumptions were created for this study, based on variations in technology assumptions along 12 specific areas. Table 3.1 provides an overview of the scenarios in this study and their associated technology assumptions. In general, two technology levels, reference and advanced, were developed for each technology area. There are several instances in which more than two levels were constructed. The specific assumptions associated with reference and advanced technology in each area are discussed in detail in the remainder of this section.

Table 3.1. An overview of the technology scenarios.

Scenario & Naming Convention	Reference (Ref)	Nuclear Reference (Nuc Ref)	Nuclear Advanced (Nuc Adv)	CCS (CCS)	Bio and CCS (BioCCS)	Renewables (RE)	End Use (EE)	End Use & Renewables (EERE)	Hydrogen & Supply (Supply)	Advanced (Adv)
Transportation: Electric Vehicles	Reference	Reference	Reference	Reference	Reference	Reference	Advanced	Advanced	Reference	Advanced
Transportation: Fuel Cell Vehicles	Reference	Reference	Reference	Reference	Reference	Reference	Advanced	Advanced	Advanced	Advanced
Transportation: Other	Reference	Reference	Reference	Reference	Reference	Reference	Advanced	Advanced	Reference	Advanced
Buildings	Reference	Reference	Reference	Reference	Reference	Reference	Advanced	Advanced	Reference	Advanced
Industry	Reference	Reference	Reference	Reference	Reference	Reference	Advanced	Advanced	Reference	Advanced
Electricity and Hydrogen CCS	No CCS	No CCS	No CCS	Advanced	Advanced	No CCS	No CCS	No CCS	Advanced	Advanced
Agricultural Productivity	Reference	Reference	Reference	Reference	Advanced	Advanced	Reference	Advanced	Advanced	Advanced
Hydrogen Production	Reference	Reference	Reference	Reference	Reference	Reference	Reference	Reference	Advanced	Advanced
Wind Power	Reference	Reference	Reference	Reference	Reference	Advanced	Reference	Advanced	Advanced	Advanced
Solar Power	Reference	Reference	Reference	Reference	Reference	Advanced	Reference	Advanced	Advanced	Advanced
Nuclear Fission	No New Nuclear	Reference	Advanced	No New Nuclear	No New Nuclear	No New Nuclear	No New Nuclear	No New Nuclear	Advanced	Advanced
Geothermal	Reference	Reference	Reference	Reference	Reference	Advanced	Reference	Advanced	Advanced	Advanced

Reference technology assumptions serve as a point of departure for the analysis. They are not frozen technology assumptions; they include substantial technological advances over currently available technology in almost every category. In addition, the reference technology assumptions are not predictions of what might happen absent future U.S. government R&D efforts or absent global policies to address climate change more generally. Given the uncertainty about how technology might evolve over the coming century, an enormous range of assumptions could be considered reasonable best guesses about the future. The reference technology assumptions are intended to lie within this range and to serve as a meaningful point of departure for the Advanced Technology Scenarios.

The Advanced Technology Scenarios can be classified into two broadly different strategies for addressing climate change through technological development. One strategy involves improvements in technologies of energy supply, allowing for the provision of energy and energy carriers (e.g., electricity generation technologies) without directly influencing the technologies used by businesses and consumers. The second strategy, end-use energy technologies, is based on altering the technologies that are available or that are used for the provision of services to businesses and consumers (e.g., heating and cooling technologies). Both of these strategies are considered in the present analysis.

The Nuclear Reference (Nuc Ref) and Nuclear Advanced (Nuc Adv) Scenarios differ from the Reference Technology Scenario in that nuclear energy is allowed to compete economically in the market for electricity generation in the future. The Nuclear Advanced Scenario features accelerated improvement in construction and operations costs relative to the Nuclear Reference. The CCS and Bio and CCS (Bio CCS) Scenarios allow for carbon capture and storage in electricity generation, liquid fuel refining, hydrogen production, and cement manufacturing. While both of these scenarios allow for bioenergy with CCS, the Bio CCS Scenario also has accelerated agricultural productivity increases, allowing for expanded bioenergy production. The Renewables Scenario (RE) also features enhanced agricultural productivity, as well as advances in solar (central and distributed), wind, and geothermal energy. The Hydrogen and Supply (Supply) scenario represents advances in all supply-focused technology areas investigated – nuclear energy, carbon capture and storage, renewable energy – as well as hydrogen production and fuel cell vehicles.

The End Use Scenario (EE) features a wide variety of advanced technologies in the buildings, industry, and transportation sectors, detailed extensively in Section 0. In addition to efficiency improvements, many of the advances modeled do not focus on reducing total primary energy consumption and whole-system emissions, but allow consumers to use fuels such as electricity and hydrogen whose production may have relatively low-cost carbon abatement options. The End Use and Renewables Scenario (EERE) also features advances in renewable energy. While renewable energy is a form of energy supply, the renewable technologies investigated are generally more distributed in nature than those of the supply-focused technology scenarios, implying a fundamentally different electricity system than, for instance, an electric sector based on nuclear energy or facilities equipped with CCS. Finally, an Advanced Scenario (Adv) is investigated, with advanced assumptions in all 12 technology areas.

3.4 The Energy System

This section discusses the energy sector assumptions used in the scenarios in this study. In MiniCAM, the energy system broadly represents processes of energy resource extraction and transformation, ultimately producing services demanded by end users. Resources are classified as either depletable or renewable; in either case, the extraction costs of a given resource are generally assumed to increase with deployment, according to an exogenous supply curve. In each time period, the market prices of all resources are then calculated based on the demands by the energy system.

Energy transformation sectors convert resources initially into fuels consumed by other energy transformation sectors, and ultimately into goods and services consumed by end users. As with any sector in MiniCAM, different technologies may compete for market share; shares are allocated among competing technologies using a logit choice formulation (described in Section 3.2). The cost of a technology in any period depends on two key exogenous input parameters—the non-energy cost and the efficiency—as well as the prices of the fuels it consumes. The non-energy cost represents all fixed and variable costs incurred over the lifetime of the equipment (except for fuel costs), expressed per unit of output. For example, a coal-fired electricity plant incurs a range of costs associated with construction (a capital cost) and annual operations and maintenance. The efficiency of a technology determines the amount of fuel required to produce each unit of output, and the prices of fuels are calculated endogenously in each time period based on supplies, demands, and resource depletion.

3.4.1 Refining

Liquid fuel refining in MiniCAM is represented in three different sectors, one of which produces fuels for the industrial sector (most of which are used as feedstocks), a second for the buildings and transportation sectors, and a third for the electricity sector. Refined liquid fuels for industry, buildings, or transportation can be produced from five different feedstocks: crude oil, unconventional oil, coal, gas, and biomass. Refined liquid fuels for electricity are only produced from crude oil.

Table 3.2. Refining technology non-energy costs and input-output coefficients.

	Non-energy cost	**Crude oil or synthetic crude**	**Natural gas**	**Electricity**	**Coal**	**Biomass**
	$ / bbl	in / out	in / out	in / out	in / out	in / out
Unconventional oil extraction	endogenous		0.106	0.080		
Crude oil refining	15.11	1.055	0.018	0.005		
Unconventional oil refining	15.11	1.055	0.018	0.005		
Coal-to-liquids	48.52				2.112	
Gas-to-liquids	32.35		1.654			
Biomass liquids	38.35					2.057

These different technology options for refining are shown in Figure 3.1; the non-energy costs and input/output coefficients are shown in Table 3.2. Non-energy costs of unconventional oil refining are assumed to be the same as crude oil refining, with additional energy costs incurred upstream of the refinery (see below). Coal-to-liquids costs are informed by the Task Force on Strategic Unconventional Fuels (2007), and biomass liquids costs reflect DOE's target in Aden et al. (2002). In summary, the energy requirements of crude oil refining are based on energy inputs and outputs for all petroleum refineries in the United States in 2005 (IEA 2007b). Due to the large energy requirements for extracting and upgrading unconventional fuels, additional energy is required upstream of the refinery (note the electricity and gas inputs to the "regional unconventional oil" sector in Figure 3.1 and Table 3.2). Unconventional oil is modeled as an equal-parts blend of two technologies: Shell's *in situ* shale oil extraction technology, and Canada's tar sands extraction technology. Shale oil extraction is assumed to require 275 kWh of electricity per barrel of synthetic crude (Bartis et al. 2005, Dooley and Dahowski 2008), and tar sands extraction and upgrading is assumed to require 1,200 cubic feet of natural gas per barrel of synthetic crude (Canada National Energy Board 2006). Once extracted and upgraded, this synthetic crude is assumed to have the same refining energy requirements and non-energy costs as crude oil.

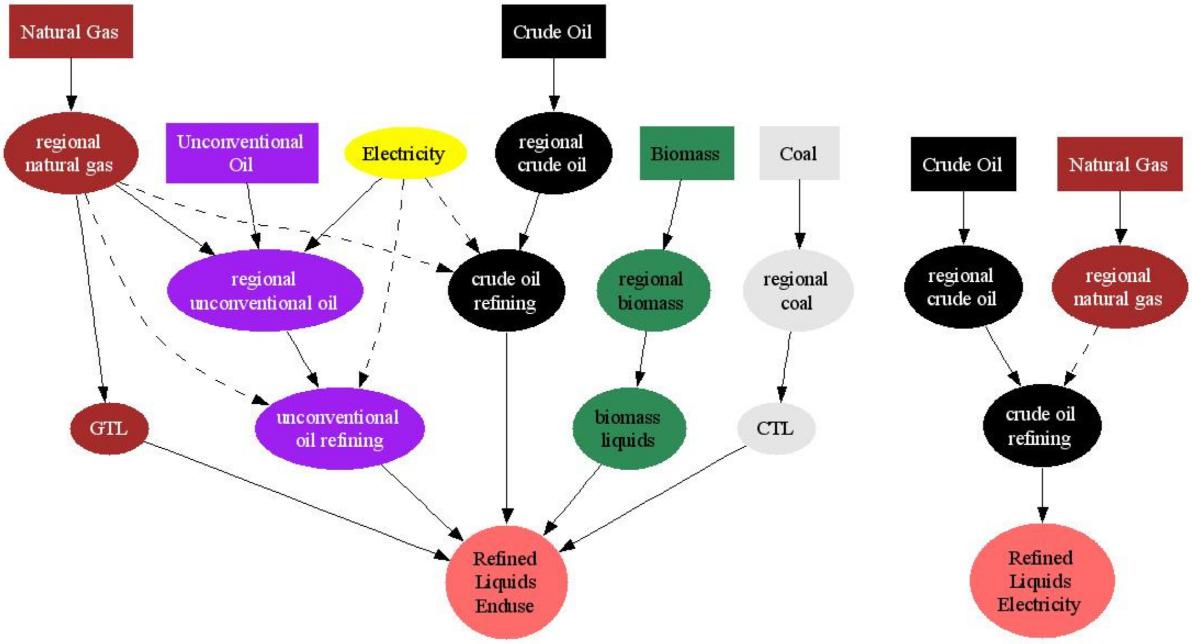

Figure 3.1. Technology options in liquid fuel refining for buildings, industry, and transportation, and in liquid fuel refining for electricity.

The biomass liquids technology has the characteristics of a cellulosic ethanol refinery that produces all required energy on-site from biomass. Technical specifications are based on Aden et al. (2002), although no excess electricity is assumed to be produced. Coal-to-liquids and gas-to-liquids are modeled similarly; the refineries modeled are optimized for production of fuels, not electricity. Therefore, although electricity is generated on-site from the input fuel, no excess electricity is sold back to the grid. The coal-to-liquids input/output coefficient is from Dooley and Dahowski (2008), and the gas-to-liquids input/output coefficient is based on Chevron's proposed plant in Nigeria (Chevron Corporation 2008). Coal-to-liquids is carbon-intensive, and the process produces several CO2 streams with different levels of capture costs. For this reason, two separate carbon capture and storage technology options are modeled for coal-to-liquids plants (detailed in Section 3.4.4).

3.4.2 Electricity

Electricity in MiniCAM can be produced from nine fuel types, each of which may have multiple production technologies. Transmission and distribution costs and energy losses apply to all centrally-produced electric generation technologies (i.e. all but rooftop solar photovoltaic). Electric generation technologies are broadly divided into two categories: existing capital and new installations. An exogenous retirement rate is assumed for both categories, but is higher for existing capital, as this category actually represents many different vintages of power plants, some of which are presently near retirement. New capital is also assigned a retirement rate, representative of capacity losses with age and unplanned shutdowns.

It is assumed that the capital costs of this existing vintage are sunk, and therefore the non-energy costs do not figure into future operating decisions. Plants may be temporarily shut down if the input fuel costs exceed the average revenue from the electricity produced, but otherwise the production of electricity from the existing vintage is not subject to competition from new technologies. In the future, new installations are needed both to replace the retired stock and to meet growing demand for electricity. The market share for new installations to meet this demand is allocated among different technologies by a two-level nested logit choice mechanism, with technologies (e.g. IGCC, combustion turbine) competing within fuels (e.g. coal, nuclear, wind).

3.4.2.1 Fossil and Biomass Electricity

Hydrocarbon-fueled power plants currently supply about two thirds of the world’s electricity. The fuel efficiency of the existing stock varies considerably; average efficiencies for existing fossil and biomass power plants are shown by MiniCAM region in Table 3.3. The lifetime of fossil and biomass power plants is assumed to be 45 years, with the existing capital stock retiring at an average rate of 2.5 percent per year. New builds are retired at 0.75 percent per year.

Table 3.3. Efficiencies (energy out / energy in) of existing stock of fossil and biomass electric power plants by MiniCAM region.

	Coal	Natural Gas	Oil	Biomass
Africa	0.37	0.37	0.30	0.10
Australia and New Zealand	0.35	0.35	0.29	0.17
Canada	0.39	0.39	0.40	0.37
China	0.32	0.38	0.33	0.25
Eastern Europe	0.32	0.30	0.30	0.28
Former Soviet Union	0.25	0.27	0.28	0.13
India	0.27	0.42	0.33	0.15
Japan	0.42	0.45	0.48	0.45
Korea	0.39	0.49	0.48	0.16
Latin America	0.35	0.40	0.35	0.30
Middle East	0.40	0.30	0.35	n/a
Southeast Asia	0.33	0.42	0.40	0.28
U.S.	0.37	0.44	0.36	0.28
Western Europe	0.38	0.48	0.37	0.28

In the future, all regions of the world are assumed to have access to the same generation technologies, and at the same non-energy costs. Cost assumptions and efficiencies of these technologies are based on the 2008 Annual Energy Outlook (EIA 2008) and are shown in Table 3.4. For each fuel, three technologies are available: a conventional technology similar to today's technology, an advanced technology, and an advanced technology with carbon capture and storage. The latter are addressed in Section 3.4.4. Performance is generally assumed to improve over time for all hydrocarbon-based technologies, but assumptions do not vary across scenarios in this analysis.

Table 3.4. Assumed non-energy costs and efficiencies of fossil fuel and biomass power plants.

	2020		**2050**		**2095**	
	Non-energy cost	Efficiency	Non-energy cost	Efficiency	Non-energy cost	Efficiency
	cents/kWh	output/input	cents/kWh	output/input	cents/kWh	output/input
Pulverized coal	3.93	0.39	3.49	0.41	2.91	0.44
Coal (IGCC)	4.42	0.43	3.42	0.47	3.17	0.50
Gas Turbine (peak)	9.83	0.38	8.72	0.40	7.28	0.43
Gas (CC)	1.82	0.55	1.41	0.64	1.31	0.70
Oil Turbine (peak)	9.83	0.38	8.72	0.40	7.28	0.43
Oil (IGCC)	3.98	0.43	3.08	0.47	2.86	0.50
Biomass	4.74	0.38	4.20	0.40	3.51	0.43
Biomass (IGCC)	5.37	0.42	4.16	0.46	3.85	0.49

3.4.2.2 Nuclear Power

Nuclear electric power in MiniCAM is represented as two technologies: the existing legacy generation of nuclear reactors (Gen II), and new, evolutionary reactors that are already available for deployment (Gen III). Both of these reactor technologies have a once-through fuel cycle and do not utilize reprocessed fuels. MiniCAM maintains an explicit accounting of nuclear fuel resources and processing costs. In general, resource limitations and processing costs do not put limitations on nuclear energy deployment. These scenarios do not explore the implications of limitations on nuclear waste disposal or advanced fuel cycles. Hence, waste disposal does not prove a limiting constraint on large scale additions to the nuclear fleet. The implications on limitations on waste disposal, along with the implications of advanced fuel cycles, have been considered, using MiniCAM, in other studies. In these scenarios, the Gen II reactors are not available for new construction; they are retired at a rate of 2.5 percent per year, and all are assumed retired by 2050. New installations are Gen III.

Three scenarios for nuclear power are investigated in this analysis. In the first, the nuclear power sector is not allowed to expand beyond present-day deployment. Reactors are replaced or upgraded as needed to maintain this level of electrical output, but nuclear power never competes economically in markets for electricity generation. In any scenarios allowing nuclear expansion (i.e. scenarios with reference or advanced nuclear technology assumptions), it is implicitly assumed that issues of safety and waste disposal are adequately addressed, and improved to the point where social acceptability does not constrain large-scale expansion of nuclear power. These improvements allow nuclear power to compete economically with all other electric generation technologies. The advanced technology scenarios are distinguished from the reference in having accelerated cost decreases in the future; reference and advanced scenario non-energy costs are shown in Table 3.5.

Table 3.5. Nuclear power plant non-energy costs (2004 cents / kWh) in the reference and advanced technology scenarios.

	Reference				**Advanced**		
	2020	**2050**	**2095**		**2020**	**2050**	**2095**
Gen III	5.09	4.93	4.72		5.09	4.67	4.10

3.4.2.3 Hydroelectricity

Hydroelectric power currently accounts for about 16 percent of the global electricity supply, and is an important component of the generation mix in many regions. The deployment of hydroelectric power is influenced strongly by political and social influences, which often play a more important role than economic considerations. For this reason, future generation from hydroelectric power is set exogenously for each region through 2095 in MiniCAM. Near-term deployment is based on inventories of present dam construction, and in the long term, relative growth rates in each region are based on the economically feasible potential in IHA (2000). Table 3.6 shows future hydroelectric output by MiniCAM region.

Table 3.6. Assumed hydroelectricity generation (EJ / yr) by MiniCAM region. Source: IEA (2007a and 2007b).

	2005	**2020**	**2050**	**2095**
Africa	0.33	0.33	0.98	1.96
Australia and New Zealand	0.14	0.14	0.18	0.25
Canada	1.31	1.39	1.55	1.79
China	1.55	2.66	3.29	4.23
Eastern Europe	0.25	0.25	0.33	0.46
Former Soviet Union	0.88	0.97	1.35	1.92
India	0.36	0.40	0.78	1.35
Japan	0.28	0.28	0.30	0.33
Korea	0.01	0.01	0.03	0.06
Latin America	2.33	2.61	3.38	4.52
Middle East	0.08	0.08	0.27	0.55
Southeast Asia	0.31	0.31	0.59	1.02
U.S.	0.98	0.98	1.01	1.05
Western Europe	1.71	1.71	1.80	1.93

3.4.2.4 Solar and Wind

Solar and wind power are abundant natural resources that can be used to produce electricity. Although solar and wind deployment worldwide is small at present (less than one percent of global electricity supply), the potential for future growth may be enormous. Integrated assessment models have historically struggled to accurately model the competition of solar and wind power within the electricity system due to their inherent availability and variability limitations.

In MiniCAM, the technologies of solar and wind power are assigned three different costs: an exogenous non-energy cost, similar to other electric technologies; endogenous ancillary costs, associated with resource intermittency; and resource costs, input as exogenous resource supply curves, representative of costs that are expected to increase with deployment as least-cost sites are used first. Non-energy costs are calculated from assumptions of capital costs, O&M costs, and capacity factors (see Table 3.7 and Table 3.8). The rooftop photovoltaic (PV) technology does not incur the transmission and distribution costs and energy losses that apply to all other electric generation technologies. As shown in Table 3.7, costs of all solar and wind technologies are assumed to decrease in the reference technology scenarios, and even further in the advanced technology scenarios. Solar costs vary by region, representative of different levels of average insolation in all regions. These estimates, developed from a GIS-based analysis, are shown in Table 3.8.

Table 3.7. Solar and wind technology cost assumptions for reference and advanced scenarios.

			Reference				**Advanced**		
		2005	**2020**	**2050**	**2095**		**2020**	**2050**	**2095**
Central PV									
Capital cost	$/kW	6875	4525	2468	1758		3446	1381	947
O&M cost	$/kW-yr	25	25	18	15		22	16	12
Storage cost adder	$/kW	480	413	342	306		355	225	180
Rooftop PV									
Capital cost	$/kW	9500	6278	3583	2793		4258	2246	1654
O&M cost	$/kW-yr	100	50	30	20		30	20	15
CSP									
Capital cost	$/kW	3004	2786	2397	1913		2219	1770	1413
O&M cost	$/kW-yr	47	43	37	30		34	27	22
CSP with storage									
Capital cost	$/kW	6008	5573	4795	3827		3731	2976	2375
O&M cost	$/kW-yr	47	43	37	30		34	27	22
Wind									
Capital cost	$/kW	1167	1124	1043	932		1082	931	743
O&M cost	$/kW-yr	36	30	28	26		30	27	22
Storage cost adder	$/kW	658	566	469	419		486	309	246

Table 3.8. Levelized non-energy costs of solar technologies in all MiniCAM regions in 2020, reference scenario (cents / kWh).

	Central PV		Rooftop PV	CSP	
		w/storage			w/storage
Africa	26.60	28.93	30.94	10.98	8.82
Australia and New Zealand	37.15	40.40	35.56	12.62	10.14
Canada	33.52	36.45	51.00	18.10	14.55
China	47.16	51.28	42.03	14.92	11.99
Eastern Europe	22.15	24.09	51.17	18.16	14.60
Former Soviet Union	46.42	50.48	51.70	18.35	14.75
India	18.53	20.16	34.44	12.22	9.82
Japan	43.24	47.02	44.53	15.80	12.70
Korea	22.27	24.21	41.59	14.76	11.86
Latin America	21.80	23.71	33.92	12.04	9.67
Middle East	35.58	38.69	31.22	11.08	8.90
Southeast Asia	17.91	19.48	33.99	12.06	9.69
U.S.	27.20	29.58	41.38	14.69	11.80
Western Europe	40.17	43.69	49.59	17.60	14.14

The intermittency-related costs owing to large-scale solar and wind expansion are not currently well understood, but do pose a potentially important limitation on renewable energy deployment. In MiniCAM, there are two technological options for maintaining grid reliability. The first option is for the renewable technologies to pay for the purchase and operation of backup gas turbines, representative of the lowest capital cost option for capacity that would be dispatched infrequently. This cost consists of the capital cost of a required amount of capacity, plus any variable O&M costs and fuel costs associated with its operation. A capacity factor of 5 percent is assumed for the backup turbines, as these would only need to be operated infrequently.

The amount of backup capacity required differs somewhat between wind and solar technologies. For solar, backup capacity is determined by the share of solar capacity relative to the total amount of capacity in the electric sector. At low levels of deployment, very little backup capacity is required, but as deployment increases, the backup requirement increases as a logistic function until at 20 percent of the grid capacity, each additional unit of solar capacity requires one unit of gas combustion turbine capacity. Note that this is not a capacity limit to solar deployment; solar power may still expand above this ratio by paying for the required backup.

For wind power, the ancillary capacity requirements are calculated as a function of the variability of the wind resource and the size of the wind generation relative to the size of the electricity sector, assuming that wind variance and normal load variance are uncorrelated. This formulation is derived from the formulation for reserve margin used in the NREL WINDS model (NREL 2006).

As a second option for maintaining grid reliability, for each central station solar or wind electric technology, there is a corresponding, more capital-intensive technology option with integrated energy storage. This generic storage technology could represent a facility with molten salt, batteries, or pumped hydroelectricity; the important feature is that the coupled system is capable of providing power at relatively constant dispatch, and thus functions as a baseload technology on the grid. There is some energy lost in the extra conversions, but no secondary fuel (e.g. gas) is required for operation.

The third and final component of the cost of renewable technologies is resource costs, calculated from exogenous supply curves. These are used for technologies with marginal costs that are assumed to increase with deployment, such as long-distance transmission line costs that would be required to produce power from remote wind resources. Only wind and rooftop PV are assigned resource supply curves; central station solar technologies are assumed to have constant marginal costs regardless of deployment levels.

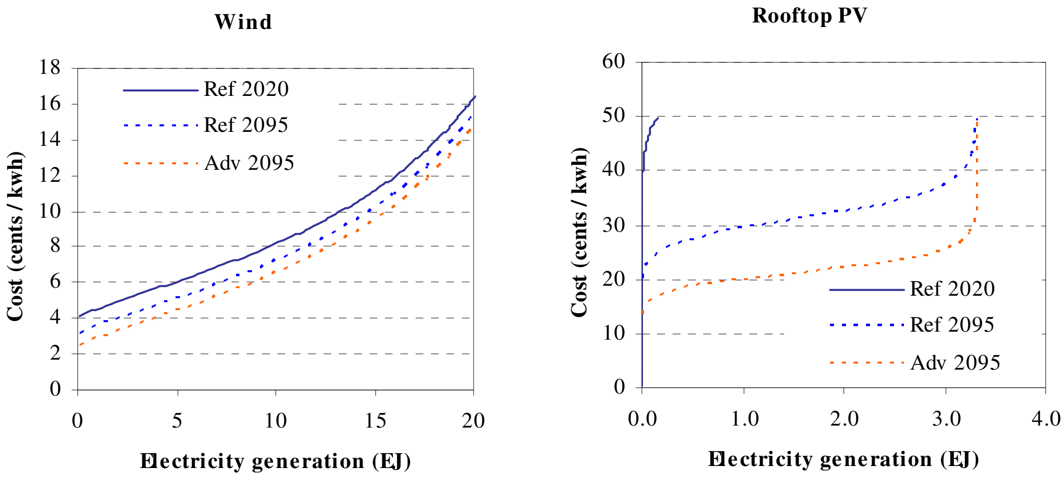

Figure 3.2. Wind and rooftop solar costs with reference and advanced technology assumptions. These supply curves include technology and resource costs, but exclude any ancillary costs.

For wind power, the supply curve for the U.S. region is based on NREL (2008), and is shown in Figure 3.2. The supply curve shown also includes technology non-energy costs, but not ancillary costs. The same supply curve is assumed for non-U.S. regions, but with maximum resource amounts scaled to estimates from GIS-based analysis, also informed by IEAGHG (2000). Assumed maximum resources for all MiniCAM regions are shown in Table 3.9. The supply curve for rooftop PV in the U.S. is from NREL (P. Denholm and R. Margolis, pers. comm.), and is also shown in Figure 3.2. Note that this represents only the rooftop PV available in the residential sector; the commercial rooftop PV supply curve would likely have lower costs per unit of energy produced. The assumed limit in non-U.S. regions, shown in Table 3.9, is based on a GIS analysis of solar irradiance by region.

Table 3.9. Maximum annual electricity production by renewable resource technology and MiniCAM region (EJ / yr). No resource limits are applied to central station solar technologies.

			Geothermal	
	Rooftop PV	**Wind**	**Hydrothermal**	**EGS**
Africa	5.2	135.6	0.4	2.3
Australia and New Zealand	0.2	12.7	0.2	1.5
Canada	0.2	17.0	0.0	0.0
China	9.2	36.3	0.8	4.8
Eastern Europe	0.9	3.1	0.0	0.0
Former Soviet Union	1.7	135.1	0.0	0.1
India	6.0	1.1	0.8	4.8
Japan	0.6	1.0	0.2	1.1
Korea	0.3	0.6	0.0	0.0
Latin America	3.4	53.3	1.0	6.1
Middle East	1.1	46.0	0.0	0.0
Southeast Asia	4.6	8.4	0.9	5.6
U.S.A	2.7	29.2	0.8	4.8
Western Europe	3.0	6.6	0.4	2.5

3.4.2.5 Geothermal

Like solar and wind, geothermal energy currently accounts for less than one percent of global electricity generation, but the potential resource may be large. For instance, a recent study assessed the feasibility of using enhanced geothermal systems (EGS) to install 100 GW (3 EJ baseload) of geothermal capacity in the U.S. alone (MIT 2006). Due to the high R&D costs that would be necessary to bring EGS to commercial deployment, however, this technology is only allowed to compete economically in advanced technology scenarios. The reference scenarios are constrained to conventional (hydrothermal) geothermal technology, which has a much smaller resource base.

Geothermal costs in MiniCAM are calculated based on an exogenous supply curve, developed from a dataset used by Petty and Porro (2007), with slight modifications to the EGS resource base. Supply curves assumed for hydrothermal and EGS are shown in Figure 3.3. Non-U.S. regions are assumed to have the same resource supply curves, but with different amounts of maximum resources. Estimates of maximum resources are based on Glitnir (2007), with the exceptions of China and India, which are each assumed to have the same available resources as the U.S. (IEA 2008; see Table 3.9).

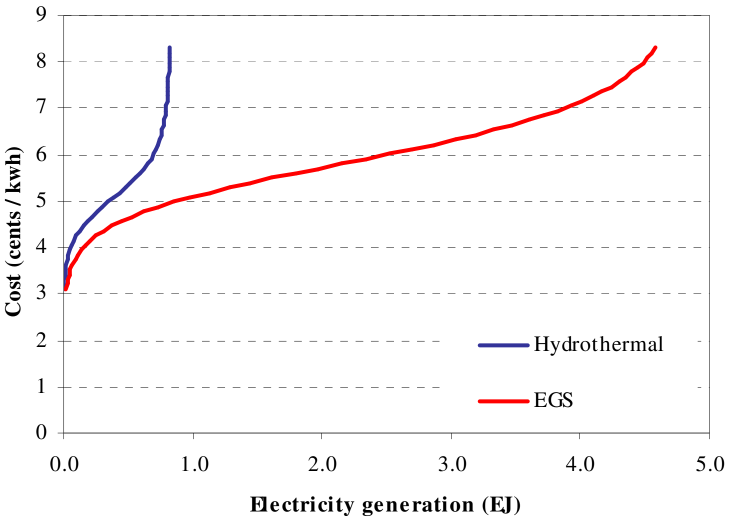

Figure 3.3. Geothermal supply curves in 2050 for the U.S. region. The EGS technology is only included in advanced technology scenarios.

3.4.3 Hydrogen

A full hydrogen economy is modeled in MiniCAM, including technologies for production, transmission and distribution, and consumption. The representation is designed to allow for a comprehensive examination of the interactions between hydrogen and other advanced technologies in the energy system. However, one limitation of the MiniCAM approach is that it does not address scale issues associated with a hydrogen infrastructure. A fixed transmission cost is assumed regardless of the scale of the hydrogen system. This is a simplification. The costs of transmission will depend heavily on scale, and discussions of large-scale hydrogen deployment often center on the issues associated with the creation of a large-scale transmission and distribution system.

Hydrogen supply is modeled in MiniCAM in similar fashion to electricity: hydrogen may be produced in central stations or in distributed “forecourts.” Central stations benefit from economies of scale, but incur transmission and distribution costs. There are more technology options for central station hydrogen production than for forecourt production. Although forecourt production can produce hydrogen only from natural gas or electricity, central stations can use natural gas, coal, or biomass, all with or without CCS, as well as direct conversion from nuclear, solar, and wind energy. In this application, wind and solar generation do not pay any intermittency-related costs.

Reference and advanced technology assumptions for hydrogen production are derived from the H2A production models (DOE 2008). Non-energy costs were calculated from these models by subtracting the feedstock fuel cost from the required break-even hydrogen price for each technology analyzed. Hydrogen production efficiencies by technology are shown in Table 3.10, and non-energy costs are shown in Table 3.11. Because the future role of hydrogen in the energy system is also highly dependent on the demand technologies, scenarios with advanced hydrogen supply technologies also have advanced fuel cell vehicles (discussed in Section 3.4.5.3).

Table 3.10. Hydrogen production efficiencies by technology in reference and advanced scenarios.

		Reference				Advanced		
		2020	2050	2095		2020	2050	2095
Central station	**Natural gas**	0.73	0.75	0.79		0.73	0.78	0.82
	Coal	0.54	0.57	0.61		0.54	0.60	0.63
	Biomass	0.45	0.48	0.51		0.45	0.50	0.52
	Electrolysis	0.63	0.68	0.73		0.63	0.72	0.76
	Nuclear	0.85	0.85	0.88		0.85	0.86	0.90
	Wind	0.63	0.68	0.73		0.63	0.72	0.76
	Solar	0.63	0.68	0.73		0.63	0.72	0.76
Distributed	**Natural Gas**	0.72	0.79	0.85		0.72	0.84	0.87
	Electrolysis	0.60	0.65	0.70		0.60	0.69	0.73

Table 3.11. Hydrogen non-energy costs by technology in reference and advanced scenarios (2004$ / GJ).

		Reference				Advanced		
		2020	2050	2095		2020	2050	2095
Central station	**Natural gas**	2.96	2.55	2.04		2.96	2.20	1.76
	Coal	8.64	7.23	5.69		8.64	6.13	4.90
	Biomass	8.58	7.18	5.65		8.58	6.09	4.87
	Electrolysis	21.31	14.54	10.34		21.31	11.15	8.91
	Nuclear	20.16	20.16	11.02		20.16	11.87	9.49
	Wind	21.31	21.31	18.35		21.31	19.77	15.80
	Solar	21.31	21.31	18.35		21.31	19.77	15.80
T&D charge		17.49	15.49	12.55		17.49	13.52	10.80
Distributed	**Natural Gas**	18.62	14.48	11.00		18.62	11.85	9.47
	Electrolysis	21.31	21.31	18.35		21.31	19.77	15.80

3.4.4 Carbon Dioxide Capture and Storage

In scenarios in which carbon dioxide capture and storage (CCS) is allowed, CCS technologies are modeled in liquid fuel refining (in coal-to-liquids plants only), electricity generation, hydrogen production, and cement production. In electric power plants, carbon capture is available only for the most advanced versions of the hydrocarbon-based generation technologies: natural gas combined cycle, and IGCC with coal, oil, and biomass. For hydrogen production, carbon capture is available as an option on central station production from coal, natural gas, and biomass. In all of these cases, technologies with carbon capture compete directly with the equivalent technologies without carbon capture. For coal-to-liquids plants, two different CCS technologies are modeled, as there are two CO_2 streams from the production technology that have different capture costs. CCS Phase 1 captures only the high-pressure, relatively pure stream of CO_2 from the CTL conversion process itself. CCS Phase 2 captures this stream, as well as a dilute and lower-pressure stream from tail gas combustion that is more costly to capture (Dooley and Dahowski 2008).

CCS can dramatically reduce CO_2 emissions, but it incurs costs associated with capturing and storing carbon. The first portion of the CCS cost includes the capital and operating costs associated with capturing CO_2 and a consequent reduction in whole-system efficiency due to extra energy requirements for separating CO_2 from flue gases. The capture costs are represented in MiniCAM as a non-energy cost penalty and an efficiency penalty, the latter applied to the primary fuel consumed by the facility. These performance penalties are applied in proportion to the amount of CO_2 released by the underlying process that is captured and stored. Table 3.12 shows the capture energy requirements and non-energy costs used in the scenarios. These characteristics are assumed to be the same across all regions.

Table 3.12. Carbon capture costs, in terms of additional energy requirements, and additional costs, by technology.

	Energy penalty			**Cost penalty**		
	GJ / ton C			**$ / ton C**		
	2020	**2050**	**2095**	**2020**	**2050**	**2095**
Refining						
Coal to liquids Phase 1	2.71	2.71	2.71	65.51	65.51	65.51
Coal to liquids Phase 2	5.65	5.65	5.65	90.45	90.45	90.45
Electricity						
Coal	2.27	1.78	1.78	28.81	26.89	26.89
Gas	4.41	3.92	3.92	78.96	73.60	73.60
Oil	3.20	2.84	2.84	57.24	53.36	53.36
Biomass	2.27	1.78	1.78	28.81	26.89	26.89
Hydrogen						
Coal	3.42	3.42	3.42	55.78	51.17	43.46
Gas	0.20	1.28	1.83	87.46	69.44	54.70
Biomass	0.00	0.00	0.00	56.49	51.78	43.97
Cement	0.00	0.00	0.00	144.37	144.37	144.37

Sources: Refining: Dooley and Dahowski (2008); Electricity: David and Herzog (2000); Hydrogen: H2A model (DOE 2008); Cement: Mahasenan et al. (2005).

The second portion of the CCS cost pertains to the transport and storage of CO_2. The assumptions regarding the costs of carbon storage do not account for a range of additional factors that might ultimately limit the deployment of carbon storage, including leakage from reservoirs, institutional issues associated with the underground injection of power plant flue gases, and public acceptance. Carbon reservoir capacity differs dramatically among world regions. The reservoir capacity in most regions of the world is more than sufficient to meet storage demands for the remainder of the century (Dooley et al. 2005). However, for two regions, Japan and Korea, limited reservoir capacity is assumed to impose an economic cost on all CCS technologies. For scenarios in which CCS is available, the assumed storage cost in Japan and Korea is $271 per ton carbon (2004 U.S.D), and in all other regions it is $56 per ton carbon.

The third portion of the costs of technologies with CCS is associated with the CO_2 that is vented to the atmosphere, either because it is uneconomic or technically infeasible to capture. Even CCS-equipped facilities do emit some CO_2, and these emissions are priced in the same way as any other carbon emissions in the energy system. The capture rates for CCS technologies are shown in Table 3.13 for all CCS technologies in the model.

Table 3.13. Carbon capture rates, by technology. The remaining CO_2 is vented to the atmosphere, and is subject to any applicable carbon prices.

	Removal fraction		
	2020	**2050**	**2095**
Refining			
Coal to liquids Phase 1	82%	82%	82%
Coal to liquids Phase 2	98%	98%	98%
Electricity			
Coal	91%	93%	94%
Gas	91%	93%	94%
Oil	91%	93%	94%
Biomass	91%	93%	94%
Hydrogen			
Coal	90%	90%	90%
Gas	90%	90%	90%
Biomass	90%	90%	90%
Cement	90%	90%	90%

3.4.5 End-Use Sectors

End-use consumers determine the total amount of energy that is consumed along with the mix of secondary fuels that supply this energy. In MiniCAM, there are three end-use sectors in each of the model's fourteen regions: buildings, industry and transportation. In this study, the end-use sectors are represented in aggregate form for all regions except the U.S., for which detailed building and transportation sectors have been implemented. The detailed U.S. sectors were used as the basis for determination of key model parameters in the non-U.S. aggregate sectors. The detailed U.S. end use representations are discussed below.

It is important to distinguish between the two factors that drive the demand for energy: the demand for energy services and the technologies that consume fuels to provide these services. Examples of service demands include the demand for vehicle miles, the demand for process heat in industry, and the demands for space heating and cooling for residential buildings. In MiniCAM, the aggregate sectors determine the total quantity of aggregate service consumed according to a sector-based demand function, which grows in response to economic and population growth and responds to changes in the prices by which these services are delivered.

Historically, per capita demand for energy has not grown at the rate of per capita gross domestic product (GDP) growth. One reason is that the demands for underlying services do not necessarily grow at the rate of GDP growth. For example, the demand for building floor space may not double with a doubling in GDP; it may grow more slowly. Similarly, as economies develop, they may move more toward service-oriented industries and away from heavy industry. For these reasons, the demands for services do not all grow at the rate of economic growth in the scenarios.

The second factor driving end-use energy demand and leading to a divergence between GDP growth and energy demand growth is improvement in the technologies that provide end-use services. More efficient vehicles, industrial processes, and space heating and cooling equipment, for example, can all lower the energy required to supply their respective services. In MiniCAM, the efficiencies of the generic end use technologies change over time to capture this technological advance.

The aggregate approach to energy demands in MiniCAM has the valuable characteristic that it separates the effects of service demand growth and future technological improvement. However, the weakness of the aggregate approach is that the services being provided by these aggregate end-use sectors are not explicitly defined. This makes it difficult to model qualitative changes in service that may have a large influence on technology choice and future energy demand by end-use sectors. For example, higher incomes may increase demand for high-speed forms of transportation, such as aviation, that have different capacities for fuel-switching than the transportation sector as a whole.

As well, end-use technologies consist of many different types of equipment used in a very wide variety of applications, and the interactions between different technologies may be important. In the buildings sector, for example, improvements in building shell thermal characteristics can reduce demands for space heating. In the industrial sector, the energy requirements for production of goods might be reduced by a number of improvements, such as (a) more efficient boilers, (b) deployment of less heat-intensive production technologies, (c) increased use of recycled materials as feedstocks, or (d) use of combined heat and power (cogeneration) systems.

In an effort to represent these kinds of interactions, and to quantitatively assess their implications for the energy system as a whole, this analysis uses detailed representations that have been developed for each of the three end-use sectors, in the U.S. region only. Actual services are explicit where possible; for instance, passenger transportation services are indicated in passenger-km. For non-U.S. regions, aggregate end-use sectors are still used, but with technology improvement rates and service demand elasticities based on analysis of the detailed U.S. model. This approach has allowed for detailed examination of end use in the U.S. and consistent representations internationally.

3.4.5.1 Buildings

The U.S. buildings sector module, shown schematically in Figure 3.4 and detailed in Kyle et al. (2008), consists of a residential and commercial sector, each represented in terms of floorspace. These sectors demand a range of building services, such as heating and lighting. The demand for these services is driven by growth in floorspace, along with an exogenous demand expansion parameter used for services whose growth rate is expected to outpace that of floorspace, such as commercial office equipment. Growth in income (GDP) only affects the demand for the building services through its effect on floorspace. While the per-capita demand for floorspace does increase with per-capita income, this demand growth is assumed to attenuate over time in the residential sector due to effects of demand saturation. Heating and cooling demands are influenced by building shell characteristics, as well as internal gain energy. This allows for assessment of the effects on heating and cooling demand from improvements in building shell thermal characteristics, more efficient lighting, or increased computer use, for example.

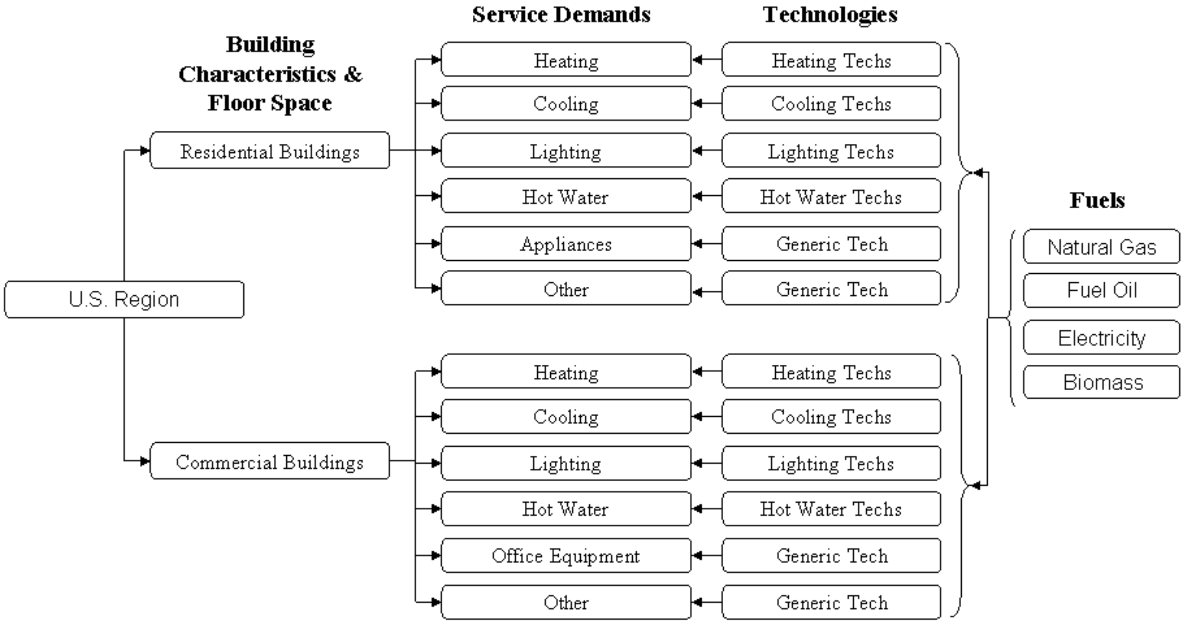

Figure 3.4. Schematic representation of the U.S. buildings sector module.

All technology efficiencies in reference and advanced technology scenarios are shown in Table 3.14, and non-energy costs are shown in Table 3.15. Base year energy consumption by technology is from the 2007 Annual Energy Outlook (EIA 2007), with lighting energy disaggregated to technologies according to NCI (2002). Near-term improvement rates are informed by EIA (2007) for heating, cooling, and water heating technologies. Improvement in office and other equipment is based on TIAX (2006). Solid-state lighting efficiencies in reference and advanced scenarios are based on NCI (2006). Long-term improvement rates were generally assumed to follow one of five technology advancement trajectories, based on the maturity of the technologies, and limited by physical constraints where applicable. Cost assumptions in MiniCAM are expressed in costs per unit of service delivered, and are developed based on assumptions of capital costs, O&M costs, and capacity factors from NCI (2004). The reference scenario generally assumes modest long-term cost decreases, and in the advanced scenario, the costs of selected high-efficiency technologies are reduced substantially.

Table 3.14. Residential and commercial sector efficiencies by service and technology.

Residential				Reference		Advanced	
Service	**Technology**	**unit**	**2005**	**2050**	**2095**	**2050**	**2095**
	Building shell	W/m2	0.232	0.182	0.150	0.163	0.125
Heating	**Gas furnace**	out / in	0.82	0.90	0.97	Same as Ref	
	Gas heat pump	out / in	n/a	n/a	n/a	1.75	2.45
	Electric furnace	out / in	0.98	0.99	0.99	Same as Ref	
	Electric heat pump	out / in	2.14	2.49	2.79	2.94	4.12
	Oil furnace	out / in	0.82	0.86	0.93	Same as Ref	
	Wood furnace	out / in	0.40	0.42	0.44	Same as Ref	
Cooling	**Air conditioning**	out / in	2.81	3.90	4.88	4.59	7.19
Water Heating	**Gas water heater**	out / in	0.56	0.61	0.64	0.79	0.88
	Gas HP water heater	out / in	0.89	1.09	1.22	1.75	2.45
	Electric water heater	out / in	0.88	0.93	0.97	Same as Ref	
	Electric HP water heater	out / in	n/a	2.46	2.75	2.75	3.45
	Oil water heater	out / in	0.55	0.56	0.59	Same as Ref	
Lighting	**Incandescent lighting**	lumens/W	14	15	16	Same as Ref	
	Fluorescent lighting	lumens/W	60	75	94	Same as Ref	
	Solidstate lighting	lumens/W	100	112	125	156	245
Appliances	**Gas appliances**	indexed	1.00	1.12	1.25	Same as Ref	
	Electric appliances	indexed	1.00	1.23	1.38	1.44	2.01
Other	**Other gas**	indexed	1.00	1.12	1.25	Same as Ref	
	Other electric	indexed	1.00	1.08	1.21	1.40	1.96
	Other oil	indexed	1.00	1.12	1.25	Same as Ref	
Commercial							
	Building shell	W/m2	0.281	0.217	0.194	0.214	0.164
Heating	**Gas furnace**	out / in	0.76	0.84	0.94	Same as Ref	
	Gas heat pump	out / in	n/a	n/a	n/a	1.75	2.45
	Electric furnace	out / in	0.98	0.99	0.99	Same as Ref	
	Electric heat pump	out / in	3.10	3.56	3.98	3.95	4.41
	Oil furnace	out / in	0.77	0.81	0.85	Same as Ref	
	Wood furnace	out / in	0.40	0.42	0.44	Same as Ref	
Cooling	**Air conditioning**	out / in	2.80	3.87	4.84	4.42	6.92
Water Heating	**Gas water heater**	out / in	0.82	0.93	0.93	Same as Ref	
	Gas HP water heater	out / in	na	na	na	1.75	2.45
	Electric water heater	out / in	0.97	0.98	0.98	Same as Ref	
	Electric HP water heater	out / in	na	2.46	2.75	2.75	3.45
	Oil water heater	out / in	0.76	0.80	0.83	Same as Ref	
Lighting	**Incandescent lighting**	lumens/W	14	15	16	Same as Ref	
	Fluorescent lighting	lumens/W	76	95	119	Same as Ref	
	Solidstate lighting	lumens/W	100	112	125	156	245
Office	**Office equipment**	indexed	1.00	1.25	1.57	1.72	2.41
Other	**Other gas**	indexed	1.00	1.17	1.31	1.36	1.90
	Other electric	indexed	1.00	1.17	1.31	1.36	1.90
	Other oil	indexed	1.00	1.17	1.31	Same as Ref	

Table 3.15. Building technology non-energy costs, in 2004$ per GJ of service delivered. Costs are levelized over the lifetime of the equipment.

Residential			Reference		Advanced	
Service	**Technology**	**2005**	**2050**	**2095**	**2050**	**2095**
	Building shell	20.99	20.99	20.99	Same as Ref	
Heating	**Gas furnace**	5.27	5.08	4.91	Same as Ref	
	Gas heat pump	n/a	n/a	n/a	17.47	15.35
	Electric furnace	6.69	6.46	6.24	Same as Ref	
	Electric heat pump	14.75	14.34	13.95	12.89	11.41
	Oil furnace	6.47	6.26	6.05	Same as Ref	
	Wood furnace	7.78	7.43	7.11	Same as Ref	
Cooling	**Air conditioning**	14.17	13.75	13.34	13.75	13.34
Water Heating	**Gas water heater**	12.73	12.37	11.42	0.00	0.00
	Gas HP water heater	n/a	n/a	n/a	20.12	19.58
	Electric water heater	12.46	12.17	11.90	Same as Ref	
	Electric HP water heater	n/a	25.76	24.97	18.09	17.64
	Oil water heater	12.73	12.40	12.09	Same as Ref	
Lighting	**Incandescent lighting**	803	768	734	Same as Ref	
	Fluorescent lighting	1012	808	646	Same as Ref	
	Solidstate lighting	2223	1986	1774	808	646
Appliances	**Gas appliances**	16.34	15.62	14.94	Same as Ref	
	Electric appliances	31.36	29.98	28.66	Same as Ref	
Other	**Other gas**	67	67	67	Same as Ref	
	Other electric	128	128	128	Same as Ref	
	Other oil	67	67	67	Same as Ref	
Commercial						
	Building shell	22.92	22.92	22.92	Same as Ref	
Heating	**Gas furnace**	1.77	1.73	1.69	Same as Ref	
	Gas heat pump	n/a	n/a	n/a	17.80	14.84
	Electric furnace	2.13	1.93	1.85	Same as Ref	
	Electric heat pump	12.87	12.42	11.98	10.78	9.12
	Oil furnace	2.06	1.99	1.92	Same as Ref	
	Wood furnace	7.78	7.43	7.11	Same as Ref	
Cooling	**Air conditioning**	11.54	11.10	10.68	11.10	10.68
Water Heating	**Gas water heater**	4.67	4.54	4.41	Same as Ref	
	Gas HP water heater	na	na	na	23.73	22.68
	Electric water heater	3.26	3.14	3.03	Same as Ref	
	Electric HP water heater	na	20.95	20.03	3.14	3.03
	Oil water heater	6.07	5.84	5.62	Same as Ref	
Lighting	**Incandescent lighting**	188	180	172	Same as Ref	
	Fluorescent lighting	137	109	87	Same as Ref	
	Solidstate lighting	362	289	230	107	101
Office	**Office equipment**	127	122	116	Same as Ref	
Other	**Other gas**	77	77	77	Same as Ref	
	Other electric	77	77	77	Same as Ref	
	Other oil	77	77	77	Same as Ref	

The advanced scenario is generally defined by higher improvement rates in selected technologies that are currently receiving research attention. For instance, the advanced technology suite has high-efficiency heat pump water heaters, but not high-efficiency oil water heaters. Note that MiniCAM does not explicitly model zero-energy buildings. The buildings sector may consume electricity produced by rooftop PV, but this electricity competes with grid-produced electricity on the basis of the relative economics. Note also that this analysis does not explicitly analyze solar water heaters, but heat pump water heaters modeled have comparable whole-system efficiencies, given that the solar component reduces annual energy requirements by 40 to 80 percent (NREL 1999). Energy-free technologies such as day-lighting are also not explicitly modeled.

Because of long building lifetimes and the age of the existing stock, as well as recent improvements in construction practices and likely further improvements in the future, residential shell efficiency is parameterized with a detailed stock model of all structures in the United States. The attributes of the existing stock are informed by the 2001 Residential Energy Consumption Survey (EIA 2001), and future improvement relative to the construction practices in 2005 for reference and advanced scenarios is informed by the BEopt program (NREL 2005). In summary, the shell efficiency of new construction improves from 2005 to 2095 by about 0.45 percent per year in the reference scenario, and by about 0.7 percent per year in the advanced scenario. The trajectory of shell efficiencies is set exogenously and does not vary by scenario; future scenarios may incorporate representations of building stocks that vary among scenarios and respond to energy prices.

3.4.5.2 Industry and Cement

Industrial sectors include a large and heterogeneous range of individual industries, and in MiniCAM, the industrial sector includes energy use by the energy transformation sector that is not accounted in liquid fuel refining or electricity generation. Fossil fuels used as feedstocks (i.e. not combusted) in industrial processes are accounted separately, as the carbon contained in the fuels is assumed not emitted to the atmosphere. The cement industry is disaggregated from the industrial sector in all regions, with energy use as well as limestone-derived process emissions accounted. While industrial output is represented in generic terms (e.g. service units), cement production is represented in tons. Cement industry energy intensity and output are based on IEA (2007c), limestone feed requirements are from Worrell et al. (2001), and process-related emissions are from Marland et al. (2005).

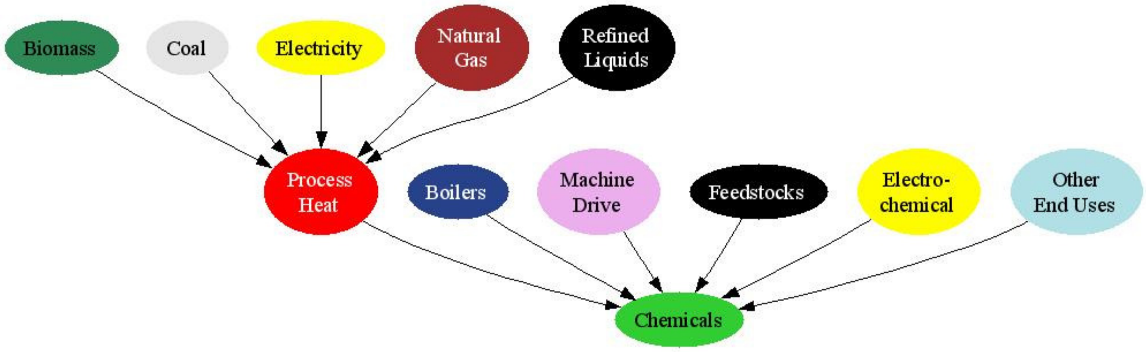

Figure 3.5. Schematic of a representative US industry in MiniCAM. Technologies compete to provide intermediate industrial services, which are required in exogenous amounts to produce output. Technological change can take place at both levels.

In the US region, the industrial sector is disaggregated into eight manufacturing industry groups (including cement) and three non-manufacturing groups. Each manufacturing industry group consumes energy to produce a range of intermediate industrial services, such as steam and machine drive (see Figure 3.5). These services are required by the industries in exogenous ratios; energy consumption by each industry and intermediate service is based on the 2002 Manufacturing Energy Consumption Survey (MECS). Figure 3.6 shows the eleven MiniCAM industries and their energy requirements, by service, in 2005. Energy consumption by non-manufacturing groups—agriculture, construction, and mining—is based on EIA (2007). All energy consumption estimates are scaled to match 1990 and 2005 IEA (2007b) estimates of fuel consumption by the industrial sector, the agricultural sector, and feedstock use. Process CO_2 emissions from limestone in the primary metals and nonmetallic minerals industries are accounted for based on EIA (2006).

While most industrial energy use can be mapped to several cross-cutting end use services, there is heterogeneity between industries in the fuel mixes used to provide these services. For instance, boilers in the pulp, paper and wood industry are mostly fueled by biomass. In several cases, services are modeled as being specific to a given industry, and base year fuel preferences are assumed to apply in the future. Cogeneration is explicitly modeled as a technology option for producing steam and process heat, competing with steam- or heat-only systems. While more capital-intensive, cogeneration technologies generally use less primary energy than separate heat and power systems (Kaarsberg and Roop 1998). In MiniCAM, cogeneration technologies are compensated for electricity produced, according to the electricity prices in each period. Therefore, the economics of cogeneration are influenced by both input fuel prices and electricity prices. Note that neither CCS nor direct nuclear technology options for industrial facilities are modeled in these scenarios.

The technology scenarios investigated in this analysis address future technological change in two areas: the equipment used to provide intermediate industrial services, and the amounts of these services required to produce a unit of output in each industry. This allows for improvements in cross-cutting technologies, such as boilers, to be assessed separately from improvements tailored to single industries, such as more advanced blast furnaces or the use of energy-efficient membrane technologies. Assumptions about improvements in general industrial technologies are listed in Table 3.16. Base year boiler efficiencies are from the Council of Industrial Boiler Owners (2003), and reference scenario efficiencies improve by 0.1% per year. In the advanced scenario, boiler and motor system efficiencies are assumed to improve by 10% and 20% between 2005 and 2035, respectively (IEA 2007c, McKane et al. 2005).

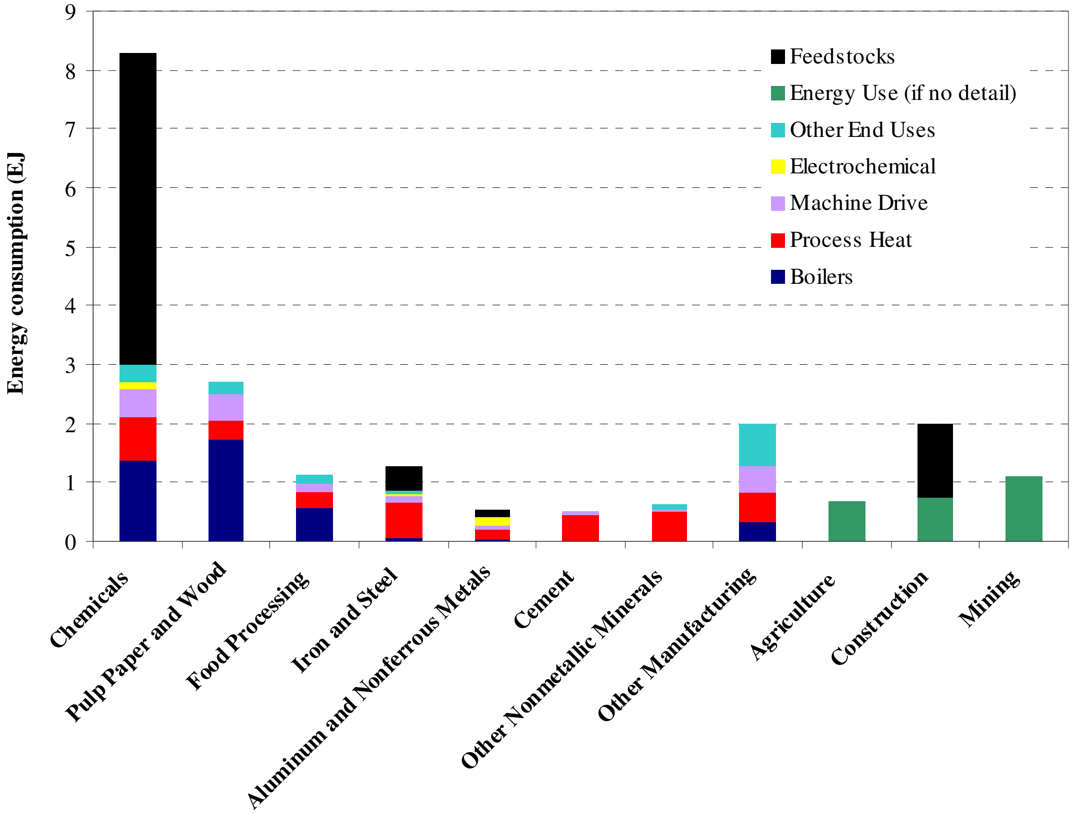

Figure 3.6. Industrial energy consumption by MiniCAM industrial group and intermediate service. Source: 2002 Manufacturing Energy Consumption (EIA 2002).

Assumptions about improvements in intermediate service requirements by industry are shown in Table 3.17. Service requirements are representative of intensities but are unitless as the services produced by industries are not explicit (with the exception of cement). The reference scenario assumes 0.35% annual improvement in intensity for all industries. The advanced scenario reflects a shift towards present-day best available manufacturing practices worldwide, as detailed in IEA (2007c), followed by long-term convergence with the reference assumptions for annual improvement rates. The specific improvements represented are detailed in the IEA report (IEA 2007c), and include steps such as switching to dry kilns in the cement industry, using membrane technologies in the chemicals industry, and increasing recycling rates in the paper industry.

Table 3.16. Intermediate service technological improvement, reference and advanced scenario. Efficiencies represent output / input, and are generally indexed to the electricity technology for each service in 2005.

			Reference		Advanced	
Intermediate Service	**Technology**	**2005**	**2050**	**2095**	**2050**	**2095**
Boilers (steam)	**Biomass**	0.74	0.77	0.81	0.85	0.91
	Coal	0.8	0.84	0.88	0.92	0.98
	Electricity	1.00	1.00	1.00	1.00	1.00
	Gas	0.8	0.84	0.88	0.92	0.98
	Oil	0.8	0.84	0.88	0.92	0.98
	Biomass CHP: steam	0.55	0.58	0.60	0.63	0.67
	Biomass CHP: electricity	0.2	0.21	0.22	0.23	0.25
	Coal CHP: steam	0.6	0.63	0.66	0.69	0.74
	Coal CHP: electricity	0.25	0.26	0.27	0.29	0.31
	Gas CHP: steam	0.6	0.63	0.66	0.69	0.74
	Gas CHP: electricity	0.25	0.26	0.27	0.29	0.31
	Oil CHP: steam	0.6	0.63	0.66	0.69	0.74
	Oil CHP: electricity	0.25	0.26	0.27	0.29	0.31
Process Heat	**Biomass**	0.85	0.89	0.93	Same as Ref	
	Coal	0.85	0.89	0.93	Same as Ref	
	Electricity	1.00	1.00	1.00	Same as Ref	
	Gas	0.85	0.89	0.93	Same as Ref	
	Oil	0.85	0.89	0.93	Same as Ref	
	Biomass CHP: steam	0.75	0.78	0.82	Same as Ref	
	Biomass CHP: electricity	0.15	0.16	0.16	Same as Ref	
	Coal CHP: steam	0.75	0.78	0.82	Same as Ref	
	Coal CHP: electricity	0.15	0.16	0.16	Same as Ref	
	Gas CHP: steam	0.75	0.78	0.82	Same as Ref	
	Gas CHP: electricity	0.15	0.16	0.16	Same as Ref	
	Oil CHP: steam	0.75	0.78	0.82	Same as Ref	
	Oil CHP: electricity	0.15	0.16	0.16	Same as Ref	
Machine Drive	**Biomass**	0.30	0.31	0.33	0.41	0.46
	Coal	0.30	0.31	0.33	0.41	0.46
	Electricity	1.00	1.05	1.09	1.36	1.53
	Gas	0.35	0.37	0.38	0.48	0.54
	Oil	0.40	0.42	0.44	0.55	0.61
Electrochemical	**Electricity**	1.00	1.05	1.09	Same as Ref	
Other End Uses	**All fuels**	1.00	1.05	1.09	Same as Ref	

Table 3.17. US industry intermediate service intensities, by industry and service, for reference and advanced technology scenarios. Intensities for cement are in GJ / ton (Process Heat and Machine Drive), and tons / ton (Limestone). All other service intensities are unitless but reflect services required to produce a unit of generic output.

			Reference			Advanced		
Industry	**Service**	**2005**	**2020**	**2050**	**2095**	**2020**	**2050**	**2095**
Chemicals	**Boilers**	0.12	0.12	0.11	0.09	0.11	0.08	0.07
	Process Heat	0.08	0.08	0.07	0.06	0.07	0.06	0.04
	Machine Drive	0.06	0.05	0.05	0.04	0.05	0.04	0.03
	Electrochemical	0.02	0.01	0.01	0.01	0.01	0.01	0.01
	Other End Uses	0.04	0.04	0.03	0.03	0.03	0.03	0.02
	Feedstocks	0.68	0.65	0.58	0.50	0.59	0.46	0.36
Food Processing	**Boilers**	0.46	0.44	0.39	0.34	Same as Ref		
	Process Heat	0.23	0.22	0.19	0.17	Same as Ref		
	Machine Drive	0.15	0.14	0.13	0.11	Same as Ref		
	Other End Uses	0.16	0.15	0.14	0.12	Same as Ref		
Iron and steel	**Boilers**	0.04	0.03	0.03	0.03	Same as Ref		
	Process Heat	0.43	0.41	0.37	0.31	0.40	0.35	0.29
	Machine Drive	0.11	0.10	0.09	0.08	Same as Ref		
	Other End Uses	0.07	0.06	0.06	0.05	Same as Ref		
	Feedstocks	0.35	0.33	0.30	0.25	0.32	0.28	0.24
Cement	**Process Heat**	3.95	3.81	3.53	3.15	3.11	2.35	2.10
	Machine Drive	0.51	0.50	0.46	0.41	0.41	0.32	0.30
	Limestone	1.50	1.50	1.44	1.29	1.43	1.34	1.28
Other Nonmetallic Minerals	**Process Heat**	0.65	0.62	0.55	0.47	Same as Ref		
	Machine Drive	0.08	0.08	0.07	0.06	Same as Ref		
	Other End Uses	0.14	0.13	0.12	0.10	Same as Ref		
	Limestone	0.11	0.10	0.09	0.08	Same as Ref		
Other Manufacturing	**Boilers**	0.13	0.13	0.11	0.10	0.12	0.11	0.09
	Process Heat	0.25	0.24	0.21	0.18	0.23	0.20	0.16
	Machine Drive	0.23	0.21	0.19	0.16	0.21	0.18	0.15
	Other End Uses	0.39	0.37	0.33	0.28	0.36	0.30	0.25
Aluminum and Nonferrous Metals	**Boilers**	0.06	0.06	0.05	0.04	0.06	0.05	0.04
	Process Heat	0.30	0.28	0.25	0.22	0.27	0.24	0.20
	Machine Drive	0.09	0.08	0.07	0.06	0.08	0.07	0.06
	Electrochemical	0.29	0.28	0.25	0.21	0.27	0.24	0.20
	Other End Uses	0.03	0.03	0.03	0.02	0.03	0.02	0.02
	Feedstocks	0.23	0.22	0.20	0.17	0.22	0.19	0.16
Pulp Paper and Wood	**Boilers**	0.56	0.53	0.48	0.41	0.51	0.41	0.34
	Process Heat	0.14	0.13	0.12	0.10	0.13	0.11	0.09
	Machine Drive	0.20	0.19	0.17	0.15	0.18	0.15	0.12
	Other End Uses	0.10	0.09	0.08	0.07	0.09	0.08	0.07
Agriculture	**All Energy Uses**	1.00	0.95	0.85	0.73	Same as Ref		
Construction	**All Energy Uses**	0.38	0.36	0.32	0.28	Same as Ref		
	Feedstocks	0.62	0.59	0.53	0.45	Same as Ref		
Mining	**All Energy Uses**	1.00	0.95	0.85	0.73	Same as Ref		

Aggregate industrial sectors in non-US regions are assumed to improve towards the best available practice in each industry as well; this is parameterized in two ways in MiniCAM. The improvements in boilers and motors assumed for the US are applied, assuming that boilers account for 35% to 40% of all hydrocarbon energy consumption by all industrial sectors (the higher rate is used in regions with steam-intensive industries; see Table 9.6 in IEA 2007c), and that motor systems account for 60% of the electricity consumption. Within any region, improvements in intensity of individual industries are applied to the aggregate industrial sector according the relative energy shares in 2005 (IEA 2007a and IEA 2007b). Regions are assumed to converge towards best available practices starting in the near term, and continuing to improve at a modest rate through 2095. In general, this results in the most aggressive future technological improvement rates in the US and Canada, and the least in Africa and Southeast Asia. This is because the stock of energy-intensive manufacturing facilities in the US and Canada tends to be older, as more recently, investments in energy-intensive manufacturing facilities have taken place in developing countries.

3.4.5.3 Transportation

The transportation sector is a large consumer of energy, particularly in the United States, where it accounts for greater than 40 percent of all final energy consumption. The overall approach to the detailed U.S. transportation sector used in this analysis is described in Kim et al. (2006); in this analysis it is disaggregated into five sectors: passenger, freight, military, pipeline, and recreational non-road vehicle use. Service demand growth by each of these is represented separately. The passenger and freight sectors are the largest energy consumers; their services are indicated explicitly in MiniCAM (as passenger-km and ton-km, respectively).

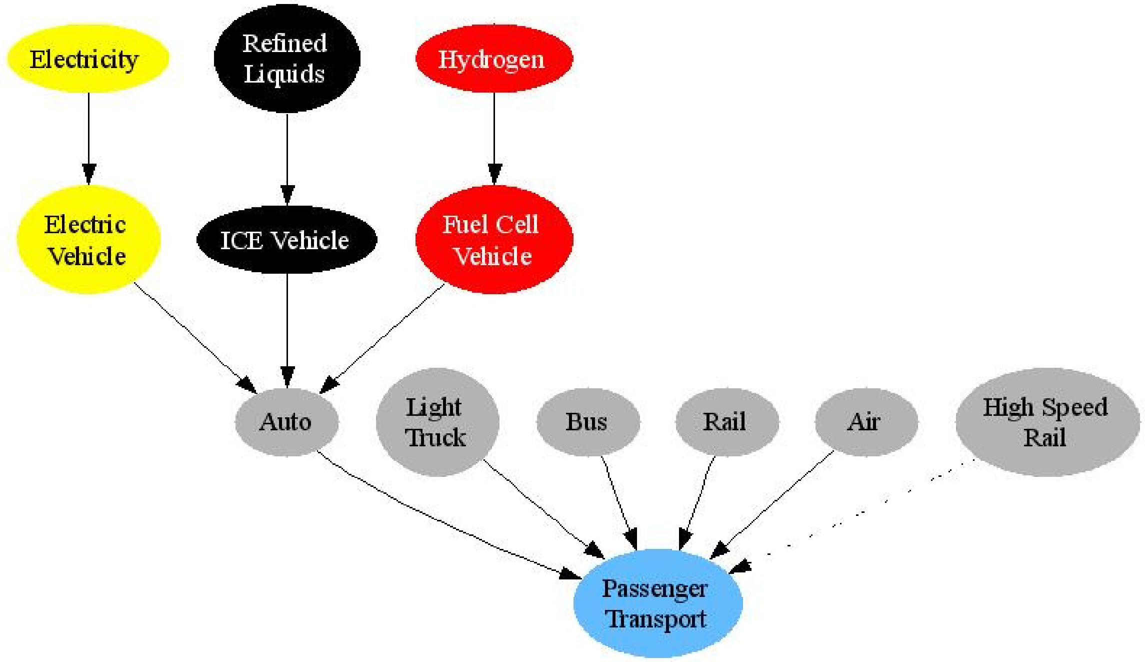

Figure 3.7. Schematic of the U.S. passenger sector. Transportation technologies compete for market share within modes, and modes compete for share of the passenger service. Modal competition includes time value cost.

A two-level nested logit technology competition is used to allocate share among different transportation technologies that compete to provide passenger and freight services; see Figure 3.7 for an illustration of the passenger sector. Specific transportation technologies compete (e.g. ICE vehicle, battery electric vehicle) for market share within modes, which themselves compete for market share of transportation service provision. Vehicle technology non-energy costs are expressed in terms of costs per vehicle kilometer, and intensities are expressed in terms of energy requirements per vehicle mile. An exogenous load factor (e.g. persons per vehicle) allows conversion between vehicle-km and passenger-km.

Table 3.18. Passenger and freight service intensity assumptions in the reference and advanced scenarios. Passenger intensities are in BTU per passenger-km, and freight intensities are in BTU per ton-km.

Mode	**Technology**		**Reference**			**Advanced**		
Passenger		**2005**	**2020**	**2050**	**2095**	**2020**	**2050**	**2095**
Auto	**ICE**	1977	1637	1366	952	1637	1122	637
	Electric	667	643	596	533	629	557	465
	Fuel cell	1252	1110	872	608	1037	711	404
Light Truck	**ICE**	2553	2114	1765	1229	2114	1449	823
	Electric	862	830	770	688	812	720	601
	Fuel cell	1617	1433	1126	785	1339	918	521
Bus	**ICE**	800	788	765	731	771	663	593
	CNG	1582	1558	1512	1446	1523	1413	1263
	Electric	357	352	341	326	352	341	326
Rail	**ICE**	1189	1171	1137	1087	1145	1062	949
	Electric	575	566	549	525	566	549	525
High-Speed Rail	**Electric**	n/a	n/a	n/a	n/a	414	384	343
Air	**Air**	1610	1551	1439	1285	1438	1147	818
Freight								
Truck	**ICE**	2131	1992	1766	1475	1861	1419	945
	Electric	720	673	596	498	628	479	319
	Fuel cell	1350	1262	1119	934	1179	899	598
Rail	**ICE**	345	339	329	315	332	308	275
	Electric	116	115	111	106	112	104	93
	Fuel cell	218	215	209	199	210	195	174
Air	**Air**	6543	6162	5464	4562	5845	4663	3323
Domestic ship	**ICE**	294	290	281	269	283	263	235
	Fuel Cell	186	183	178	170	179	166	149
International Ship	**ICE**	139	137	133	127	134	124	111
	Fuel cell	88	87	84	80	85	78	70

In the passenger sector, the modal competition is influenced by average technology costs, as well as the time value of transportation. This is calculated in each period based on the average transit speed of each mode (exogenous), and the wage rate, calculated from the per-capita GDP in each time period. The time value limits service demand growth in the passenger sector as incomes rise, and also puts a premium on fast modes of transportation, such as airplanes. No time value is assumed in freight transport, or the other transportation service demands.

Non-energy costs in transportation in base years are from Davis and Diegel (2007) and the Bureau of Transportation Statistics (2007). Costs are assumed constant through 2095 for existing technologies. Fuel cell vehicles are assigned non-energy costs that are 15 percent higher than ICE vehicles in 2020, dropping to 10 percent in 2050 (reference), and matching ICE costs in 2050 (advanced). Electric vehicles start at 10 percent more costly in 2020, and drop to 5 percent in 2050 (reference) and also match ICE costs in the advanced. The advanced scenario assumptions also include high-speed rail. Because of the difficulty of economically modeling large infrastructural decisions such as building up high-speed rail networks, this technology is only allowed with limited availability, representative of deployment in several corridors only. The assumed costs are based on Levinson et al. (2001).

Advanced and reference fuel intensity assumptions are presented in Table 3.18. Base year energy consumption by technology and fuel intensity are generally derived from the 2007 Transportation Energy Data Book (Davis and Diegel 2007). International shipping fuel intensity is derived from total global shipping service (UNCTAD 2006) and global bunker fuel use (IEA 2007a and 2007b). Assumptions for near-term improvement of existing transportation technologies are based on EIA (2007). Long-term improvement rates and intensities of new transportation technologies are roughly based on consultation with experts at DOE. The assumed speed and energy intensity of high-speed rail are based on four existing high-speed rail systems worldwide (CCAP & CNT 2006).

3.5 Agriculture, Land Use, and Bioenergy in MiniCAM

3.5.1 The Agriculture and Land Use Model

Land-use practices have several effects on stabilization. The conversion of grasslands and forests to agricultural land results in a net emission of CO_2 to the atmosphere. This has been the largest of all sources of anthropogenic land use emissions historically. In the future, biomass energy crops will compete for agricultural land with traditional agricultural crops, linking land use with the energy system. Efforts to capture carbon in terrestrial reservoirs, such as forests, may place a damper on deforestation activities, and potentially lead to afforestation or reforestation activities.

To capture these dynamics, MiniCAM includes a model that allocates the land area for each of MiniCAM’s 14 regions among different land uses, tracks production from these uses, and tracks carbon flows into and out of terrestrial reservoirs. The MiniCAM agriculture, land use, land cover, terrestrial carbon cycle module determines the demands for and production of products originating on the land, the prices of these products, the allocation of land to competing ends, the rental rate on land, and the carbon stocks and flows associated with land use.

Land is allocated between alternative uses based on expected profitability, which in turn depends on the productivity of the land-based product (e.g. mass of harvestable product per ha), product price, the rental rate on land, and non-land costs of production (labor, fertilizer, etc.). The allocation of land types takes place in the model through global and regional markets for agricultural products. These markets include those for raw agricultural products as well as those for intermediate products such as poultry and beef. Demands for most agricultural products, with the exception of biomass products, are based primarily on income and population. Land allocations evolve over time through the operation of these markets, in response to changes in income, population, technology, and prices.

The costs of supplying agricultural products are based on regional characteristics, such as the productivity of land and the variable costs of producing the crop. Exogenous assumptions are made for the rate of increase in agricultural productivity. The productivity of land-based products is subject to change over time based on future estimates of crop productivity change.

The advanced technology assumptions adopts the assumptions from the UN Food and Agricultural Organization (FAO, 2003), which are available for the next 30 years. The FAO estimates generally assume higher potential for increased productivity in developing countries, relative to developed regions. Beyond 2030, the advanced technology assumptions assume convergence to a rate of 0.5 percent annually for the remainder of the century. For the reference technology assumptions, the productivity growth over the next thirty years is assumed to be 0.75 percent of the FAO assumptions, converging to 0.375 percent per year for all crops in the second half of the century. This assumption is based on a conservative slowing of growth from the available projections of the first decades, but is highly uncertain. In recent years, declines in crop productivity growth in some regions have led to concern that crop productivity growth may plateau or stagnate. Conversely, new research in crop management, crop breeding programs and genetic modification of crops has the potential to greatly increase crop productivity in the future (Tilman et al., 2002). Crop productivity change assumptions have a powerful effect on model results reported here, and therefore we report the implications of alternative assumptions about the future path of productivity.

The boundary between managed and unmanaged ecosystems is assumed to be elastic in the MiniCAM. The area of land under cultivation expands and contracts with the land rental rate. Thus, increased demands for land result in higher rental rates and expansion into unmanaged ecosystems and vice versa.

Historical land use is taken from the FAOSTAT ResourceSTAT land database while historical agricultural production and harvested cropland area are taken from the FAOSTAT database for 1990 and 2005 (http://www.faostat.fao.org, accessed November, 2007). Cropping systems are divided into nine categories (rice, wheat, corn, other grains, oil crops, fiber crops, fodder crops, sugar crops, and miscellaneous crops) and animal production is represented by five categories (beef, dairy, pork, poultry, and other ruminants). Feed for animal production is split into pastured and mixed production systems following the methodology of Bouwman et al. (2005). Under this categorization, animal feed is supplied both by pasture land and by grain and fodder crops and thus future demand for animal products impacts land allocation in MiniCAM.

Carbon is distributed among fifteen reservoir types: unmanaged forests, other unmanaged land, managed forests, nine food and fiber crop types, bioenergy crops, pasture, and non-arable land. Stocks of terrestrial carbon (both above-ground and below ground) have been adapted from Jain and Yang (2005). Fluxes of carbon result from changes in land-use between model simulation periods. Thus, an increase in cropland may cause a reduction in forest land. As the carbon stock of initial use (forest) is greater than that of the resulting use (cropland) a pulse of carbon is emitted to the atmosphere from the land-use change.

3.5.2 Bioenergy in MiniCAM's Agriculture and Land Use Model

One purpose of the agriculture and land use model is to capture the potential prices and availability of biomass products by explicitly capturing the interaction of land devoted to biomass with other uses of land. The supply characteristics of biomass are derived from the land-use model. The demand for biomass is derived endogenously from the energy component of the model. For example, the larger the value of carbon, the more valuable biomass is as an energy source and the greater the price the energy markets will be willing to pay for biomass. Conversely, as populations grow and incomes increase, competing demands for land may drive down the amount of land that would be available for biomass production at a given price.

There are three types of bioenergy in the MiniCAM: traditional bioenergy production and use, bioenergy from waste products, and purpose-grown bioenergy. Traditional bioenergy consists of straw, dung, fuel wood and other energy forms that are utilized in an unrefined state in the traditional sector of an economy. Traditional bioenergy use, although significant in developing nations, is a relatively small component of global energy. Traditional biomass is modeled as becoming less economically competitive as regional incomes increase over the century.

Bioenergy from waste products are fuels that are consumed in the modern sectors of the economy, but which are byproducts of another activity, for example black liquor in the pulp and paper industry or crop residues in agriculture. The availability of byproduct energy feedstocks is determined by the underlying production of primary products and the cost of collection. The total potential waste available is calculated as the total mass of the crop less the portion that is harvested for food, grains, and fibers, and the amount of biomass needed to prevent soil erosion and nutrient loss and sustain the land productivity. The amount of potential waste that is converted to bioenergy is based on the price of bioenergy. However, the bioenergy price does not affect production of the crop from which the waste is derived. For example, an increase in the price of bioenergy would increase the share of the wheat crop collected for use as bioenergy, but the higher bioenergy price would not affect the total production of wheat. Instead, the higher bioenergy price would result in higher purpose-grown energy crops, discussed next.

The third category of bioenergy is purpose-grown energy crops. Purpose-grown bioenergy refers to crops whose primary purpose is the provision of energy. These would include for example, switchgrass and woody poplar. As noted earlier, we consider only "second generation" cellulosic bioenergy crops. Non-cellulosic crops, e.g. oils and sugars, are not included as potential purpose-grown bioenergy feedstocks in this analysis.

The profitability of purpose-grown, "second-generation" bioenergy depends on the expected profitability of raising and selling that crop relative to other land-use options in MiniCAM. This in turn depends on numerous other model factors including: bioenergy crop productivity (which in turn depends on the character of available land as well as crop type and technology), the rental rate on land, non-energy costs of crop production, cost and efficiency of transformation of purpose-grown bioenergy crops to final energy forms (including liquids, gases, solids, electricity, and hydrogen), cost of transportation to the refinery, and the price of final energy forms. The price of final energy forms is determined endogenously as a consequence of competition between alternative energy resources, transformation technologies, and technologies to deliver end-use energy services. In other words, prices are determined so as to match demand and supplies in all energy markets.

A variety of crops could potentially be grown as bioenergy feedstocks. The productivity of those crops will depend on where they are grown—which soils they are grown in, climate characteristics and their variability, whether or not they are fertilized or irrigated, the availability of nitrogen and other minerals, ambient CO_2 concentrations, and their latitude. In this analysis we assume that a generic bioenergy crop, with characteristics similar to switchgrass, can be grown in any region. Productivity is based on region-specific climate and soil characterizes and varies by a factor of three across the MiniCAM regions.[7]

This study allows for the possibility that bioenergy could be used in the production of electric power and in combination with technologies to provide CO_2 emissions captured and stored in geological reservoirs (CCS). This particular technology combination is of interest because bioenergy obtains its carbon from the atmosphere and if that carbon were to be captured and isolated permanently from the atmosphere the net effect of the two technologies would be to produce energy with negative CO_2 emissions.

3.5.3 Pricing Carbon in Terrestrial Systems

Efficient climate policies are those that apply an identical price to greenhouse gas emissions wherever they occur. Hence, an efficient policy is one that applies identical prices to land use change emissions and fossil and industrial emissions. This efficient approach was used in this study. In all the stabilization scenarios, CO_2 emissions from the terrestrial sphere are assumed to be valued equally with CO_2 emitted by fossil fuel and industrial sources.[8]

Carbon in terrestrial systems can be priced using either a flow or a stock approach. The flow approach is analogous to the pricing generally discussed for emissions in the energy sector: landowners would receive either a tax or a subsidy based on the *net flow* of carbon in or out of their land. If they cut down forest to grow bioenergy crops, then they would pay a tax on the CO_2 emissions from the deforestation. In contrast, the stock approach applies a tax or subsidy to landowners based on the *carbon content* of their land. If the carbon content of the land changes, for example, by cutting forests to grow bioenergy crops, then the tax or subsidy that the landowner receives is adjusted to represent the new carbon stock in the land. The stock approach can be viewed as applying a “carbon” rental rate on the carbon in land. Both approaches have strengths and weaknesses. Real-world approaches may not be explicitly one or the other. The stabilization scenarios in this report are based on the stock approach.

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[7] In MiniCAM crop yields exhibit diminishing returns as production of any crop expands to less suitable land; we do not model a fixed yield. In this paper we have assumed that for a given soil and climate bioenergy crop yields increase at the generic rate of 0.375 percent per year.

[8] A change in atmospheric CO_2 concentration has the same impact on climate change no matter what the source. Thus, to a first approximation land-use emissions have the same impact as fossil emissions. But, there are important differences. Land-use emissions do not have the same impact on atmospheric concentrations as fossil emissions because land-use emissions also imply changes in the future behavior of the carbon-cycle. A tonne of carbon emitted due to deforestation, for example, is associated with a decrease in forest that might act as a carbon sink in the future.

4.0 The Reference Scenario

4.1 Introduction to the Reference Scenario

This section describes the Reference Scenario. The Reference Scenario combines reference technology assumptions, and assumes that no explicit actions are taken regionally, nationally, or globally to limit greenhouse gas emissions. The Reference Scenario is not a prediction. In fact, the explicit assumption of no climate policy throughout the 21st century will almost certainly be proved wrong. Its principal function is to serve as a point of departure to understand the implications of various policies to limit the concentration of greenhouse gases. It is a plausible point of departure for analysis of stabilization and the role of advanced technology. A wide range of equally plausible Reference Scenarios could have been developed for this exercise. Along these lines, the Reference Scenario assumes no new nuclear builds globally over the course of the century. This is a useful counterfactual assumption for establishing the value of nuclear power in addressing climate change, but the associated Reference Scenario represents perhaps a less realistic future than one that includes new nuclear construction. Hence, we have included both a Reference Scenario and a Nuclear Reference Scenario that maintains the assumption of no climate policy but adds in new nuclear builds, as economic, for comparison.

In addition to its role as a starting point for further scenario analysis, the Reference Scenario provides insight into how the global energy system and greenhouse gas emissions might evolve under its unique assumptions about population growth, changes in land and labor productivity, evolution of technology, and endowments of resources such as crude oil, natural gas, and coal. Together, these forces govern the supply and demand for energy, industrial goods, and agricultural products—the activities that lead to greenhouse gas emissions. The greenhouse gas emissions in the Reference Scenario are not predetermined; they are the result of the interactions between these various drivers over the 21st century.

The Reference Scenario does not assume that technology remains frozen at today's levels. Substantial advances occur in the Reference Scenario across virtually all of the relevant technological areas considered in the analysis: energy supply and transformation technologies, end-use technologies, and agricultural technologies. The advanced technology scenarios, to be discussed in Section 5, differ from the Reference Scenario in that they assume *additional* improvements in technology beyond those in the Reference Scenario.

The stabilization scenarios in Section 5 also differ from the Reference Scenario in that they assume a global effort to limit greenhouse gas emissions, albeit to differing degrees of stringency. The assumption that no actions are taken to address climate change in the Reference Scenario is consistent with the role of the Reference Scenario as a starting point for further analysis, but it is not likely that such a future will actually come to pass. Countries are already undertaking actions to limit the growth in greenhouse gas emissions. For example, the a range of bills have been under discussion in the U.S. congress, the E.U. is committed to a goal of 20 percent reductions by 2020, and discussions will take place at the UNFCCC Conference of Parties in Copenhagen in late 2008 on international architectures for climate mitigation. Further, a range of policies already in effect in the U.S. and beyond have climate benefits, such as CAFE standards and appliance efficiency standards. Although many of these policies were not targeted initially at climate mitigation, climate is increasingly becoming an important justification for their existence.

Beyond these two distinguishing characteristics – reference technology assumptions and the absence of concerted climate mitigation – the Reference Scenario is identical to the stabilization cases in Section 5. For example, the demographic and population assumptions, the underlying growth in labor productivity, the underlying demands for energy services and agricultural products are identical across all the scenarios in this report (although price effects result in some differences in consumption). Hence, comparing the stabilization scenarios to the Reference Scenario allows for explicit exploration of two important issues: the implications of stabilization and the role of advanced technology in achieving stabilization.

The remainder of this section explains the key characteristics of the Reference Scenario. Section 4.2 describes the assumptions regarding population and economic growth; Section 4.3 explains the evolution of the energy system; and Section 4.4 presents the evolution of agriculture and land use. Finally, Section 4.5 presents the greenhouse gas emissions in the Reference Scenario, which represents combined results of the various interacting factors described in the sections that precede it.

4.2 Population and Economic Growth

In the Reference Scenario, population growth in the developing countries is accompanied by particularly strong economic growth in nations such as India and China, and later in Latin America, the Middle East, and Africa, shifting the weight of global economic output. This also shifts energy demand and, consequently, greenhouse gas emissions away from the currently developed countries and toward the currently developing countries. The population and economic assumptions underlying the Reference Scenario provide a common foundation to all the scenarios in this analysis, including the stabilization scenarios.

Economic growth in each of the model's 14 regions is governed by three factors, each of which is an input to the model: labor productivity, labor force participation, and total population. Economic output is calculated as the product of the first two factors, modified by an energy-service price elasticity. For each region, assumed values for these parameters do not vary across technology scenarios or stabilization scenarios. However, stabilization incurs economic costs, which would be manifest in lower economic output in the stabilization scenarios. Similarly, improved technologies, such as those in the advanced technology scenarios, decrease the costs of energy in general, which tends to increase economic output. These factors imply that final economic output in the stabilization scenarios will differ from the Reference Scenario, but the underlying economic and demographic forces do not.

The population assumptions used in these scenarios are based on a combined analysis of the median scenario by the United Nations (UN 2005) and a Millennium Ecosystem Assessment (MEA 2005) Techno-Garden Scenario from the International Institute for Applied Systems Analysis. Starting with the underlying population scenario, the labor force was estimated from age and gender-specific labor force participation rates applied to the relevant cohorts, then summed and adjusted by a fixed unemployment rate. Important trends past and present trends were explicitly considered, including the increasing rate of labor force participation by females in the U.S. economy, the aging of the baby boomers, and evolving labor participation rates in older cohorts, reflecting the consequences of changing health and survival rates. Labor force productivity growth rates vary over time and across regions to represent these evolving demographics.

The population and aggregate economic characteristics of the Reference Scenario are shown in Figure 4.1. Population increases from roughly six billion today to over eight billion by the end of the century, with the majority of this growth in developing economies. The scenarios do not exhibit exponential growth. If recent growth rates were to continue throughout the 21st century, the end-of-century population would be well over 10 billion. However, the scenarios exhibit a demographic transition from high birth and death rates to low death rates and eventually to low birth rates, reflecting assumptions that birth rates will decline to replacement levels or below, particularly as standards of living increase. For some countries, birth rates are already below replacement levels, and maintaining these rates will result in population decline for these countries.

Economic output exhibits a similar shift toward the developing nations. The U.S. continues labor productivity growth of roughly 1.5 percent annually throughout the century, within the range of rates that is consistent with the historical record. This leads to economic output roughly five times that of today. The developing economies, such as China and India, exhibit substantially higher labor productivity growth rates particularly early in the century, and several regions, including Africa, Latin America, and the Middle East, emerge from low initial growth to the same sorts of growth rates experienced recently in India and China. As a result, global gross domestic product (GDP) grows from roughly 40 trillion dollars in 2000 to over 300 trillion dollars (in 2005 U.S.$, MER) by the end of the century, with China, India, and Southeast Asia producing roughly 150 trillion dollars combined.

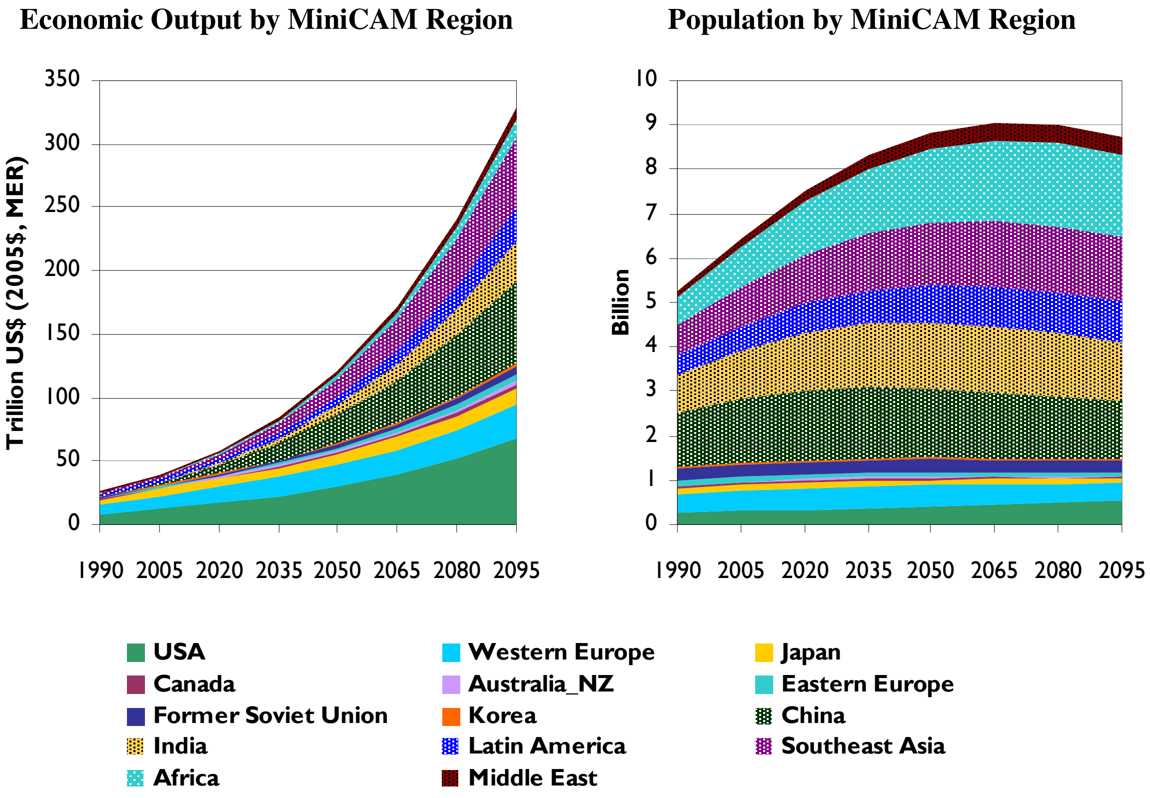

Figure 4.1. Population and GDP by MiniCAM region in the Reference Scenario.

4.3 The Energy System

With an increasingly prosperous global economy comes an increase in the ability to purchase the wide range of products and services that energy provides. Figure 4.2 shows the consumption of final energy in the Reference Scenario. Final energy represents the energy that is consumed in end uses. It differs from primary energy in that it does not account for conversion losses for generating intermediate energy carriers such as electricity. For this reason, final energy is always lower than primary energy.

In total, consumption of final energy roughly triples by the end of the century. However, the rate of growth slowly declines over the century, despite the more substantial increases in economic output, for three reasons. First, the demand for many end-use services may tend to saturate with increasing wealth; that is, there comes a point at which increasing prosperity does not bring forth a commensurate increase in consumption of particular services. For example, as people demand larger and larger houses, the benefit of each incremental square foot declines. Similarly, as income increases, the demand for travel increases, but this growth is mitigated by the increasing value that consumers place on their time. Second, improvements in end-use technologies reduce the energy required to provide each service. As discussed in Section 3, the Reference Scenario assumes annual improvements in the efficiency of end-use technologies. This reduces the rate of growth of final energy consumption.

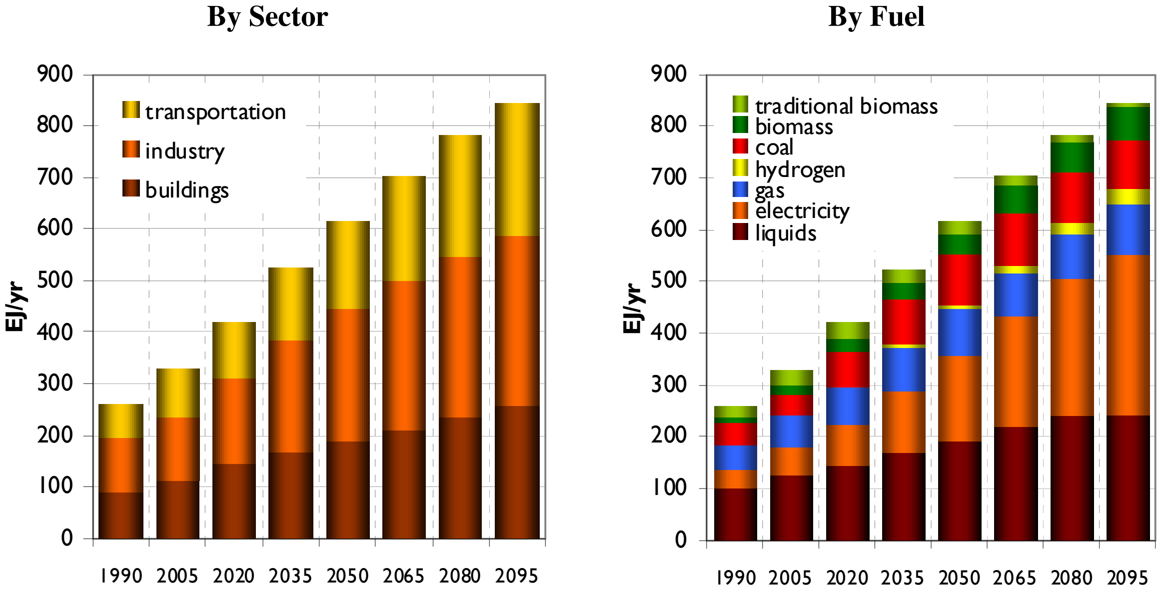

Figure 4.2. Global final energy consumption by sector and fuel

Finally, the Reference Scenario exhibits increasing electrification in both the buildings and industrial sector, which results in the global trend toward electrification as shown in Figure 4.2. Because electricity can generally provide greater service for a given input (e.g., a heat pump is more efficient than a gas furnace), increasing electrification puts downward pressure on final energy growth; however, primary energy consumption increases more than final energy consumption because energy is lost during the production of electricity. This trend toward increased electrification is an important characteristic of the scenarios, because it raises the importance of technologies that can reduce or eliminate the carbon emissions that result from electricity generation.

Increasing consumption of final energy leads to a roughly commensurate increase in the production of energy. Figure 4.3 shows global primary energy consumption by fuel in the Reference Scenario. Today, primary energy is roughly 400 EJ. By the end of the century, this increases over three-fold, to over 1200 EJ, roughly proportional to the growth in final energy consumption.

Renewable energy sources such as solar and wind power and bioenergy experience substantial growth in this scenario. Spurred on by the substantial improvements in costs and performance that were described in Section 3, these energy sources, together with nuclear power, provide over 300 EJ of primary energy by the end of the century—a level that exceeds total global primary energy production 1990 and is approaching that in 2000 (roughly 400 EJ). This is a dramatic expansion in the deployment of these technologies across the globe. As discussed earlier, the reference scenario holds nuclear energy production constant over the century. Figure 4.3 also shows primary energy in the Nuclear Reference Scenario. The production of energy from non-emitting sources is larger in this scenario than in the Reference Scenario; however the core role of fossil energy sources is unchanged.

Despite the growth in carbon-free energy sources, fossil fuels remain the dominant energy source throughout the century because of the enormity of the global resource of fossil fuels and their ease of use. By the end of the century, the fossil base is more than double that of today. Yet, the Reference Scenario also includes a transition away from conventional oil, which is the primary source of transportation fuel today. Conventional oil prices rise as the lower-cost elements of the resource base are exhausted and more expensive grades must be recovered. As conventional oil prices rise, a range of alternative fuels, primarily synthetic fuels from coal and unconventional sources of oil (e.g., tar sands and oil shales), become competitive in transportation markets. The broad availability of these sources allows the transportation energy consumption to increase, as discussed above, while the energy system transitions from conventional oil in the second half of the century. However, the production of liquid fuels derived from synthetic fuels and from unconventional oil sources are both more carbon intensive than production from crude oil, implying upward pressure on carbon emissions.

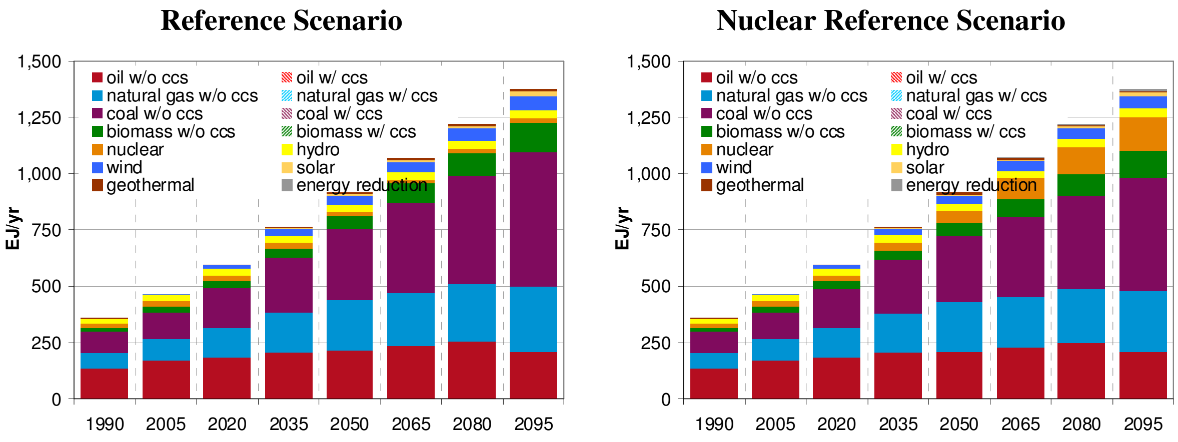

Figure 4.3. Global primary energy in the Reference Scenario and the Nuclear Reference Scenario

4.4 Land Use, Land-Use Change, and Terrestrial Sequestration

4.4.1 Land Use and Land-Use Change

Increasing population and increased standards of living, both of which are characteristics of the Reference Scenario, increase the demand for agricultural products. In particular, increasing standards of living are associated with an increase in the demand for secondary, more intensive agricultural products, such as beef and poultry. Both of these factors are reflected in the global land allocation in the Reference Scenario, as shown in Figure 4.4.

In general, crop land remains roughly constant over the century, declining somewhat later in the century. This decrease arises despite increased demand for food products, because agricultural productivity, including biomass crops, is assumed to increase over the century under both reference and advanced technology assumptions (see Section 3.5). Without this growth in agricultural productivity, there would be greater displacement of unmanaged lands in the Reference Scenario. Over time, in the Reference Scenario, demands for managed lands, including dedicated bioenergy crops, food and fodder crops, pasture land, and managed forest, put pressure on unmanaged lands.

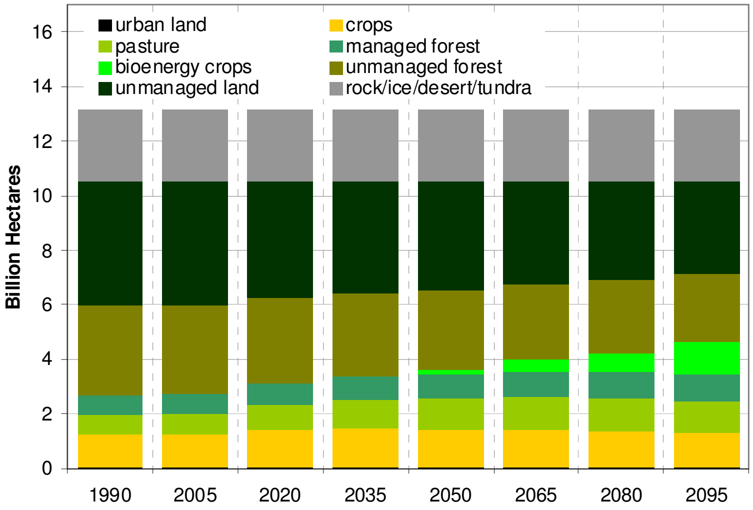

Figure 4.4. Global distribution of land in the Reference Scenario

4.5 Emissions, Concentrations, and Radiative Forcing

One outcome of population and economic growth is increasing fossil and industrial CO_2 emissions throughout the century. The left panel in Figure 4.5 shows the CO_2 emissions in the Reference Scenario from fossil and other industrial (cement) sources in both the Reference Scenario and the Nuclear Reference Scenario. Fossil and industrial CO_2 emissions rise in the Reference Scenario by over threefold, from about 7.5 GtC/yr in 2005 to over to over 22 GtC/yr in 2095. This is roughly commensurate with threefold growth in primary energy consumption in the Reference Scenario. Emissions are slightly lower in the Nuclear Reference Scenario, due to the deployment of nuclear power in electricity applications rather than fossil power. Net land use emissions remain roughly constant over the century and near zero. The cumulative result is increasing atmospheric concentrations of CO_2, as shown in the right panel of Figure 4.5. Not only do CO_2 concentrations triple relative to preindustrial levels, they are on the rise as the century closes, foretelling increasing concentrations well into the 22nd century.

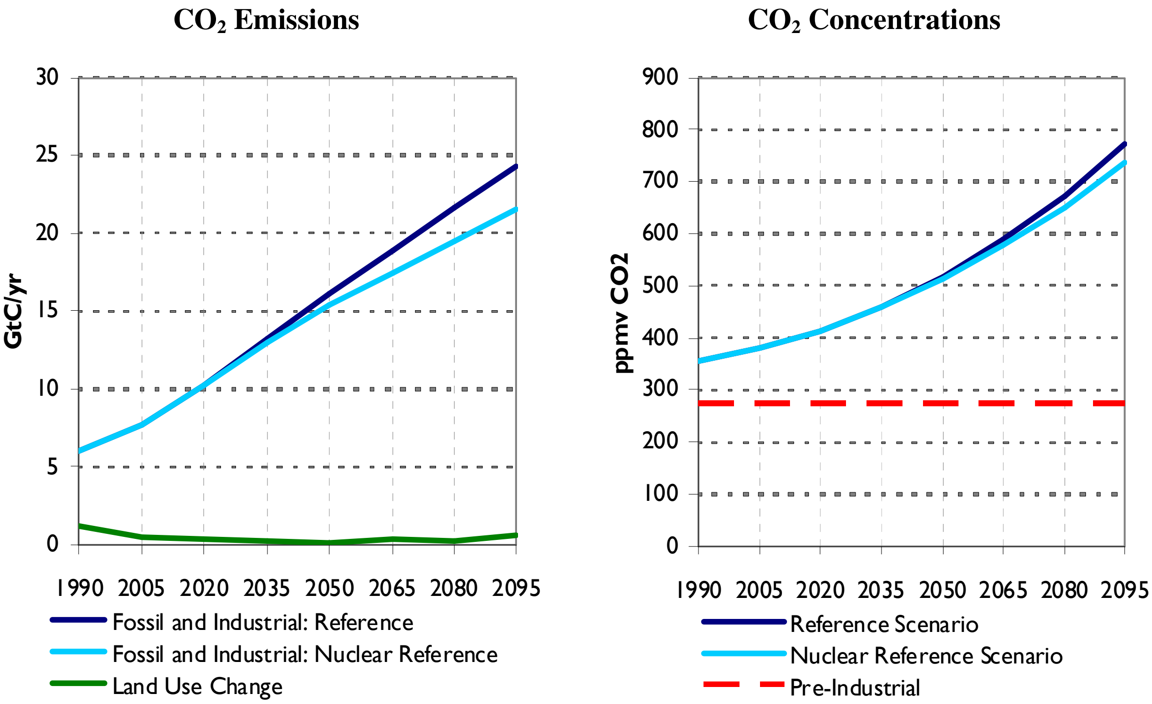

Figure 4.5. CO_2 emissions from fossil and other industrial (cement) sources and CO_2 concentrations in the Reference Scenario

The fossil and industrial CO_2 emissions from the Reference Scenario chosen for this analysis are roughly in line with the emissions from the CCSP scenarios. However, many recent studies indicate that if current trends in emissions growth in emerging economies such as China and India were to continue unabated throughout the century, emissions toward the end of the century could be much higher.

5.0 Advanced Technology and Stabilization

5.1 Introduction to the Stabilization Scenarios

This section discusses a set of scenarios that simulate stabilization of atmospheric concentrations of greenhouse gases, and it examines the role of advanced technology in reducing the economic impacts of achieving stabilization. An exhaustive set of scenario details is provided in the companion appendices to this report, so the focus in this section is on higher level insights and themes of the scenarios. Readers are encouraged to explore the appendices for more details.

The scenarios discussed in this section differ from the Reference Scenario discussed in Section 4 in two ways. First, most of the scenarios discussed here include advances in technology beyond those that were assumed in the Reference Scenario. Second, the stabilization scenarios are based on the assumption that the nations of the world adopt a cost-effective, cooperative mechanism for limiting greenhouse gas emissions. Two hypothetical long-term CO_2 stabilization levels were examined in the study: 450 ppmv and 550 ppmv. Conversely, the Reference Scenario assumes no explicit actions are taken in the future to mitigate greenhouse gas emissions.

The stabilization scenarios demonstrate two fundamental strategic insights that must frame any discussions of technology and climate. First, the scenarios demonstrate that a range of technologies will contribute to the achievement of stabilization goals. In no scenario is a single technology responsible for all (or even most) of reductions in greenhouse gas emissions. Instead, across the scenarios, multiple technologies and technology areas make important contributions. Second, advanced technology can dramatically lower the economic costs of stabilizing CO_2 concentrations. Lower economic costs are not only valuable in their own right, they are also tied to the feasibility of reaching different concentration limits, given that countries will make decisions on mitigation, either explicitly or implicitly, by comparing the costs and benefits.

The remainder of this section proceeds as follows. Section 5.2 discusses the greenhouse gas emissions trajectories and the resulting concentrations and radiative forcing levels in the stabilization scenarios, and Section 5.3 explores the variations in the energy system to meet the different stabilization levels given the differing assumptions about how technology might evolve over the coming century. In Section 5.4, the implications for land use and the terrestrial sequestration are characterized across scenarios. Section 5.5 discusses the economic implications of stabilization under the various technology assumptions.

5.2 Emissions, Radiative Forcing, and Concentrations

CO_2 is unique among the greenhouse gases in that it is not destroyed in the atmosphere. Instead, atmospheric CO_2 concentrations reflect the distribution of carbon among the ocean, terrestrial biosphere, and the atmosphere, which in turn is driven by a group of processes known as the carbon cycle. These processes are such that the introduction of CO_2 from fossil fuel combustion or other industrial sources into the atmosphere will set up a chain of events that redistribute the carbon over time within the atmosphere-ocean-terrestrial system. Over time, the CO_2 will be moved from the atmosphere into the oceans and potentially into the terrestrial biosphere. However, that partitioning process will still leave some of the CO_2 in the atmosphere for many thousands of years—leading to an essentially permanent increase in atmospheric CO_2 concentrations. For this reason, stabilizing CO_2 concentrations at any level requires that emissions eventually decline toward zero. The final stabilization level determines the total cumulative quantity of CO_2 that can be emitted into the atmosphere. The associated profile of emissions over time is determined in large part by economic considerations and the evolving rate of carbon uptake by the ocean. For many stabilization levels, emissions can continue to occur for many years beyond the point in time at which the concentration is stabilized because the ocean, and potentially the terrestrial biosphere, will continue to take up carbon. But these uptake processes will decline over time as the carbon cycle eventually returns to equilibrium.

Figure 5.1 shows the CO_2 concentration trajectories under reference technology assumptions for the two stabilization levels considered in this study. The timing of stabilization differs between the two concentration limits. The more stringent the stabilization goal, the more quickly it will need to be reached to achieve and maintain it. In the 450 ppmv scenario, stabilization is reached not long after mid-century. In the 550 ppmv scenario, stabilization is only occurring near the end of the century.

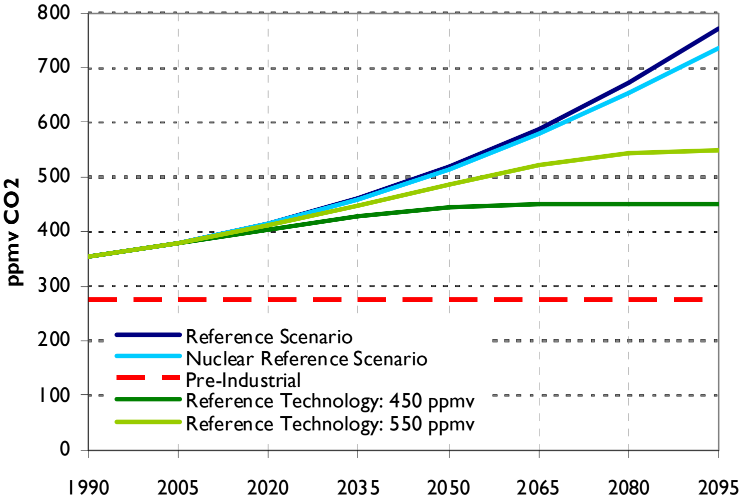

Figure 5.1. CO_2 concentrations across stabilization levels under reference technology assumptions.

The degree to which emissions must be constrained to achieve stabilization varies substantially over the two stabilization levels (Figure 5.2). Under the 450 ppmv limit, emissions peak and begin a decline almost immediately; under the 550 ppmv limit, emissions peak at roughly mid-century. Total cumulative emissions from fossil and industrial sources from 2000 through 2100 are roughly 1550 GtC in the Reference Scenario. Emissions must be decreased by roughly 650 GtC over the century to reach the 550 ppmv limit; emissions must be decreased by almost 1000 GtC to reach the 450 ppmv limit.

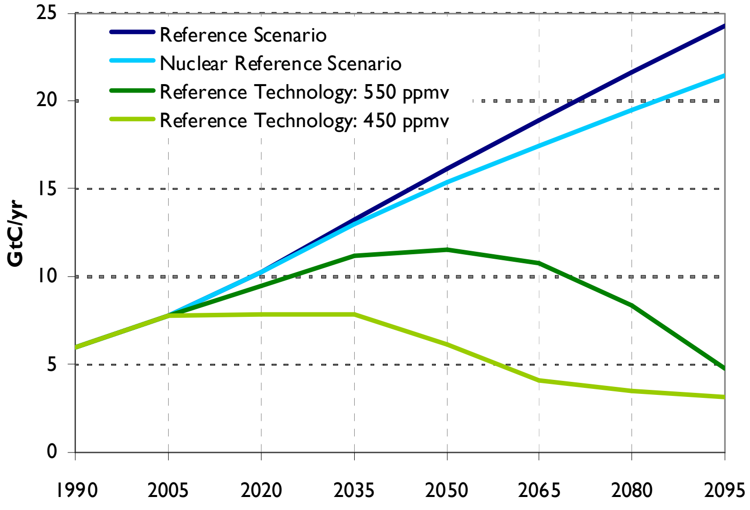

Figure 5.2. CO_2 emissions across stabilization levels under reference technology assumptions.

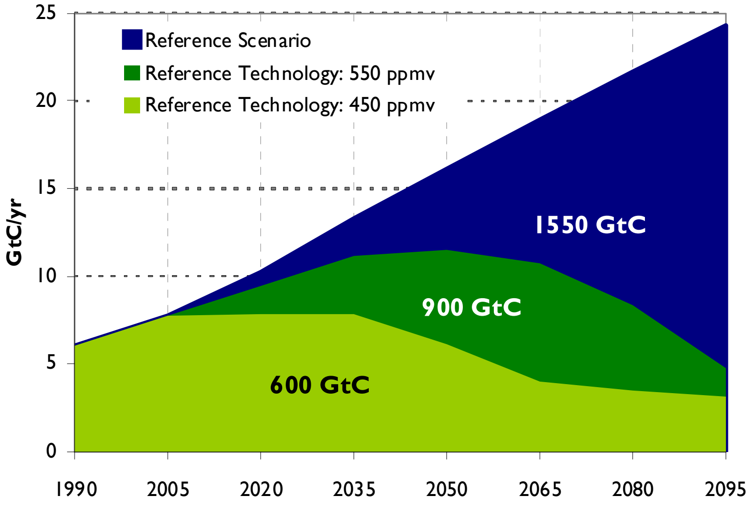

Figure 5.3. Potential scale of CO_2 emissions reductions to stabilize greenhouse gas concentrations. Cumulative emissions from 2000 - 2100

5.3 The Energy System

The energy sector is the largest source of CO_2 emissions, and CO_2 is the most important of the greenhouse gases. Thus, emissions limitations required for stabilization will have a strong impact on the energy sector. Three figures are shown in this section: primary energy across scenarios (Figure 5.4), electricity across scenarios (Figure 5.5), and transportation fuels consumption across scenarios (Figure 5.6). All are shown for the more stringent, 450 ppmv stabilization limit.

Several themes deserve emphasis when considering the shifts in the energy system. First, changes in the energy sector (compared to the Reference Scenario) come in two forms: reductions in energy use and shifts in the mix of energy supply sources toward those that emit less. Reductions in energy use can arise from (1) increases in the efficiency of end-use technologies resulting in more energy-efficient vehicles, buildings, and industrial processes; (2) use of more efficient energy supply technologies, such as more efficient fossil power plants; and (3) reductions in the demand for energy services, for example, driving cars fewer miles or setting thermostats lower in the winter. All of the scenarios exhibit these three forms of energy reduction, but there are differences in the emphasis and over time. In the scenarios with advanced end use assumptions (EE, EERE, and Adv), a greater proportion is due to improved end use technologies than in the other scenarios. Across all scenarios, at higher levels of emissions reduction, energy use reductions are increasingly due to the price effect: demand for energy decreases in response to the increased cost of energy, which is due to the cost associated with the carbon constraints. These reductions in service demand increase as the stabilization level is tightened. Those scenarios with fewer technological options experience higher carbon prices, and therefore have a larger energy reduction effect. For example, although the EE 450 and Ref 450 scenarios have relatively similar energy reductions, a substantially greater proportion of these reductions come from advanced end use technology in the EE 450 scenario than in the Ref 450 scenario, and the Ref 450 scenario has correspondingly higher carbon prices, as will be discussed later.

The role of end-use technologies in stabilization is not exclusively one of decreasing end-use energy through improved efficiency. An equally important role for end-use technologies is to facilitate switching to fuels that emit less carbon. For example, one response to increased carbon constraints in these scenarios is increased electrification. As the electricity system shifts toward technologies that emit less carbon, it becomes a more appropriate fuel for end-use applications. In fact, in several scenarios, electricity production increases with stabilization. Switching to hydrogen or biofuels in transportation provides similar benefits, if hydrogen can be generated from fossil fuels with carbon capture and storage or from sources such as nuclear, wind, or solar power. These adjustments in end-use fuel mix can only occur if the appropriate end-use technologies have been developed and are cost-effective. For example, electrification of heating in buildings depends on the cost and performance of electric heat pumps or other alternatives that use electricity instead of fuel. Similarly, the penetration of hydrogen into transportation can only occur if cost-effective hydrogen-powered vehicles are developed. This effect is demonstrated by comparing the levels of reduction in electricity production relative to primary energy consumption.

Regardless of the technology assumptions, one constant across the stabilization scenarios is a reduction in the consumption of freely-emitting fossil fuels and deployment of low- or zero-carbon energy sources. The impact on fossil fuel consumption is largely dependent on the presence or absence of CCS. Futures with the option for CCS can include greater use of fossil fuels for any stabilization limit than those without CCS. The presence of CCS allows for greater fossil consumption in two ways. First, fossil energy with CCS can serve as a low-carbon option. Hence, in many of the scenarios with CCS, there is substantial deployment of fossil energy with CCS. This allows for a continuation of coal and natural gas as primary electricity fuels. For example, in the CCS 450 and the BioCCS 450 scenarios, natural gas and coal with CCS are the largest electricity producers. The second role for CCS is to sequester carbon from bioenergy sources while producing an intermediate fuel such as electricity or hydrogen. Because bioenergy crops are themselves a low-carbon fuel, the use of CCS with bioenergy crops can lead to negative emissions. This allows for greater emissions from fossil sources. Hence, in all the scenarios with CCS, not only is the consumption of fossil fuels higher because of the option to use them with CCS, but the consumption of freely-emitting fossil fuels is higher because of the negative emissions from using bioenergy crops with CCS.

Although the necessity to deploy low- or zero-emitting sources is a constant in all the stabilization scenarios, there is enormous variation in the energy mixes globally by 2050 and leading to the end of the century. The relative roles of different technologies depend on technologies available and the choices that societies make about deploying particular technologies (e.g., nuclear energy). Scenarios with greater opportunities in renewable energy will use more renewable energy; scenarios with the option for CCS will use CCS; and so forth. What is clear is that differences in technological improvements along with the choices that society makes about deploying technologies such as nuclear power over the coming years will have an enormous impact on the nature of the energy system should the world choose to address global climate change. Without a priori knowledge of how these forces might unfold, there is a powerful logic that supports the need for a hedged portfolio approach to RD&D investments for climate change.

The diversity of technologies contributing to emissions reductions is apparent not just across scenarios, but also within scenarios: a range of technology options are valuable in any future in which the world's nations choose to limit greenhouse gas emissions. This diversity in the energy mix is a characteristic of the world today, and is caused by several factors that will likely continue throughout the century. One important cause is the heterogeneity of energy end uses. For example, electricity is a more effective energy source for air conditioning, but it has not yet proven a viable fuel for transportation applications, where portable, liquid fuels dominate. The range of different uses for energy in industrial, transportation, agricultural, and building end uses leads to the requirement for a diverse mix of fuels. Another cause is regional variation. In some regions, wind resources may be plentiful, and hence wind power relatively inexpensive, whereas it may not be competitive in others. In addition, many countries value a diversified energy portfolio as a way to hedge against risk. Moreover, a great deal of energy capital is long-lived, meaning that shorter-term fluctuations in investment patterns cannot fully alter the capital stock, and the effects of these fluctuations persist for many decades. An individual technology may become dominant for years of even decades—for example, natural gas combined cycle turbines were the electricity technology of choice for new installations in the U.S. in the 1990s—but the stock of technologies in total remains diversified.

Equally important to RD&D decision making is the timing of emissions reductions and deployment of low- or zero-carbon technologies and advanced end use technologies. In these scenarios, by 2050, low- and zero-emissions technology deployment has not just begun, but is in full swing, implying that substantial deployment and R&D efforts will need to have taken place well before 2050 if a 450 ppmv stabilization limit is to be reached. For a 550 ppmv limit, the timeline is stretched further into the future. Regardless of the stabilization level, behind these explicit shifts in the energy system are all the activities that are necessary to develop the technologies to the cost and performance levels assumed in the analysis. These include R&D, demonstration projects, and early niche deployment that can lead to important technology learning. Many of these activities can take decades. As discussed in Section 3, all the scenarios assume substantial progress in virtually every energy technology, and the advanced technology scenarios assume even greater advances. Simply put, these levels of advance require actions today to develop, improve, demonstrate, and deploy the technologies that will allow the world to control the costs of emissions reductions in the future.

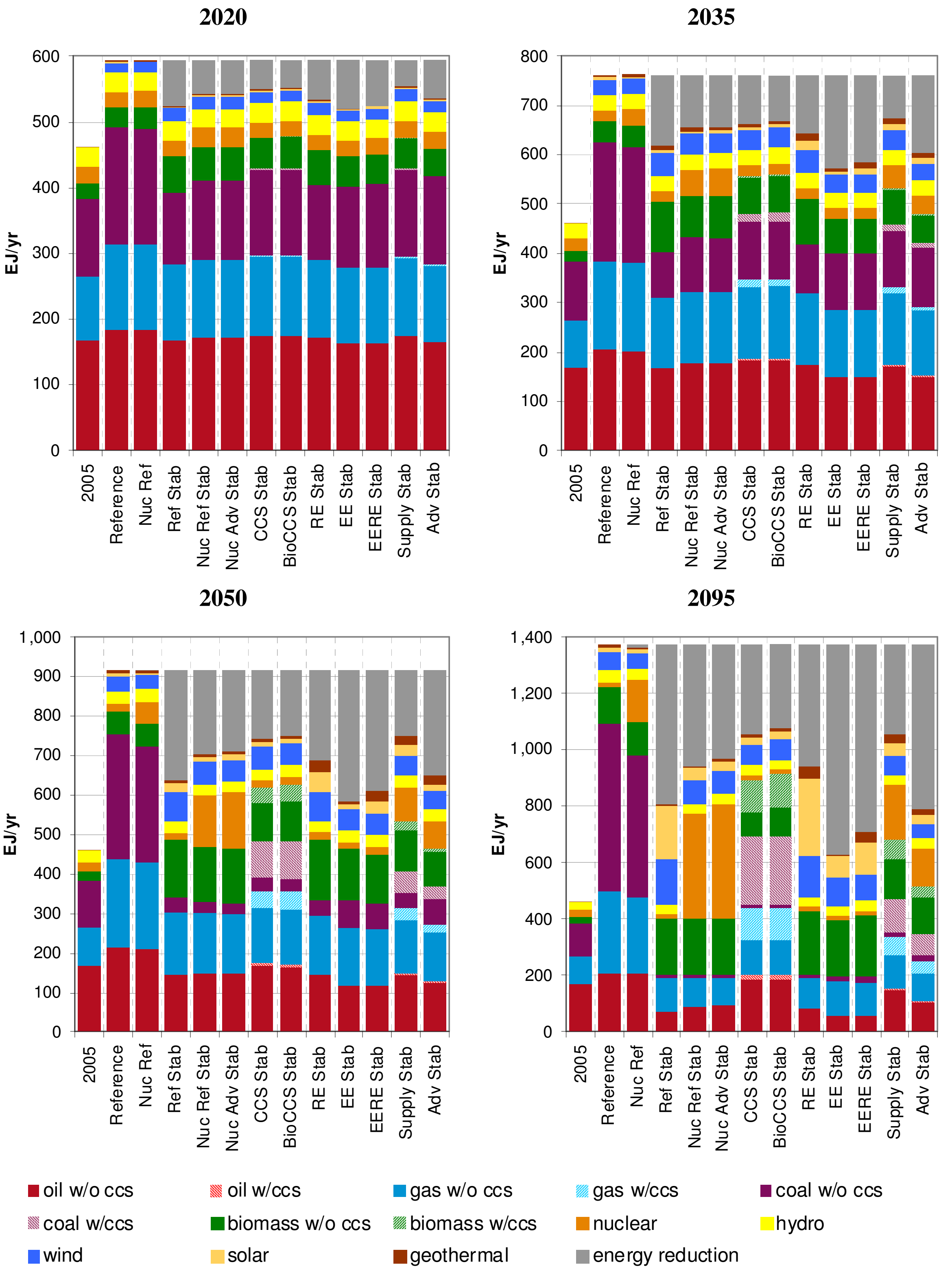

Figure 5.4. Global primary energy consumption across 450 ppmv stabilization scenarios: 2020, 2035, 2050 and 2095.

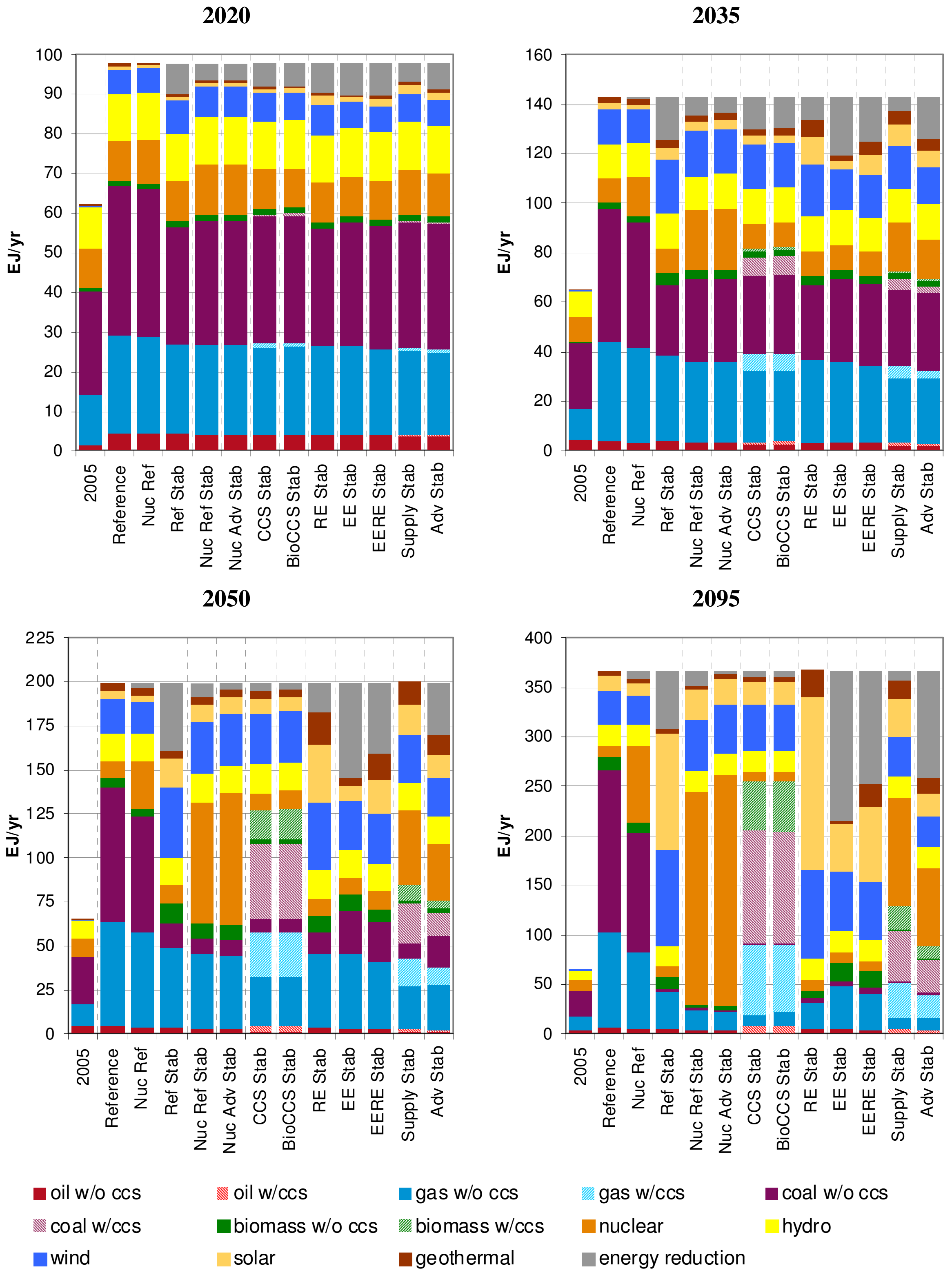

Figure 5.5. Global electricity production across 450 ppmv stabilization scenarios: 2020, 2035, 2050 and 2095.

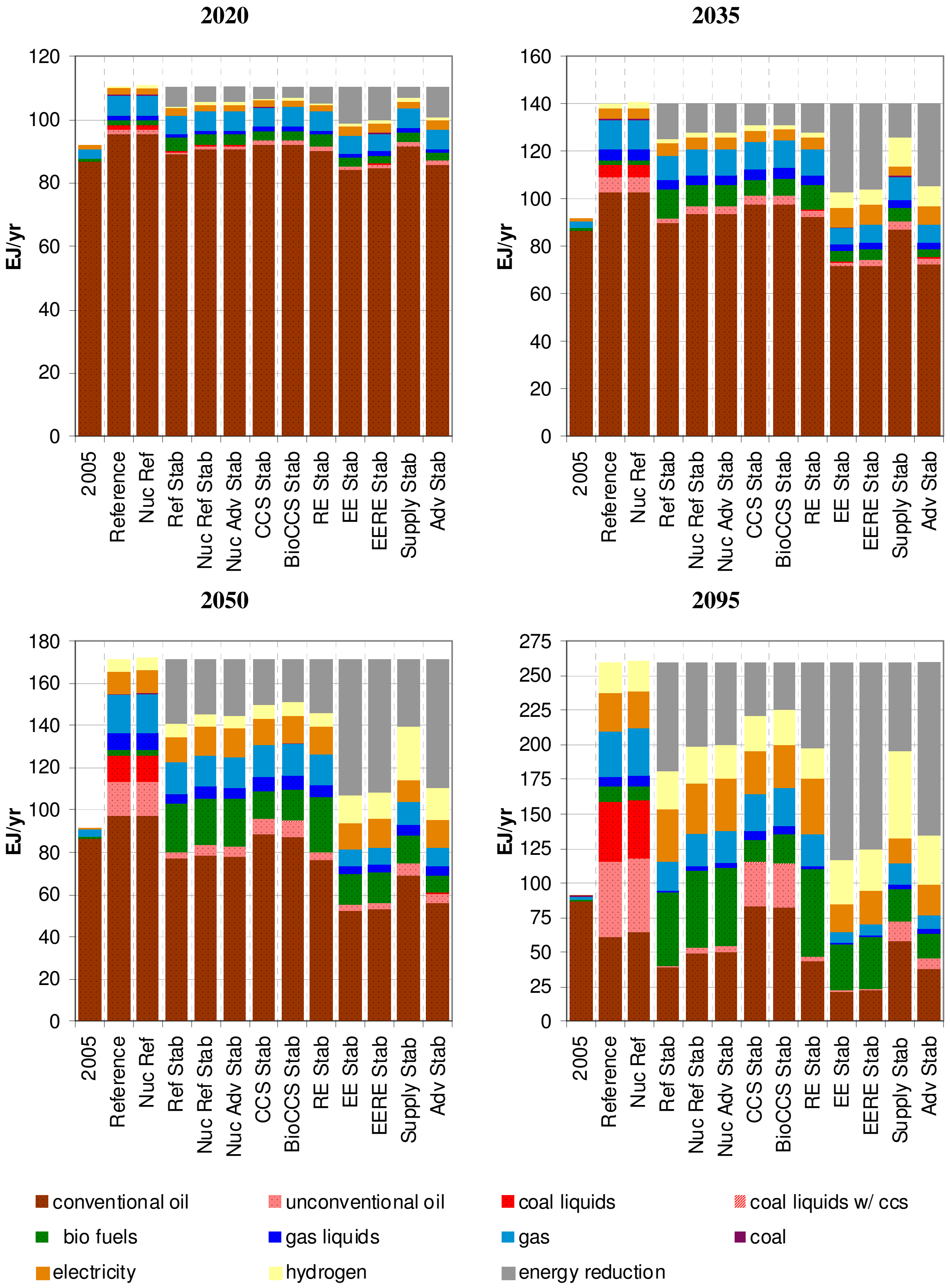

Figure 5.6. Global transportation fuels consumption across 450 ppmv stabilization scenarios: 2020, 2035, 2050 and 2095.

5.4 Land Use, Land-Use Change, and Terrestrial Sequestration

The distribution of land for different uses can be altered in stabilization scenarios through at least two countervailing forces. One force is the demand for bioenergy. Because bioenergy is net carbon neutral[9], the demand for bioenergy increases with constraints on carbon emissions because it can substitute for higher-carbon alternatives such as gasoline. Bioenergy is particularly valuable in transportation applications, because there are fewer low-carbon alternatives for fossil-derived liquid fuels than there are for fossil-fired electricity. It is also valuable in electricity applications when CCS is available, so that it can serve as a negative emissions source. Increasing use of land for bioenergy must come at the expense of other land uses, either unmanaged, managed forest, or agriculture. The second force arises because converting unmanaged lands or managed forests to bioenergy crops can result in net carbon emissions if the land has a lower carbon content (carbon stored per hectare of land) when used for bioenergy crops than if left in its existing state. As discussed in Section 3, MiniCAM applies the value of carbon not just to the energy system, but also to agricultural and other terrestrial systems. Converting lands from higher to lower carbon content uses therefore incurs a cost, or economic penalty. This, in turn, limits the amount of forests or unmanaged lands that will be converted to bioenergy crop production (and agriculture).

The outcome of this interplay depends on the technology assumptions and the level of stabilization. However, regardless of the stabilization level, if terrestrial carbon emissions are valued at a rate commensurate with fossil and industrial emissions, as is the case in these scenarios, there is a limit on the land committed to dedicated bioenergy crops. For example, dedicated bioenergy land in 2095 is 0.33 billion hectares in the Reference Scenario and 0.28 billion hectares in the bioCCS 450 scenario (Figure 5.7). However, bioenergy production increases from roughly 110 EJ/yr to 165 EJ/yr (Figure 5.8). The largest single noticeable effect on land use in the bioCCS 450 scenario relative to the Reference Scenario is not bioenergy production; it is the move into higher carbon content land uses such as forests and a decrease in land dedicated to crops. These higher carbon content uses of land are more valuable under a stabilization regime. Coincident with this change in land use is a dramatic increase in the price of crops and bioenergy as these crops fight for land with sources that can better store carbon. This leads to lower food demand and a shift away from less productive foods, such as beef, towards those that require the least land.

Bioenergy production increases despite the decrease in land for dedicated bioenergy crops for two reasons. First, roughly half of the bioenergy comes from waste crops, such as corn stover, which does not require additional land. Second, with the changes in the relative values of crops and land, there is a redistribution of production so that dedicated bioenergy crops are grown on lands with higher productivity in the BioCCS 450 scenario relative to the Reference Scenario.

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[9] The carbon in the fuel was obtained from the atmosphere. Thus, when it is oxidized and returned to the atmosphere, the net effect is to leave atmospheric carbon abundance unaffected. Indirect effects through land-use change emissions and increased demands for transportation and other energy services are handled separately as discussed in this section.

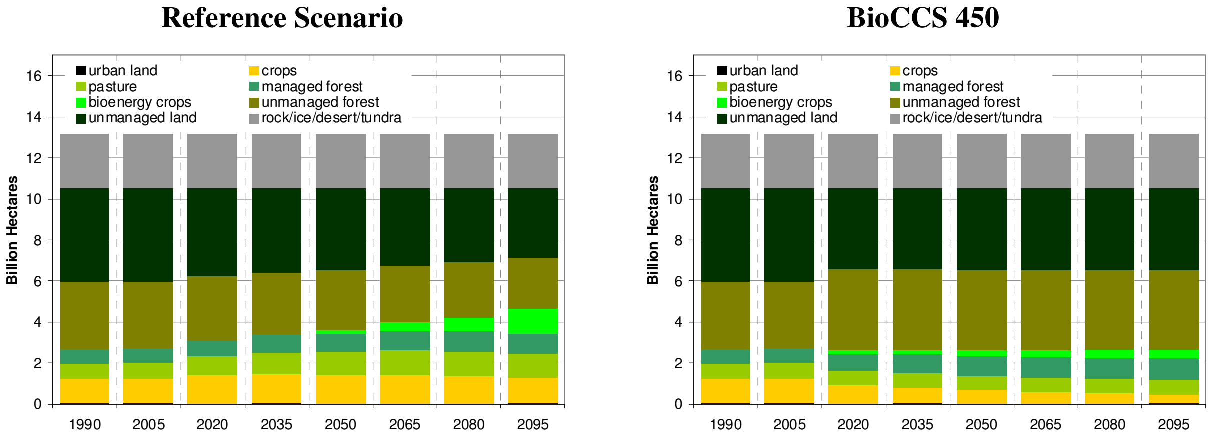

Figure 5.7. Global distribution of land uses in the Reference Scenario and the BioCCS 450 scenario

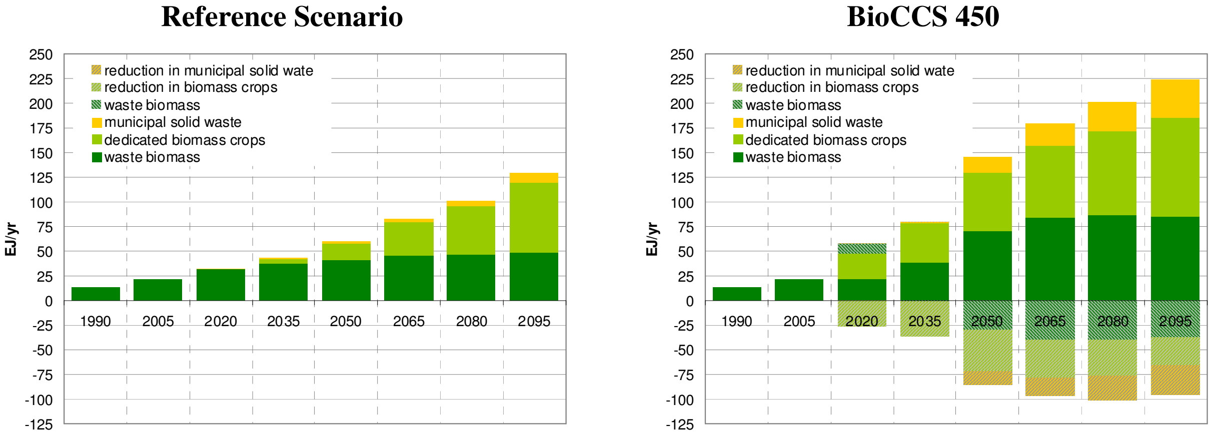

Figure 5.8. Global bioenergy production in the Reference Scenario and the BioCCS 450 scenario

5.5 Advanced Technology and the Costs of Stabilization

Ultimately, the role of technology in stabilization is to reduce the costs of achieving stabilization. All of the stabilization scenarios in this study reach their defined CO_2 concentration limits, and they do so using different technology mixes over time. If stabilization is to be achieved, these sorts of dramatic changes in the energy system will be required, regardless of technology. However, the availability of technology can have a dramatic effect on the economics of stabilization, and therefore on the feasibility. Going from reference technology assumptions to advanced technology assumptions, in these drops carbon prices by the end of the century and total discounted mitigation costs by roughly fivefold. The 550 ppmv scenario tells a similar story. Within the different technology scenarios, there is variation in costs as well, with some scenarios leading to more substantial cost reduction than others.

The cost results from these scenarios should be interpreted only as indicative of the character of costs; they should not be taken as precise estimates, for several reasons. For one, the cost numbers are also based on the assumption of a fully cooperative and economically efficient global approach to climate mitigation, as would be the case with a global tradable permit scheme or a global monetary value placed on carbon that rises gradually over time. Real-world approaches to climate mitigation could deviate substantially from this ideal, and the associated costs could be much higher. In addition, the costs are based on the large set of model assumptions supporting all of these scenarios. Different assumptions about key drivers, such as population growth, economic growth, and technological change, could dramatically alter these cost results. Assumptions embodied in the architecture of the model, such as the flexibility to substitute electricity for fossil fuels in end-use applications, could also have large effects on costs. For these and other reasons, it is important to focus on orders of magnitude and relative differences among scenarios when interpreting cost numbers from integrated assessment models such as MiniCAM.

Technology is the focus of this study. The value of a technology improvement can be estimated as the difference between the cost of stabilization with and without the improvement. Different technology assumptions could lead to different relative technology values, and a wide range of both reference and advanced technology assumptions in many technology areas could be considered plausible. Hence, the appropriate interpretation is not that these represent the specific values of R&D in each of these areas, but rather that they provide insights into the value of technological advances based on the specific reference assumptions and the specific advanced assumptions used in this study.

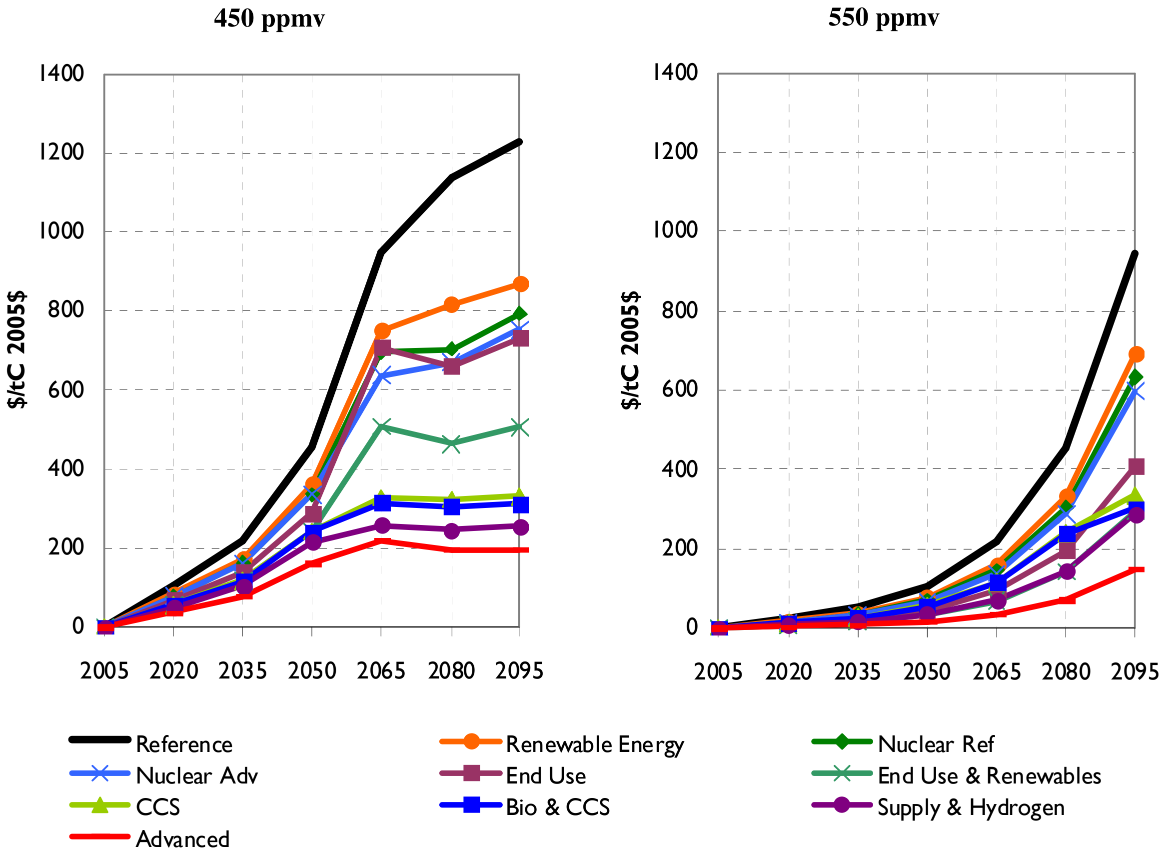

Figure 5.9. Global price of carbon across scenarios; 450 ppmv and 550 ppmv.

These caveats aside, the cost trajectories exhibit several characteristics that are common to the cost analyses of climate mitigation found in the published literature. For example, across scenarios, costs begin low and rise over time. As has been discussed in previous sections, a gradual increase in the value of carbon, and therefore the degree of mitigation and the associated costs, is a characteristic of mitigation approaches that minimize the present value of the cumulative costs of mitigation. Total annual costs are also higher in the more stringent stabilization scenarios, as one would expect. In addition, the difference between costs increases as the emissions constraint becomes more stringent. An important reason for this is that as the level of the emissions reduction increases, carbon must be removed from more and more costly sources. For example, in many scenarios, removal of carbon from the electricity sector is less costly than from the transportation sector because there are more low- or zero-carbon substitutes in the electricity sector than in the transportation sector. In such a case, initial emissions reductions therefore are concentrated more heavily in the electricity sector and then gradually move to the more costly reductions in transportation.

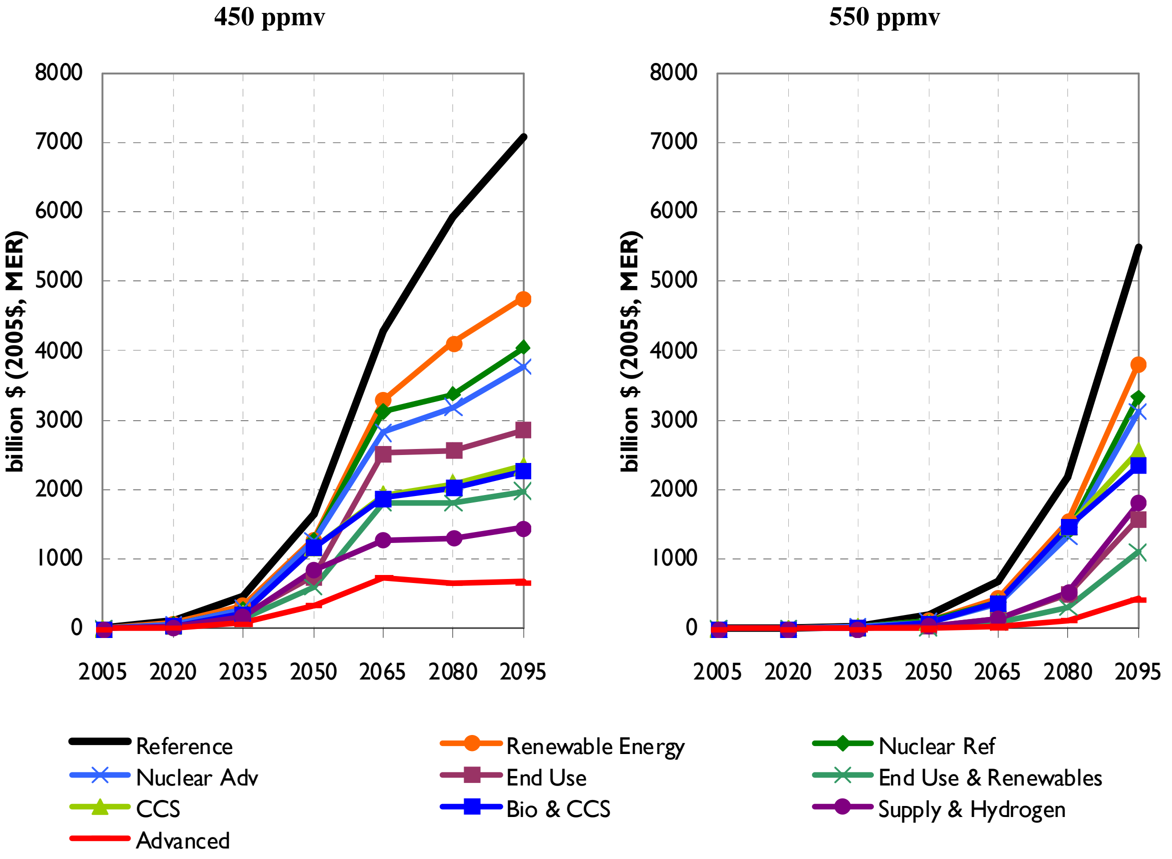

Figure 5.10. Total annual global costs of constraining carbon emissions across scenarios (undiscounted in 2005$): 450 ppmv and 550 ppmv.

By far, the most important insight of the cost results is that technology advancement has serious implications for the costs of stabilization. Technology is fundamental for addressing climate change. The cost benefits of the technological advances in this study reach into the trillions of dollars on an annual basis. Furthermore, the more options that are available, the lower will be the costs. These results reinforce the need for explicit inclusion of technology instruments, such as RD&D funding, in the climate mitigation policy portfolio, and the call for a diversified approach to technology development to maximize the chance of multiple successes.

Table 5.1. Cumulative discounted global costs of stabilization (percent discount rate), 2005 through 2095 across scenarios: 450 ppmv and 550 ppmv (2005 U.S.$, MER).

	450 ppmv	550 ppmv
Reference	11.6	2.5
Renewable Energy	8.5	1.6
Nuclear Ref	7.8	1.5
Nuclear Adv	7.4	1.4
End Use	5.6	0.6
End Use & Renewables	4.1	0.4
CCS	5.6	1.3
Bio & CCS	5.5	1.3
Supply & Hydrogen	3.9	0.6
Advanced	1.9	0.1

6.0 Summary

The analysis described in this report was conducted in support of the ongoing strategic planning process of the CCTP. It was conducted by staff members of Pacific Northwest National Laboratory (PNNL), working primarily at the Joint Global Change Research Institute—a collaboration between PNNL and the University of Maryland at College Park.

The main focus of the work was to analyze the role that advanced technology could play in stabilizing atmospheric CO_2 concentrations. Over the last century, global population and economic growth have been leading to increased emissions and concentrations of greenhouse gases. Although the impact of these increasing concentrations is not completely understood, concern is growing, and various means for reducing these emissions are being explored. Advanced technology is an important component of any emissions reduction scheme, because it is potentially the key to lowering the costs of emissions reductions.

Several key themes emerged from the analysis. Here we highlight three. These themes are not new, but they are fundamental to effectively addressing the climate-technology linkage. First, there are potentially substantial roles for a wide range of technologies in climate change mitigation. Future technological advances cannot be predicted today, so any number of technologies may take on substantial future roles, depending on a wide variety of factors, including improvements in cost and performance. The fact that a technology is not promising today does not mean that at some future date it will not have evolved sufficiently to play an important role. Furthermore, even if a single technology were to make dramatic leaps forward, it would not necessarily become a “silver bullet” or single technology solution to the climate problem. The magnitude and complexity of the climate change challenge and the energy system that sits at the core of the climate challenge will likely would allow for substantial contributions from a variety of technologies.

Second, this study has reinforced the impact that technology can have on the costs of mitigation. The specific cases modeled suggest that accelerated technology development offers the potential to reduce the present discounted cost of stabilization by hundreds of billions to trillions of dollars globally. The more technologies that are able to compete effectively, the lower will be the costs of mitigation.

Third, there is an increasing need for efforts develop and to deploy climate change technologies. This study has explored the interplay between the nature of future technological developments and the deployment of technology for the purposes of mitigation. In all of the stabilization scenarios, the energy system looks substantially different by the end of the century than it does today. The magnitude and pace of the transformation will depend both on the pace of technology development and the degree and timing of emissions mitigation activities. Limiting atmospheric CO_2 concentrations to 450 ppmv implies greater urgency to transform the energy system to low and non-greenhouse gas emitting technologies than either the Reference Scenario or the 550 ppmv stabilization scenarios. For example, limiting CO_2 concentrations to 450 ppmv requires that the global energy system is largely non-emitting by 2050. Long-term goals carry implications for urgent near-term actions to develop and deploy technologies that will reduce CO_2 emissions.

The implication of these three themes is the need for an active and hedged portfolio to energy technology development, with investments along a range of potential mitigation technologies. Limiting CO_2 concentrations will require near-term movements on the path to a very different future energy system with multiple technologies supplying energy and converting energy for use, there is uncertainty in what this future will look like, but it is clear that advanced technologies can ease the transition. Technology policy instruments that can prepare for dramatic transformations of the energy system through technology experimentation, exploration, development, and deployment are a crucial element of a comprehensive approach to climate mitigation.

7.0 References

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