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Pacific Northwest
National Laboratory
Operated by Battelle for the
U.S. Department of Energy

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Prepared for the U.S. Department of Energy
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# 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 three broad classes of advanced technology futures, developed by PNNL for the CCTP. Each of these classes of futures qualitatively describes a set of technological developments and associated possibilities for technology deployment over the 21st century that could lead to stabilization of atmospheric greenhouse gas concentrations. The three classes differ from one another in the way that energy supply technologies are assumed to improve and be deployed over the coming century. One class envisions that cost-effective carbon capture and storage technologies are successfully developed, allowing for low-carbon use of fossil fuels. Another class envisions a transition over the century toward renewable and nuclear energy sources. A third final class envisions the development of new, breakthrough technologies such as fusion and novel biomass and solar-energy systems, leading to their deployment in the second half of the century. All the three classes also include advances in a range of technological areas relevant to climate change, including non-$CO_2$ greenhouse gas mitigation technologies, technologies for sequestering carbon in terrestrial systems such as agricultural soils, and improvements in energy end-use technologies. These generic classes of futures, without specific technology assumptions, serve as a framework for interpreting past analyses and for conducting further CCTP analysis activities.

PNNL then constructed specific, illustrative examples of each advanced technology future within an integrated assessment model called MiniCAM. In consultation with the CCTP and CCTP working groups, PNNL developed specific model assumptions for each of the three technology futures and then analyzed the energy, emissions, and economic implications of these technology assumptions for stabilizing the long-term, combined radiative-forcing effects of carbon dioxide ($CO_2$), nitrous oxide ($N_2O$), methane ($CH_4$), and a set of fluorine-containing industrial chemicals known as F-gases. Each of the three sets of advanced technology assumptions were explored under four greenhouse gas stabilization levels, leading to $CO_2$ concentrations of roughly 450, 550, 650, and 750 parts per million by volume (ppmv) of $CO_2$. The Advanced Technology Scenarios were compared to five scenarios with continued, but more modest, technological advances: a Reference Case without any emissions constraints and four Baseline Cases leading to the same four stabilization levels.

Several important observations regarding the role of advanced technology in climate change mitigation emerge from the analysis of the scenarios in this report. 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, as well as contributions to emissions reductions in non-$CO_2$ greenhouse gases and carbon sequestration in terrestrial systems. Second, accelerated technology development offers the potential to dramatically reduce the costs of stabilization. Under the assumptions of this study, the Advanced Technology Scenarios reduced the cumulative costs of stabilization over the century, compared to the Baseline Cases, by 50% or more, leading to economic

benefits of hundreds of billions to trillions of dollars globally. Finally, the time at which advanced technologies will need to be developed and deployed depends on the stringency of the emissions constraint. Under the most stringent emissions constraint considered in this study, corresponding roughly to $CO_2$ stabilization at 450 ppmv, emissions reductions from advanced technologies begin occurring within a decade or two. Under the least stringent emissions constraint considered in this study, corresponding roughly to $CO_2$ stabilization at 750 ppmv, these emissions reductions begin in 2040 or beyond.

The full report provides a more complete description of the technology futures, documents the assumptions used in the illustrative scenarios, and provides a thorough analysis of the results.

# Contents

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# Acronyms and Abbreviations

| | |
|---|---|
| BSS | Beyond the Standard Suite |
| CC | combined cycle |
| CCS | carbon capture and storage |
| CCTP | U.S. Climate Change Technology Program |
| CLC | Closing the Loop on Carbon |
| FAO | United Nations Food and Agriculture Organization |
| GDP | gross domestic product |
| GWP | global warming potential |
| HCFCs | hydrochlorofluorocarbons |
| HFCs | hydrofluorocarbons |
| IGCC | integrated gasification combined cycle |
| IPCC | Intergovernmental Panel on Climate Change |
| MAC | marginal abatement cost |
| NEB | New Energy Backbone |
| O&M | operations and maintenance |
| PFCs | perfluorocarbons |
| PNNL | Pacific Northwest National Laboratory |
| | |
| 2000$ | U.S. dollars adjusted to the year 2000 |
| EJ | Exajouoles |
| GJ | Gigajoules |
| GtC | Gigatonnes carbon |
| GtC-eq | Gigatonnes carbon equivalent |
| kgC | Kilogram carbon |
| kWh | Kilowatt-hour |
| ppmv | parts per million by volume |
| tC | Tonne carbon |
| $Wm^{-2}$ | Watts per square meter |
| yr | Year |

# 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 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 aerosols, such as soot, and the greenhouse gases, which include carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$), and fluorinated gases such as halocarbons. 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 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). Not surprisingly, many governments view measures to foster technological change as integral to their policies toward climate change (Abraham 2004).

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 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.

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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.

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 conducting two tasks. First, working closely with the CCTP, PNNL formulated a set of three broad classes of advanced technology futures that might lead to stabilization of atmospheric greenhouse gas concentrations. Each of these classes of futures qualitatively describes a set of future technological developments and associated possibilities for technology deployment. The three classes were designed to be largely orthogonal in order to capture a wide range of possible futures. The classes are differentiated in terms of energy technology characteristics and energy technology deployment because of the importance of the energy system in stabilizing $CO_2$ concentrations. These three generic classes of futures, without specific technology assumptions, serve as a framework for interpreting past analyses and for conducting further CCTP analysis activities.

Second, PNNL constructed specific, illustrative examples of each technology future within an integrated assessment model called MiniCAM, which was developed by PNNL. In consultation with the CCTP and CCTP working groups, PNNL developed specific model assumptions for each of the three technology futures and then analyzed the energy, emissions and economic implications of these technology assumptions for stabilizing the long-term combined radiative-forcing effects of $CO_2$, $N_2O$, $CH_4$, and a set of fluorine-containing industrial chemicals known as F-gases, including sulfur hexafluoride ($SF_6$), hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs). This suite of gases serves as the basis for the U.S. carbon intensity targets. These three sets of technology assumptions were explored under four hypothetical greenhouse gas emissions constraints linked to four greenhouse gas stabilization levels. This report describes the technology futures, documents the assumptions used in the illustrative 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 *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. 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. Chapter 2 provides an overview of the approach to the development of the scenarios. Chapter 3 introduces the MiniCAM model and discusses key assumptions underlying the different technology scenarios. Chapter 4 presents the Reference Case, 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 Case 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. Chapter 5 then discusses the stabilization scenarios. Sixteen scenarios are presented, representing combinations of four sets of technology assumptions (Reference Case technology and the three versions of advanced technology futures) and four stabilization levels. Chapter 6 summarizes the work and then puts the results into the context of the CCTP’s strategic planning goals. Appendices A and B provide detailed results from all the scenarios.

# 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 100-year planning horizon toward eventual stabilization of atmospheric concentrations of greenhouse gases. Structuring the scenarios for this purpose required the resolution of a number of study design issues. This chapter 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), the manner in which emissions reductions are spread over time, and the tradeoffs between reductions in different gases. These issues are discussed in Section 2.2. The final category involves the development of the broad classes of technology futures, the transformation of these futures into specific sets of MiniCAM model inputs, and the overall approach to implementing these scenarios in MiniCAM. This is discussed in Section 2.3. Model inputs are discussed in detail in Chapter 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. Although $CO_2$ is the most important greenhouse gas involved in climate change, non-$CO_2$ greenhouse gases are also important. For this reason, this study applies a broader definition of stabilization that includes the significant non-$CO_2$ greenhouse gases.

With a more inclusive set of greenhouse gases, an aggregate metric is needed that can represent their combined effects. 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 $CH_4$. A combined metric that explicitly accounts for these differences is therefore needed.

The metric used in this study 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 atmospheric temperature, 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, typically expressed in terms of watts per square meter ($Wm^{-2}$). In this study, radiative forcing is always specified to be the change in the Earth's energy balance relative to preindustrial times.

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.

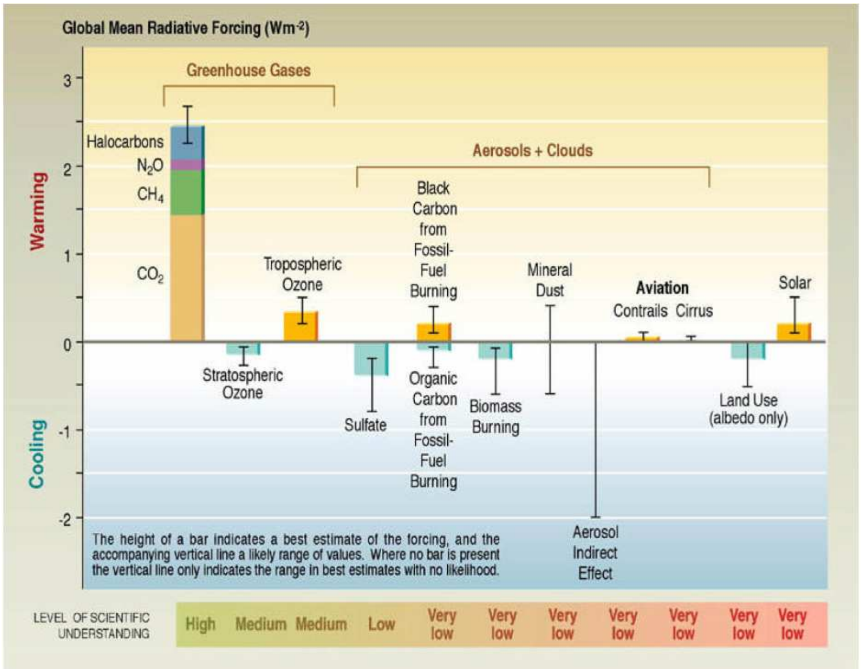


**Figure 2.1**. Radiative forcing of various atmospheric constituents and relative uncertainties (IPCC 2001a)

This study focuses on the greenhouse gases. Stabilization is defined in terms of the radiative forcing of the primary greenhouse gases: $CO_2$, $CH_4$, $N_2O$, and a set of fluorine-containing industrial chemicals known as F-gases, including $SF_6$, HCFCs, HFCs, and PFCs. Some of these substances (e.g., $CH_4$ and most HFCs) remain in the atmosphere for decades; others (e.g., $CO_2$ and $N_2O$) remain for a century or so; and some (e.g., PFCs and $SF_6$) remain for thousands of years. This suite of gases forms the basis for the U.S.'s carbon intensity targets, and they also form the basis for the Climate Change Science Program's ongoing scenario analysis efforts (CCSP 2005, CCSP 2006).

To link the scenarios in this study with previous scenario efforts, the radiative forcing stabilization levels were explicitly chosen so that the resulting $CO_2$ concentrations would roughly correspond to levels commonly considered in previous studies: 450 ppmv, 550 ppmv, 650 ppmv, and 750 ppmv. Table 2.1 shows the radiative forcing stabilization levels and the associated $CO_2$ concentrations used in these scenarios. Note that the total forcing shown is that for the suite of greenhouse gases listed above. This is higher than the forcing from the specified $CO_2$ concentration level alone.

**Table 2.1**. Radiative forcing stabilization levels ($Wm^{-2}$) and approximate $CO_2$ concentrations (ppmv)

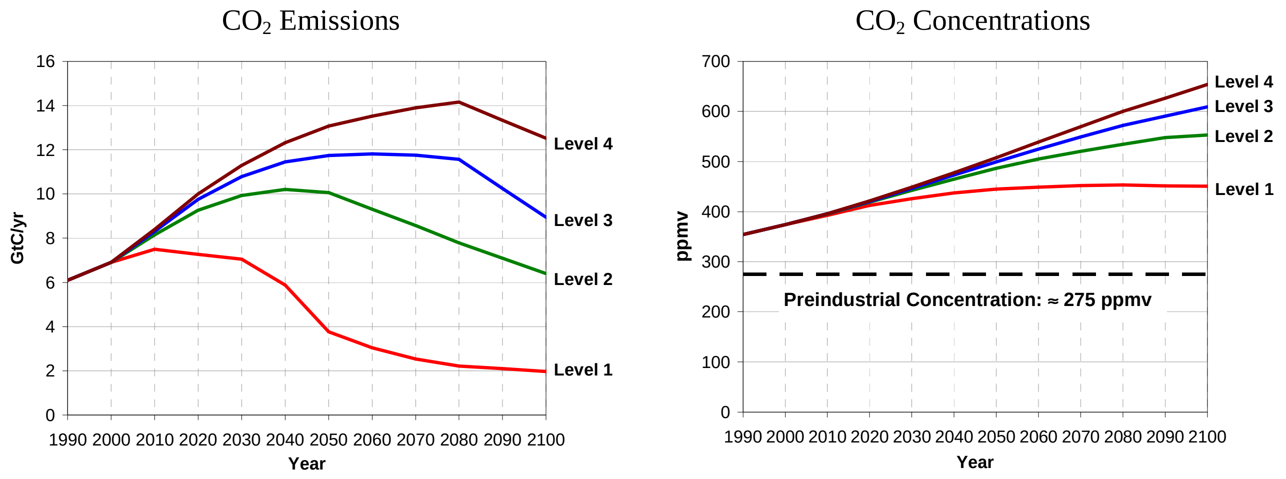
| | Approximate Long-Term $CO_2$ Concentration (ppmv) | Increase in $CO_2$ from Preindustrial Concentration (ppmv) | Total Radiative Forcing from Greenhouse Gases Relative to Preindustrial ($Wm^{-2}$) |
|---|---|---|---|
| *Most Stringent Constraint:* Level 1 | 450 | 172 | 3.3 |
| Level 2 | 550 | 272 | 4.5 |
| Level 3 | 650 | 372 | 5.6 |
| *Least Stringent Constraint:* Level 4 | 750 | 472 | 6.5 |

## 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 and when they occur, along with the distribution of emissions reductions among greenhouse gases along both of these dimensions. 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. 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. It is assumed in the construction of these scenarios.

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 reductions, emissions peak and then decline toward levels at which they are balanced by removal or destruction in natural systems. Figure 2.2 shows four global $CO_2$ emissions trajectories that were used in these scenarios along with the resulting $CO_2$ concentration trajectories.


$CO_2$ Emissions

$CO_2$ Concentrations

**Figure 2.2**. $CO_2$ emissions trajectories (emissions from fossil and other industrial sources) and resulting $CO_2$ concentrations under the four stabilization levels[2]

Figure 2.2 shows that the time at which emissions peak and the time at which $CO_2$ concentrations stabilize depend on the stringency of the stabilization level. The more stringent the stabilization level, the earlier emissions must peak and concentrations must be stabilized. $CO_2$ emissions peak within one to two decades in Level 1 (450 ppmv), roughly at mid-century for Level 2 (550 ppmv), and near the end of the century for Level 3 (650 ppmv) and Level 4 (750 ppmv). Stabilization is achieved in this century for Level 1 (450 ppmv); concentrations are nearing their stabilized levels by 2100 for Level 2 (550 ppmv); and stabilization does not occur until well into the next century for Level 3 (650 ppmv) and perhaps even beyond for Level 4 (750 ppmv). Because MiniCAM's model horizon extends only to the end of the century, it was necessary to specify end-of-the-century $CO_2$ concentrations and radiative forcing levels that were lower than their final levels for those scenarios not fully stabilizing in this century.

A final consideration in implementing stabilization is the tradeoff between reductions in different gases. The approach used in these scenarios was to apply a market price to the emissions of non-$CO_2$ greenhouse gases based on the price of carbon and the 100-year global warming potential (GWP) for these gases as defined by the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report (IPCC 2001b). The GWP of a gas is a measure of its climatic impact relative to that of $CO_2$. The GWP is defined as the integrated radiative forcing from one unit of emissions of a given greenhouse gas relative to the forcing from one unit of $CO_2$ emissions. GWPs were used to help determine the amount of emissions mitigation for non-$CO_2$ greenhouse gases in the stabilization scenarios. The implicit price on $CH_4$ emissions in any period, for example, is equal to the value of carbon times the GWP for $CH_4$. Reductions in the emissions of these gases therefore increase with the value of carbon, until the point at which emissions reductions for a particular sector reach some maximum.[3]

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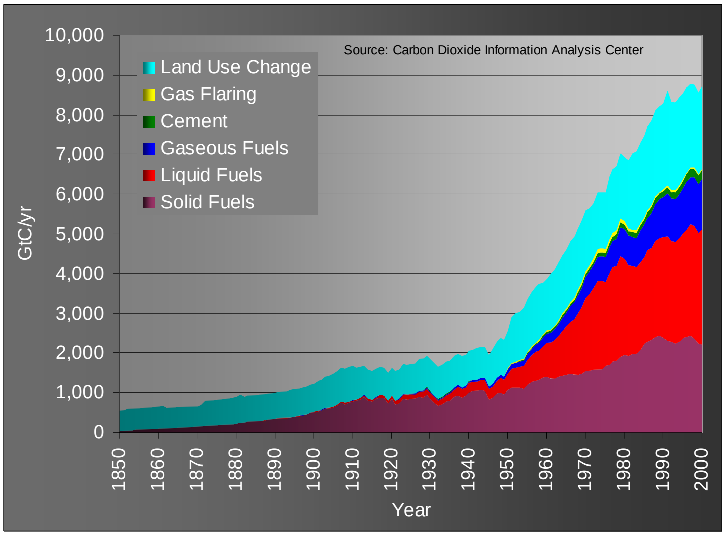
[2] The $CO_2$ emissions and concentration pathways shown in this figure are based on reference technology assumptions in the scenarios. With advanced technology scenarios, $CO_2$ emissions differ because of differences in the reductions in radiative forcing from non-$CO_2$ greenhouse gases, differences in terrestrial sequestration, and differences in net emissions from terrestrial systems.

[3] Another approach to the treatment of non-$CO_2$ greenhouse gases is to embed them with $CO_2$ into a full intertemporal optimization based on meeting the long-term stabilization target. With such an approach, emissions reductions in short-lived gases such as $CH_4$ take place closer to the point in time at which radiative forcing is stabilized than with the approach used in this study. Reducing short-lived, high GWP gases such as $CH_4$ earlier in the century has the potential to slow the rate of change in temperature, although the rate of temperature change was not specifically addressed in this study. Analysis of the rate of temperature change would also need to consider the effects of aerosols.

## 2.3 Constructing the Technology Scenarios

As discussed in Chapter 1, the scenarios are based on three classes of technology futures. These classes were constructed to be general; they do not specify particular technology characteristics, but focus instead on the general characteristics of the future energy system. A range of specific futures could fit into any of the three classes.

The technology futures are constructed primarily around differences in energy production technologies, although a range of other technology areas is also critical for climate change, as will be discussed shortly. Adjustments in the way that energy is produced will play a prominent role in efforts to stabilize greenhouse gas concentrations because of the energy system's increasingly dominant role in anthropogenic $CO_2$ emissions, as shown in Figure 2.3.



Source: Carbon Dioxide Information Analysis Center

**Figure 2.3**. Historical anthropogenic carbon emissions by source

To develop these three classes of futures, a wide range of existing scenario analyses were reviewed, including Shell International (Shell 2001), the National Academy of Sciences (NAS 1999), the United Kingdom Department of Trade and Industry (UKDTI 2000, UKDTI 2001), Natural Resources Canada (NRCA 2000), the World Business Council for Sustainable Development (WBCSD 1999), the International Energy Agency (IEA 2002), and the Post-SRES modeling runs developed by the IPCC and included in the IPCC's Working Group Report on Mitigation (IPCC 2001b). These were supplemented by consultations with experts in R&D planning, technology, climate change, and economics. Each of these advanced technology futures portrays a distinct evolution of the energy system over the coming century.

> **Technology Future 1: Closing the Loop on Carbon (CLC):** This future is based on the assumption that carbon capture and geologic storage (CCS) is both economically and technically viable. The corresponding implication is that fossil fuels are able to continue to play a significant role in the global energy system even under emissions constraints. In this future, fossil-based energy systems can become carbon-neutral and remain the backbone of the energy system through the century.
>
> **Technology Future 2: New Energy Backbone (NEB):** This future is based on a global energy transition over the coming century. Nuclear fission and renewable energy sources become dominant,

reducing the proportionate role of fossil fuels and gradually replacing them as the backbone of the energy system. This scenario might arise as a result of improvements in renewable and/or nuclear fission cost and performance that enable them to capture a larger share of the energy market based purely on their inherent advantages, or, conversely, limitations that would inhibit other options such as carbon capture and storage.

**Technology Future 3: Beyond the Standard Suite (BSS):** This future also envisions a transition in the global energy system away from fossil fuels. In this scenario, however, the transition is to other advanced technologies that are not part of the currently available suite. Examples might include nuclear fusion, space-based solar power, or dramatic improvements in biotechnology that revolutionize the production of biofuels.

Starting from these three broad futures, four sets of specific model assumptions were generated for the MiniCAM model: a set of reference technology assumptions and three sets of advanced technology assumptions corresponding to the three futures. Reference technology assumptions serve as the starting point for the analysis. Advanced technology assumptions are then used to explore and illustrate the implications of further advances in technology. It is important to note that the reference technology assumptions are not predictions of the future. They serve as a plausible point of departure for consideration of additional technological advances. The specifics of the assumptions underlying these four technology scenarios are provided in Chapter 3.

In total, 17 scenarios were generated, as shown in Table 2.2. These scenarios include:

- A **Reference Case** that includes (1) the reference technology assumptions and (2) no actions aimed specifically at reducing greenhouse gas emissions.
- Four **Baseline Scenarios** that include (1) the reference technology assumptions and (2) four emissions pathways corresponding to the four long-term stabilization levels.
- Twelve **Advanced Technology Scenarios** that combine (1) the three sets of advanced technology assumptions (CLC, NEB, and BSS) with (2) the four emissions pathways corresponding to the four long-term stabilization levels

Although these futures focus on variations in energy production technologies, a range of other technologies and technology areas are also valuable in addressing climate change, as mentioned above. This includes improvements in end-use energy technologies, technologies associated with the emissions of non-$CO_2$ greenhouse gases, and technologies associated with land use and land-use change. Technological advances in these areas were also included in the Advanced Technology Scenarios, as will be discussed in Chapter 3.

The exploration of these 17 scenarios forms the basis for this report. Understanding the differences between the scenarios provides insights into the potential role of technology. Most importantly, the analysis demonstrates that with the requisite technological advances, any of the three technology futures can serve as a blueprint for managing the economic consequences of stabilizing greenhouse gas concentrations.

**Table 2.2**. The 17 scenarios in the analysis

| Name | Technology Assumptions | Stabilization Level |
|---|---|---|
| **Reference Case** | | |
| REF REF | Reference | No Constraint |
| **Baseline Scenarios** | | |
| REF Level 4 | Reference | Level 4 |
| REF Level 3 | Reference | Level 3 |
| REF Level 2 | Reference | Level 2 |
| REF Level 1 | Reference | Level 1 |
| **Advanced Technology Scenarios** | | |
| CLC Level 4 | Closing the Loop on Carbon | Level 4 |
| CLC Level 3 | Closing the Loop on Carbon | Level 3 |
| CLC Level 2 | Closing the Loop on Carbon | Level 2 |
| CLC Level 1 | Closing the Loop on Carbon | Level 1 |
| NEB Level 4 | New Energy Backbone | Level 4 |
| NEB Level 3 | New Energy Backbone | Level 3 |
| NEB Level 2 | New Energy Backbone | Level 2 |
| NEB Level 1 | New Energy Backbone | Level 1 |
| BSS Level 4 | Beyond the Standard Suite | Level 4 |
| BSS Level 3 | Beyond the Standard Suite | Level 3 |
| BSS Level 2 | Beyond the Standard Suite | Level 2 |
| BSS Level 1 | Beyond the Standard Suite | Level 1 |

# 3.0 Modeling Framework and Technology Assumptions

## 3.1 Introduction

This chapter discusses the model assumptions used to create the Reference Case scenario and the three sets of illustrative Advanced Technology Scenarios within the modeling framework developed by Pacific Northwest National Laboratory (PNNL), called MiniCAM. Chapter 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 chapter describes the model and the technology assumptions used in this analysis. The resulting scenarios are discussed in Chapter 4 (for the Reference Case) and Chapter 5 (for the 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. This chapter 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 chapter 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 the land-use model in MiniCAM, which is important for consideration of biomass energy as well as carbon sequestration in terrestrial systems. Section 3.6 describes the methodology used to generate scenarios of carbon sequestration in terrestrial systems. Section 3.7 discusses the treatment of non-$CO_2$ greenhouse gases.

## 3.2 ObjECTS 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 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 upcoming Climate Change Science Program scenarios. MiniCAM was one of the six models included in the Intergovernmental Panel on Climate Change *Special Report on Emissions Scenarios*. MiniCAM has been constructed to allow for substantial focus on technology and the implications of technology for emissions mitigation.

The version of the model used here is called ObjECTS MiniCAM, which is a new version of MiniCAM with an object-oriented structure written in C++. The new structure provides additional flexibility to create and refine individual sectors of the model. These advances have been heavily utilized in this analysis. For example, the analysis here includes, among others, new representations of wind power, solar power, nuclear power, and the U.S. buildings and transportation sectors.

MiniCAM models the energy and industrial system, including land use, in an economically consistent global framework. It has sufficient technical detail to enable analysis of a wide variety of technology systems and impacts over medium to long timescales (up to 100 years in the future). 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 and economic growth rates and the operation of other sectors of the economy are assumptions to the model.

MiniCAM operates over a projected time horizon of 100 years 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. At this equilibrium set of prices, production levels, demand, and market penetration are mutually consistent.

A key benefit of integrated assessment models is that they can be used to explore the interactions between different sectors that would otherwise be difficult to discern. For example, gasoline production will increase with a rise in the gasoline price, which drives a decrease in gas demand and increases in the 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 provide energy to meet these demands, including fossil fuels, biomass (traditional biomass such as use of wood for cooking and modern biomass that can be used as a fuel for electricity production or as a feedstock for biofuels or hydrogen production), electricity, hydrogen, and non-biomass 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, solar photovoltaics, and breakthrough technologies such as space solar and fusion. Hydrogen can be produced from coal, oil, natural gas, biomass, and electrolysis. Synthetic fuels can be derived from coal, oil, natural gas, and biomass. MiniCAM also includes capture and geologic storage of $CO_2$ from fossil fuels and commercial biomass produced from residues or by dedicated energy crops.

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. A primary purpose of the land-use model is to represent the competition between the use of land to support production of biofuels and the use of land for agriculture. In addition, if biofuels begin to move into unmanaged lands, the land-use module is able to capture deforestation effects. The land-use model also calculates net carbon emissions from land-use changes.

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, although these other substances were not considered in establishing the stabilization levels in this study, and are therefore not discussed here. 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.

## 3.3 Overview of the Technology Scenarios

Chapter 2 explained that 17 scenarios were constructed for this study. These 17 scenarios were based on four sets of technology assumptions: the reference technology assumptions and three sets of advanced technology assumptions, Closing the Loop on Carbon (CLC), New Energy Backbone (NEB), and Beyond the Standard Suite (BSS). Each of the three sets of advanced technology assumptions provides an illustrative example of a distinct technology future that might provide a basis for stabilization of greenhouse concentrations and radiative forcing.

The four sets of technology assumptions were developed by varying underlying technology assumptions in ways that would best capture the key elements of the underlying technology futures. Table 3.1 provides an overview of the four sets of technology assumptions. In general, two technology levels, reference and advanced, were developed for each technology area. In the case of carbon capture and storage technologies, three levels were created to allow for meaningful penetration of carbon capture and storage in the Advanced Technology Scenarios not focused on this technological system, NEB and BSS.

**Table 3.1**. An overview of the four sets of technology assumptions

| | | Technology Assumptions | | | |
|---|---|---|---|---|---|
| | | **Reference** | **CLC** | **NEB** | **BSS** |
| **Energy System** | **End Use** | Reference | Advanced | Advanced | Advanced |
| | **Hydrogen** | Reference | Advanced | Advanced | Advanced |
| | **Carbon Capture and Storage** | Reference | Advanced | Intermediate | Intermediate |
| | **Nuclear** | Reference | Reference | Advanced | Reference |
| | **Wind** | Reference | Reference | Advanced | Reference |
| | **Solar** | Reference | Reference | Advanced | Reference |
| | **Breakthrough Technologies** | None | None | None | Advanced |
| | **Terrestrial Sequestration** | Reference | Advanced | Advanced | Advanced |
| | **Non-$CO_2$ Greenhouse Gases** | Reference | Advanced | Advanced | Advanced |

The CLC scenarios include the most aggressive assumptions regarding carbon capture and storage, but assume reference technology for the remaining elements of the energy sectors. The NEB scenarios use advanced technology assumptions for renewables and nuclear energy, and assume some improvement in carbon capture and storage technologies. The BSS scenarios assume the development of breakthrough technologies, such as fusion, advanced biotechnology and space solar power, along with the same improvements in carbon capture and storage technology as the NEB scenarios.

The scenarios are organized around variations in primary energy supply, but a number of other areas of technological advance were also included in the scenarios. All Advanced Technology Scenarios utilize advanced technology assumptions for energy end use, non-$CO_2$ greenhouse gases, terrestrial sequestration, and hydrogen.

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.

## 3.4 The Energy System

This section discusses the energy sector assumptions used in the scenarios in this study. As background, energy technologies in MiniCAM are typically represented by two key parameters: efficiency and non-energy cost. For example, a coal-fired electricity plant incurs a range of costs associated with construction (a capital costs) and annual operations and maintenance. These costs are integrated into the non-energy cost. In addition, the cost of generating electricity from a coal-fired power plant depends on the quantity of fuel required to generate a unit of electricity, which is a function of the efficiency of the plant, along with the price of coal, which is endogenously determined in MiniCAM based on supplies, demands, and resource depletion. When technologies deviate from this basic approach, the differences are discussed as appropriate below.

### 3.4.1 Fossil and Biomass Electricity

Hydrocarbon energy sources, primarily fossil fuels, currently supply the majority of the world's electricity. MiniCAM contains highly detailed representations of fossil and biomass electricity generation technologies, with multiple technologies available for each fuel. Hydrocarbon electricity efficiencies and non-energy costs do not vary across scenarios.

MiniCAM divides electricity generation technologies into two categories: facilities that are already in place and operating (existing capital) and new installations. MiniCAM uses a vintage structure to represent the lifetimes and retirement rates of both categories of equipment. All fossil power plants are assumed to have a 45-year lifetime. However, a small fraction of the existing capital is retired annually to represent capacity losses with age in addition to any unplanned shutdowns. Existing capital is retired more rapidly than new installations because existing capital actually represents many different vintages of power plants, some of which are nearer to retirement than others. Plants are also temporarily shutdown if the expense of running the plant exceeds its revenue.

The efficiency of existing capital varies by region, just as real-world capital stocks vary by region. For example, existing coal-fired power plants in the U.S. are more efficient than those in China on average. These efficiencies are shown in Table 3.2. Non-energy costs for the aggregate capital are assumed to be insignificant because decisions regarding the use of existing capital, as opposed to the deployment of new capital, are based on variable costs only, because the capital costs for capacity already in place are considered sunk costs and not considered in the operating decisions.

**Table 3.2**. Efficiencies (lower heating value) of existing hydrocarbon electric capital

| | Coal | Natural Gas | Oil | Biomass |
|---|---|---|---|---|
| **Africa** | 0.36 | 0.29 | 0.35 | 0.36 |
| **Australia and New Zealand** | 0.36 | 0.40 | 0.41 | 0.36 |
| **Canada** | 0.36 | 0.50 | 0.40 | 0.36 |
| **China** | 0.31 | 0.44 | 0.32 | 0.31 |
| **Eastern Europe** | 0.40 | 0.27 | 0.42 | 0.40 |
| **Former Soviet Union** | 0.36 | 0.33 | 0.39 | 0.36 |
| **India** | 0.28 | 0.25 | 0.41 | 0.28 |
| **Japan** | 0.43 | 0.45 | 0.45 | 0.43 |
| **Korea** | 0.38 | 0.37 | 0.38 | 0.38 |
| **Latin America** | 0.31 | 0.29 | 0.31 | 0.31 |
| **Middle East** | 0.37 | 0.37 | 0.34 | 0.37 |
| **Southeast Asia** | 0.41 | 0.28 | 0.34 | 0.41 |
| **U.S.** | 0.37 | 0.37 | 0.39 | 0.37 |
| **Western Europe** | 0.41 | 0.41 | 0.40 | 0.32 |

As demand for electricity grows, the existing stock of electricity technologies is not sufficient to meet demand. New installations supply the difference between demand and the electricity generated by existing installations. Deployment of new installations is determined in MiniCAM through a two-level, nested, logistic choice mechanism. First, output is allocated across the primary fossil fuels and other options such as nuclear, wind, and solar power based on the average marginal cost of producing electricity using a given fuel. After this distribution has occurred, output is allocated using the same methodology across available generation technologies for the fuel.

In the future, all regions of the world are assumed to have access to the same generation technologies for new power plant installations. For each fuel, two technologies are generally available: a conventional technology similar to today's technology but with improvements over time, and an advanced technology. (The integration of these technologies with carbon capture and storage will be described in Section 3.4.4.) The conventional technologies in the model are pulverized coal, generic biomass, gas turbines and oil turbines. In 2005, the only advanced technology available is the natural combined cycle (CC). In 2020, integrated gasification combined cycle (IGCC) plants are available using coal, oil, and biomass as fuels.

Non-energy costs for the technologies were built up offline from detailed specifications, which included capital costs, capacity factors, and variable and fixed operating and maintenance costs. All factors were based on a consideration of a range of data sources, including assumptions used in near-term forecasts from the Energy Information Administration. However, citable data sources beyond the first part of the century are sparse, so generic assumptions are generally used to derive longer term data. After 2020, all non-energy costs were reduced individually by 0.1% annually. The improvements in efficiency over time were designed to attenuate as they trend toward a predetermined maximum value. Non-energy costs and efficiencies for hydrocarbon electric technologies are shown in Table 3.3 and Table 3.4.

**Table 3.3**. Non-energy costs for new hydrocarbon electric technologies (cents/kWh)

| | 2020 | 2050 | 2095 |
|---|---|---|---|
| **Pulverized Coal** | 3.1 | 3.0 | 2.9 |
| **Coal (IGCC)** | 3.3 | 3.1 | 2.9 |
| **Gas Turbine** | 1.8 | 1.7 | 1.7 |
| **Gas (CC)** | 1.4 | 1.3 | 1.2 |
| **Oil Turbine** | 1.8 | 1.7 | 1.7 |
| **Oil (IGCC)** | 3.0 | 2.8 | 2.6 |
| **Biomass** | 1.4 | 1.4 | 1.3 |
| **Biomass (IGCC)** | 1.5 | 1.4 | 1.4 |

**Table 3.4**. Efficiencies for new hydrocarbon electric technologies (lower heating value)

| Technology | 2020 | 2050 | 2095 |
|---|---|---|---|
| **Pulverized Coal** | 0.41 | 0.42 | 0.44 |
| **Coal (IGCC)** | 0.49 | 0.50 | 0.50 |
| **Gas Turbine** | 0.40 | 0.41 | 0.43 |
| **Gas (CC)** | 0.57 | 0.65 | 0.70 |
| **Oil Turbine** | 0.40 | 0.41 | 0.43 |
| **Oil (IGCC)** | 0.49 | 0.50 | 0.50 |
| **Biomass** | 0.40 | 0.41 | 0.43 |
| **Biomass (IGCC)** | 0.48 | 0.49 | 0.49 |

Power plants do not run continuously. Some run around-the-clock with the exception of down periods for maintenance (base-load) and some run less frequently to meet variations in electricity demand (peaking or intermediate load). In MiniCAM, technologies for peaking plants are included in the oil and gas subsectors. These peaking technologies have the same efficiencies as the equivalent base-load technology, but the capacity factor is substantially lower to represent the lower utilization of the plants. This results in higher capital costs per unit output.[4]

### 3.4.2 Nuclear Power

MiniCAM includes a complete representation of the nuclear energy system, including resources, fuel fabrication, power and waste generation, and the potential reprocessing of waste into new fuels. The model contains global uranium and thorium resources based on grades with increasing extraction costs, regional nuclear fuel fabrication and reprocessing industries that incorporate ore conversion, enrichment, fabrication, and reprocessing costs. The model considers various nuclear fuels and options for new nuclear power plants with specific fuel requirements, thermal efficiencies and capital and operating and maintenance (O&M) costs. The quantity and composition of nuclear wastes generated by the different reactor technologies are tracked. Accumulated spent uranium and fissile material can be an input for fabricating new fuels. The cost for interim storage of waste and the charge for permanent disposal are added to the cost of nuclear plants.

The set of nuclear technologies available under reference technology assumptions includes the existing legacy generation of nuclear technologies (Gen II), evolutionary reactors that are currently available for deployment (Gen III), and future technologies that are a departure from the current evolutionary designs (Gen IV). The Gen II and Gen III reactors in these scenarios have a once-through fuel cycle and do not utilize reprocessed fuels. The Gen IV reactor represents a breeder technology that creates new nuclear fuels and utilizes reprocessed fuels. In the model, Gen II reactors do not compete for new investments and are retired by the middle of the century. New Gen III reactors are available for investment today and Gen IV reactors become available for deployment after 2030. Non-energy costs, including capital and O&M costs, of nuclear technologies are shown in Table 3.5. Gen IV reactors are assumed to have capital costs that are 20% higher than Gen III reactors, and the non-energy costs of both reactors are assumed to improve at a rate of 0.1% per year. Gen II, Gen III and Gen IV reactors have different fuel characteristics and fuel costs. Nuclear fuel costs are determined endogenously by the model based on fuel characteristics and resource costs.

The advanced technology assumptions include the same classes of nuclear technologies as the reference technology assumptions. However, the advanced technology assumptions include improvements to the economic characteristics of future technologies. The nuclear fuel characteristics of the reactor technologies are assumed to be the same as in the reference technology assumptions; however, research and development in nuclear technologies are assumed to lower the capital and O&M costs of nuclear technologies. The non-energy costs of Gen III and Gen IV reactors under the advanced technology assumptions are lower than those in the reference technology assumptions by 20% and improve at a rate of 0.1% per year. The advanced technology non-energy costs of nuclear technologies are also shown in Table 3.5.

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[4] The peaking plants also do not shutdown when their variable costs exceed their revenue, because the electricity price they would receive depends on short-term price spikes that would be much higher than the average electricity price used in the model.

**Table 3.5**. Non-energy costs for nuclear electric technologies (2000$/kWh)

| | 2020 | 2050 | 2095 |
|---|---|---|---|
| **Reference** | | | |
| **Gen II*** | -- | -- | n/a |
| **Gen III** | 0.047 | 0.045 | 0.043 |
| **Gen IV** | n/a | 0.054 | 0.051 |
| **Advanced** | | | |
| **Gen II*** | -- | -- | n/a |
| **Gen III** | 0.038 | 0.037 | 0.035 |
| **Gen IV** | n/a | 0.044 | 0.039 |

*Not available for new deployment

### 3.4.3 Solar and Wind Power

Wind and solar power are abundant natural resources, which can be used to produce electricity. 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. MiniCAM represents two characteristics of wind and solar power: the amount of the resource that might be economically provided in any region at a given price and the degree to which intermittency issues might limit the penetration into the electrical grid. Reference technology and advanced technology assumptions are examined here for both of these components of cost.

In the version of MiniCAM used for these scenarios, the wind resource is modeled using two wind supply curves for each region. One supply curve represents the cost and availability of onshore wind and the other represents the cost and availability of offshore wind resources. These supply curves together give the amount of wind that could be provided economically at a given electricity price. Captured in these curves are both the costs and performance of wind turbines and the resource base for wind power. For these scenarios, reference technology and advanced technology supply curves were generated. The supply curves were derived from an IEA dataset (IEA 2000), updated to account for improved wind turbine technologies. Note that the calculations used in the IEA dataset incorporate a limit to the maximum wind resource allowed per area, which may underestimate the amount of wind available in some regions. This might be a particular problem for regions with significant wind resources in sparsely populated areas such as the United States. This was, however, the only global wind resource estimate available for use in this study. Table 3.6 provides information on the quantity of wind in each region over time that might be provided at different prices with both reference and advanced technology.

The solar resource is modeled in a simpler fashion than wind. Solar is modeled as an unlimited resource with fixed marginal costs. This cost represents the total cost of collecting the solar resource, including land costs, solar cell capital costs, and O&M expenses. The marginal costs of solar power, excluding ancillary power costs, are provided in Table 3.7.

**Table 3.6**. Wind production (billion kWh/yr) by price (cents/kWh), and by region—includes offshore and onshore

| | 2020 | | | 2050 | | | 2095 | | |
|---|---|---|---|---|---|---|---|---|---|
| **REFERENCE** | 4 c/kWh | 6 c/kWh | 8 c/kWh | 4 c/kWh | 6 c/kWh | 8 c/kWh | 4 c/kWh | 6 c/kWh | 8 c/kWh |
| **Africa** | 626 | 2,002 | 6,006 | 681 | 2,176 | 6,528 | 797 | 2,683 | 7,035 |
| **Australia_NZ** | 15 | 165 | 422 | 17 | 190 | 486 | 26 | 213 | 572 |
| **Canada** | 50 | 581 | 993 | 55 | 632 | 1,088 | 62 | 681 | 1,161 |
| **China** | 400 | 1,752 | 2,878 | 435 | 1,904 | 3,128 | 549 | 2,047 | 3,149 |
| **Eastern Europe** | 246 | 536 | 626 | 267 | 583 | 686 | 305 | 593 | 690 |
| **Former Soviet Union** | 5,259 | 11,475 | 13,202 | 5,717 | 12,474 | 14,385 | 6,524 | 12,680 | 14,414 |
| **India** | 28 | 101 | 175 | 30 | 110 | 190 | 36 | 120 | 216 |
| **Japan** | 39 | 79 | 109 | 43 | 87 | 118 | 48 | 91 | 119 |
| **Korea** | 23 | 43 | 55 | 25 | 47 | 60 | 28 | 49 | 60 |
| **Latin America** | 1,536 | 2,792 | 3,778 | 1,688 | 3,050 | 4,129 | 1,897 | 3,171 | 4,264 |
| **Middle East** | 867 | 2,502 | 3,003 | 943 | 2,720 | 3,264 | 1,224 | 2,784 | 3,290 |
| **Southeast Asia** | 564 | 1,062 | 1,358 | 613 | 1,160 | 1,476 | 689 | 1,207 | 1,480 |
| **U.S.** | 87 | 1,001 | 1,693 | 94 | 1,088 | 1,849 | 107 | 1,173 | 1,969 |
| **Western Europe** | 200 | 856 | 1,417 | 218 | 944 | 1,576 | 336 | 1,013 | 1,613 |
| **ADVANCED** | | | | | | | | | |
| **Africa** | 744 | 2,002 | 6,006 | 1,144 | 4,104 | 8,984 | 1,327 | 4,903 | 9,787 |
| **Australia_NZ** | 18 | 191 | 439 | 49 | 310 | 882 | 94 | 403 | 1,089 |
| **Canada** | 60 | 581 | 1,068 | 86 | 883 | 1,475 | 160 | 987 | 1,542 |
| **China** | 400 | 1,752 | 2,878 | 862 | 2,603 | 3,577 | 1,042 | 2,828 | 3,621 |
| **Eastern Europe** | 246 | 536 | 627 | 424 | 693 | 791 | 461 | 723 | 805 |
| **Former Soviet Union** | 5,259 | 11,475 | 13,208 | 9,060 | 14,718 | 16,285 | 9,862 | 15,147 | 16,389 |
| **India** | 33 | 121 | 175 | 54 | 154 | 297 | 64 | 169 | 340 |
| **Japan** | 39 | 82 | 109 | 65 | 115 | 137 | 74 | 124 | 151 |
| **Korea** | 23 | 45 | 55 | 38 | 60 | 68 | 41 | 63 | 71 |
| **Latin America** | 1,707 | 2,914 | 3,778 | 2,485 | 3,858 | 5,137 | 2,701 | 4,141 | 5,405 |
| **Middle East** | 1,031 | 2,502 | 3,003 | 1,982 | 3,258 | 3,746 | 2,187 | 3,358 | 3,787 |
| **Southeast Asia** | 564 | 1,110 | 1,358 | 937 | 1,466 | 1,674 | 1,013 | 1,551 | 1,722 |
| **U.S.** | 103 | 1,001 | 1,821 | 148 | 1,511 | 2,483 | 276 | 1,671 | 2,573 |
| **Western Europe** | 200 | 859 | 1,417 | 633 | 1,311 | 1,960 | 746 | 1,494 | 2,124 |

**Table 3.7**. Solar costs excluding ancillary costs (cents/kWh, 2000$)

| Year | 2020 | 2050 | 2095 |
|---|---|---|---|
| **Reference** | 14.1 | 9.7 | 7.1 |
| **Advanced** | 13.2 | 7.9 | 4.7 |

Many electricity technologies can be operated whenever required. Wind and solar technologies, however, are intermittent; they only operate when there is sufficient wind or solar energy available. This intermittency is potentially an important limitation on the deployment of both wind and solar power, although the ultimate degree to which this limitation might ultimately bind is not well understood and is an area of current research. The intermittency of wind and solar power incurs additional costs to account for the ancillary generation capacity that would be required to be in place to supply electricity when the wind is not blowing or the sun is not shining, so as to maintain the current level of reliability in the electricity sector. Note that the generation costs shown in Table 3.6 and Table 3.7 already include the effect of lower capacity factor (average output over maximum output) for wind and solar generation technologies.

Ancillary costs consist of two parts: a capacity charge, reflecting the cost of building additional dispatchable capacity, and a cost for running or generating electricity from the backup capacity. The backup capacity cost is calculated based on the capital cost of a natural gas turbine, considered representative of the lowest capital cost option for capacity that would be dispatched infrequently. Capacity costs, efficiencies and technical change for the natural gas turbine are consistent with the assumptions about the technology when used a primary power generator. This is the primary component of the ancillary cost. It is assumed that backup capacity would be run or operated to generate electricity very infrequently. A capacity factor of 5% was used for backup gas turbines. The cost for running the backup is calculated using the same methodology as for calculating the costs for a standard electricity plant. In the future, other technologies, such as large capacity batteries or compressed air storage, could also serve this backup requirement if their capital costs were comparable to the cost of a natural gas turbine, without significantly changing the wind results.

For wind power, 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. The formulation is derived from the formulation for reserve margin used in the NREL WINDS model (http://www.nrel.gov/analysis/winds/). To capture potential advanced technology benefits, such as smart grids, that might allow wind to provide a greater proportion of electricity, the ancillary capacity requirements are lower under advanced technology than under reference technology.

Backup capacity for solar power is modeled using a similar, but simpler, approach. Backup capacity is determined by the share of solar capacity relative to the total amount of capacity in the electricity sector. It was assumed that at low solar penetration very little backup capacity was required, and as the share increased the amount of backup increased until it reached a predefined point where one unit of backup was required per additional unit of solar output. This is the limit of the backup function; no more than 1 unit of backup per unit of solar output is ever required. This point was chosen differently in the reference and advanced technology assumptions to reflect additional grid management improvements in the Advanced Technology Scenarios. The ratio was 1/5 under reference technology assumptions and 1/4 under advanced technology assumptions. This requirement is not a capacity limit; solar penetration may increase above this ratio by paying for the required backup. This approach to solar power probably underestimates the role of solar power in some regions and overestimates its potential in other regions. An improved implementation of both solar and wind technologies is being developed.

### 3.4.4 Carbon Capture and Storage

The option of carbon capture and storage was used in these scenarios for both electricity generation and hydrogen production. In electricity, carbon capture is available for new, advanced versions of the associated generation technologies, such as natural gas combined cycle and IGCC. For hydrogen production, carbon capture is available as an option on central station production from coal and natural gas. Electricity or hydrogen plants with carbon capture compete directly with the equivalent technologies without carbon capture.

Carbon capture and storage can dramatically reduce $CO_2$ emissions, but it also incurs costs associated with capturing and storing carbon. In these scenarios, no differences were assumed in capture characteristics. Instead, to represent factors that might limit deployment of carbon capture and storage, the costs of carbon storage differ across cases.

The costs of capturing carbon include capital and operating costs associated with capturing the $CO_2$ and a reduction in power plant efficiency due to extra energy requirements for separating $CO_2$ from flue gases.

The capture costs for electric power plants and the associated effects of capture on plant efficiency are represented through a non-energy cost and a parasitic energy requirement. Both of these are applied to electricity facilities based on the $CO_2$ emissions of the underlying electricity plant, which vary by fuel. New versions of the underlying generation technology with carbon capture compete with otherwise identical technologies without carbon capture. Table 3.8 and Table 3.9 show the capture energy requirements and non-energy costs used in the scenarios (derived from David and Herzog 2000). These characteristics are the same across regions.

**Table 3.8**. Carbon capture energy requirement by fuel (kWh/kgC)

| | 2020 | 2050 | 2095 |
|---|---|---|---|
| **Coal** | 0.63 | 0.49 | 0.49 |
| **Gas** | 1.23 | 1.09 | 1.09 |
| **Oil** | 0.89 | 0.79 | 0.79 |

**Table 3.9**. Additional non-energy cost by fuel for carbon capture (2000$/kgC)

| | 2020 | 2050 | 2095 |
|---|---|---|---|
| **Coal** | 0.030 | 0.028 | 0.028 |
| **Gas** | 0.083 | 0.078 | 0.078 |
| **Oil** | 0.060 | 0.056 | 0.056 |

With respect to hydrogen production, carbon capture is only available for central station hydrogen production; it is assumed that a distributed production station would not be large enough for it to be economical to attach to carbon storage. Hydrogen capture is implemented in the same way as electricity capture—as an independent paired technology with lower efficiencies and higher non-energy costs. See Section 3.4.9 for the efficiencies and capital costs of hydrogen production technologies used in these scenarios.

Whether carbon is captured in electricity generation or hydrogen production, the second portion of cost is that of storing the carbon. In these scenarios, the assumptions regarding the costs of carbon storage are used as a proxy for a range of additional factors that might ultimately limit the deployment of carbon storage, including leakage from reservoirs, institutional issues associated with the injection of power plant flue gases underground, and public acceptance issues. For these scenarios, three sets of storage assumptions were developed: reference technology, advanced technology, and intermediate technology. Reference technology assumes costs that are very high compared to current estimates; however, as will be discussed in Chapter 5, this does not completely forestall the deployment of carbon capture and storage under stringent stabilization constraints. Advanced technology assumes highly competitive storage costs. Intermediate technology lies in between. Table 3.10 shows the carbon storage costs in three regions of the world under the three technology assumptions.

**Table 3.10**. Carbon storage costs ($/tC, 2000$)

| | Japan | Korea | Rest of World |
|---|---|---|---|
| **Reference** | 924 | 924 | 924 |
| **Intermediate** | 544 | 544 | 544 |
| **Advanced** | 544 | 544 | 114 |

Carbon reservoir capacity differs dramatically among regions of the world. Recent analysis indicates that 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, at least two regions, Japan and Korea, have limited reservoir capacity that could significantly hold back deployment in those regions. For this reason, the costs of storage remain high in these regions even under advanced technology assumptions, as shown in Table 3.10.

The percentage of carbon that is captured is assumed to be constant across regions and electricity generation technologies, and it increases over time with improved available capture technologies. The capture rates for selected years are shown in Table 3.11. These rates do not differ between advanced and reference technology.

**Table 3.11**. Capture rates for electricity technologies

| 2020 | 2050 | 2095 |
|---|---|---|
| 0.91 | 0.93 | 0.94 |

### 3.4.5 Breakthrough Technologies

To help understand the effects of an unlimited and relatively inexpensive electricity generation technology, an unspecified breakthrough electricity technology was implemented in these scenarios. No specific breakthrough technologies are assumed, but examples might include nuclear fusion, space-based solar power, or an unspecified breakthrough in biotechnology that allows for low-cost unlimited electricity. The breakthrough technology is represented as an electricity generation technology with constant marginal costs, no backup requirement or limit on capacity, and no associated emissions. This technology is not differentiated by region. Reference technology costs are set high enough that the technology does not compete in the electricity market. The advanced technology assumptions are constructed so that the breakthrough occurs in the 2050 timeframe, allowing the technology to compete for new electricity installations only thereafter. The technology continues to improve after the breakthrough in 2050. Table 3.12 shows the cost assumptions for breakthrough technologies in the scenarios.

**Table 3.12**. Breakthrough technology costs (cents/kWh, 2000$)

| Year | 2020 | 2050 | 2095 |
|---|---|---|---|
| **Reference** | 98.0 | 98.0 | 98.0 |
| **Advanced** | 98.0 | 7.6 | 4.9 |

### 3.4.6 Biomass

Commercial biomass is supplied to the energy sectors by two sources: dedicated energy crops and residue streams. Dedicated energy crops are grown explicitly for its energy content. These are modeled in MiniCAM through the agriculture and land-use model, which is discussed below in Section 3.5. Biomass residue streams are byproducts of other activities, such as producing food crops, harvesting and processing timber, or urban waste streams. The supply of biomass from residue streams is determined according to a regional supply curve. These supply curves represent largely the costs of collecting and processing the waste biomass.

In MiniCAM, energy crops and waste biomass are treated as one globally traded aggregate product, which is then available for use in the energy system, with appropriate transportation costs. Biomass can then be used directly to produce heat in the building and industrial sectors, or converted first to electricity, synthetic gas, refined oil, or hydrogen. Descriptions of the transformation of biomass into electricity and hydrogen are included in Section 3.4.1 and Section 3.4.9.

Converting biomass to refined liquid, such as ethanol, can be a crucial pathway to reducing carbon emissions from the transportation sector. This product is considered a full substitute for refined oil derived from conventional crude. Biomass may also be converted to synthetic gas and burned in buildings and industry as a replacement for conventional natural gas. Biomass conversion efficiencies and non-energy cost are equal across regions and are shown in Table 3.13.

**Table 3.13**. Biomass conversion costs ($/GJ, 2000$)

| | 2020 | 2050 | 2095 |
|---|---|---|---|
| **Liquid Fuel** | 13.6 | 9.5 | 9.5 |
| **Synthetic gas** | 9.8 | 9.8 | 9.8 |

### 3.4.7 Hydroelectric Power

Hydroelectric power is an important contributor to global electricity generation, but due to the strong political and social influences on its deployment, it is inherently difficult to model. In MiniCAM, hydroelectric power generation is determined by an exogenously specified regional pathway. China and Latin America are the largest producers, accounting for nearly half of hydropower generation combined. Hydroelectric power production is shown in Table 3.14.

**Table 3.14**. Hydropower production (EJ)

| | 2020 | 2050 | 2095 |
|---|---|---|---|
| **Global** | 14.2 | 22.3 | 32.3 |
| **China** | 1.5 | 3.4 | 6.7 |
| **Latin America** | 4.5 | 7.4 | 8.4 |

### 3.4.8 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.

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 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 energy required to provide end-use services is adjusted to account for these technological advances, which vary by region, end-use sector, and model period.

Reference and advanced technology for the end-use sector differ in terms of the rate of end-use technological change. The reference technology assumption is that technology improves at a rate of approximately 0.5% annually in the U.S., with the rates in other countries dependent on their degree of convergence toward the U.S. per capita economic output. To be clear, this is the rate of efficiency improvement, not the rate of energy intensity improvement, which will be higher because it includes not just technological change, but also divergence between service demands and economic growth as discussed above. The rate of efficiency improvement is difficult to observe historically, whereas energy intensity (energy per GDP) improvements are often quoted in literature on end-use energy consumption.

For the advanced technology assumptions, the rates of efficiency improvement were increased so that the total demands for energy in each sector would be 10% lower by the end of the century than under reference technology assumptions were energy prices to remain constant. In reality, however, energy prices increase over time in all scenarios, so the actual reduction in energy demand observed in the Advanced Technology Scenarios without any policies to address climate change approaches 13%.

The mix of energy demands among fuels is as important for climate change as the total demand for energy. After total energy demand has been determined for each sector, it is distributed among fuels according to a modified logistic choice mechanism, which accounts for consumers' inherent preferences for certain fuels. For example, in the building sector, electricity is positively biased as it is a more useful energy carrier because it can power computers, light bulbs, and appliances. Other fuels may be biased against, such as non-commercial biomass, which has been phased out as countries have developed. The fuels available to supply services vary by end-use sector. Within each fuel type, a single aggregate technology is modeled which determines the average non-energy cost of fuel and the efficiency of converting the fuel into a service. For transportation, the fuels are oil, natural gas, electricity, hydrogen, and coal. For buildings, the fuels available are oil, gas, coal, electricity, hydrogen, biomass, and non-commercial biomass. For industry, the available fuels are oil, natural gas, coal, electricity, hydrogen and biomass. The industrial end-use sector also separates the demand for oil used as a feedstock from oil used as an energy source, as the oil used as a feedstock was assumed to not result in $CO_2$ emissions.

The detailed representations of the U.S. buildings and transportation add additional capabilities to the model by describing the service demands in physical terms, separating the services into discrete components, and enumerating the technologies. For buildings, demands include heating, cooling, lighting, hot water, and an aggregate demand that includes end uses such as appliances and information technology. These demands are based on the square footage of commercial and residential buildings, which are assumed to grow over time. A range of technologies, such as heat pumps, solid state lighting, and air conditioners, are available to provide these services. In the detailed transportation model, two demands are calculated: tons-miles for freight and passenger-miles for passenger transportation. These demands are then distributed to modes such as motorcycles, automobiles, and trains. The technologies which supply these demands include rail, internal combustion engine automobiles, and hydrogen powered automobiles. The detailed buildings and transportation sectors provide a deeper level of insight into end-use energy demands and the role of technology in reducing end-use energy consumptions. The information gained from the detailed models was used to calibrate the parameters for the aggregate models, allowing the rest of the world to be consistent with the U.S. only models.

### 3.4.9 Hydrogen

Hydrogen is not an energy source; it is an energy carrier. MiniCAM includes a full hydrogen economy, including production, transmission, distribution, and consumption. This complete implementation of hydrogen also allows for the examination of the interaction between hydrogen and other advanced technologies, such as nuclear, wind, and solar. Reference and advanced technology assumptions were developed for these scenarios.

Reference and advanced technology differ in two major ways. First, the costs of hydrogen technologies in the transportation sector were decreased significantly for advanced technology. In the aggregate end-use sectors, this meant a reduction in the non-energy cost of hydrogen in transportation; in the detailed transportation model, this was implemented in passenger vehicles. Second, the efficiencies of the wind and solar hydrogen production technologies were increased under the advanced technology assumptions.

Hydrogen production is an established technology, and hydrogen production costs were assumed to be the same across the scenarios. Hydrogen production can be categorized by whether it is centrally produced (central station) and then distributed to end uses or whether it is generated more closely to the end uses (distributed), for example, at a hydrogen filling station that would be similar to today’s gas stations. Central station production represents large facilities that benefit from economies of scale, but incur extra costs to transport hydrogen to the consumer. Central station producers may also benefit from carbon capture and storage opportunities that are not available to smaller plants. Distributed station production represents smaller facilities, with higher production costs but locations convenient to the hydrogen consumers.

The central station options implemented in MiniCAM are natural gas steam reforming, coal chemical, nuclear production of hydrogen through thermochemical process, hydrogen from biomass, and grid-based electrolysis. The distributed station options implemented are natural gas steam reforming, grid-based electrolysis, and wind- or solar-driven electrolysis. No differentiation in parameters is assumed across regions. The efficiencies and non-energy costs for the technologies were derived from the National Research Council Hydrogen report (NRC 2004). The data in this report specified parameters for 2020 and 2050. Parameters for 2035 were calculated using a linear interpolation, and values for later periods were calculated using an assumed 0.001% improvement in efficiency and a 0.05% decrease in capital costs annually. Hydrogen production technologies are not available prior to 2020, and nuclear driven thermochemical production is not available until 2035. Hydrogen generated from nuclear plants occurs directly from the reaction, so does not have a meaningful efficiency. Wind- and solar-generated hydrogen also benefit from the removal of the requirement of ancillary capacity, because the generation is not part of the electricity grid. Hydrogen production efficiencies and non-energy costs are shown in Table 3.15 and Table 3.16.

**Table 3.15**. Hydrogen production efficiencies (%)

| | 2020 | 2050 | 2095 |
|---|---|---|---|
| **Central Station** | | | |
| **Natural Gas** | 74 | 78 | 82 |
| **Natural Gas (CCS)** | 67 | 73 | 76 |
| **Coal** | 62 | 71 | 74 |
| **Coal (CCS)** | 59 | 69 | 72 |
| **Nuclear** | - | - | - |
| **Biomass** | 33 | 52 | 54 |
| **Electricity** | 75 | 85 | 89 |
| **Distributed** | | | |
| **Natural Gas** | 56 | 65 | 68 |
| **Electricity** | 75 | 85 | 89 |
| **Wind** | 75 | 85 | 89 |
| **Solar** | 75 | 85 | 89 |

**Table 3.16**. Hydrogen non-energy costs ($/GJ, 2000$)

| | 2020 | 2050 | 2095 |
|---|---|---|---|
| **Central Station** | | | |
| **Natural Gas** | 6.4 | 4.8 | 3.8 |
| **Natural Gas (CCS)** | 9.8 | 6.6 | 5.3 |
| **Coal** | 17.0 | 11.8 | 9.4 |
| **Coal (CCS)** | 18.6 | 13.2 | 10.5 |
| **Nuclear** | - | 32.4 | 25.9 |
| **Biomass** | 82.7 | 40.6 | 32.4 |
| **Electricity** | 51.5 | 4.3 | 3.4 |
| **Distributed** | | | |
| **Natural Gas** | 48.5 | 26.3 | 21.0 |
| **Electricity** | 62.1 | 15.2 | 12.1 |
| **Reference Wind** | 167.8 | 21.8 | 17.4 |
| **Advanced Wind** | 62.6 | 8.1 | 6.5 |
| **Reference Solar** | 242.8 | 34.9 | 27.9 |
| **Advanced Solar** | 90.6 | 13.0 | 10.4 |

Central station hydrogen also incurs transportation and distribution expenses. These costs include pipeline and trucking costs as well as additional capital required at the distribution facility, such as storage tanks. Distributed production occurs at the distribution facility, such as the gas station, so the costs of storage and distribution are included in the production costs. Distribution and dispensing costs are provided in Table 3.17.

**Table 3.17**. Hydrogen transportation and distribution costs ($/GJ, 2000$)

| Year | 2020 | 2050 | 2095 |
|---|---|---|---|
| **Distribution** | 3.55 | 2.62 | 2.09 |
| **Dispensing** | 4.57 | 3.30 | 2.64 |

### 3.4.10 Cement Production

Cement production has been separated from the aggregate industrial sector in order to better represent the emissions created by the process of turning limestone into cement. This emission can be potentially large, especially in rapidly growing economies. Demand for cement is based on analysis of historical cement demands. At low incomes, cement demand increases with income. At higher income levels, demand growth slows. Because the emissions from cement production can be a significant fraction of global carbon emissions under stringent $CO_2$ emissions limits, an option was added to capture and store the carbon emissions. This capture technology is similar to the technologies that capture emissions from electricity, but it has a higher capital cost. The technology is assumed to capture all emissions with an additional capital cost of 214 $/ton of carbon. The carbon storage costs used are dependent on the scenario and equal to those used for electricity and hydrogen.

## 3.5 Land Use and Land-Use Change

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 impact historically. In the future, biomass energy crops will compete for agricultural land with traditional agricultural crops, linking land use with the energy system. Finally, the quantity of land in different uses defines the potential for specific sequestration options. For example, the amount of soil carbon that can be sequestered in agricultural soils through practices such as no-till agriculture will be determined in part by the extent of agricultural lands.

For these reasons, MiniCAM includes a model that allocates the land area for each of MiniCAM’s 14 regions among four major land uses: crops, pasture, managed forests, and unmanaged forests. Crops are further subdivided into a range of individual crop types including food grains, coarse grains, oil crops, and biomass crops.

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. 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. Demands for most agricultural products, with the exception of biomass products, are based primarily on income and population.

The land-use model has several related purposes in climate change scenario development. One of these is to better 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 derives 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.

A second purpose of the land-use model is to capture greenhouse gas emissions from particular land uses as well as emissions (or sinks) as land moves in and out of different uses. Emissions of non-$CO_2$ greenhouse gases are tied to relevant drivers related to land use. For example $CH_4$ from ruminant animals is proportional to beef production. Unmanaged land can be converted to agro-forestry, which tends to result in net $CO_2$ emissions from tropical regions in the early decades. MiniCAM treats the effects on carbon emissions due to gross changes in land use (e.g., from forests to biomass production) using a regional average emission factor for such conversion. This emission is included in the global carbon cycle, so that the calculation of carbon dioxide concentrations includes the effect of land-use changes.

The effects of changing land uses on $CO_2$ emissions can potentially be large, and ideally policy makers would like a lever so that they can influence land-use decisions. The effects of biomass production are of particular interest with respect to $CO_2$ emissions. As the value of biomass crops increases, there is greater incentive to convert unmanaged land into biomass crops, which may result in substantial $CO_2$ emissions from the unmanaged lands as these may contain large carbon stocks. Hence, a comprehensive approach to carbon management must include valuation of carbon not just in the energy sector, but also in land use. In the current version of the land-use module, a simplified mechanism is used that focuses on the conversion of unmanaged land to biomass. A cost is added to commercial biomass production based on the value of carbon and the difference between the amount of carbon in biomass and unmanaged lands. This mechanism tends to limit the penetration of biomass into unmanaged lands when $CO_2$ emissions are constrained.

A final purpose of the land-use model in the context of these scenarios is as an input to the development of scenarios of carbon sequestration in terrestrial systems. For example, the agricultural land areas and allocations serve as an input to the scenarios of carbon sequestration in agricultural soils. The following sections describe the approaches taken to carbon sequestration in agricultural soils, reforestation, and carbon sequestration in grasslands.

## 3.6 Carbon Sequestration in Terrestrial Systems

Potentially, any type of land use or land-use change could be managed for enhanced terrestrial carbon content, but three broad types of land have been identified as having the largest potential for carbon storage by Watson et al. (2000): agricultural soils, forestry, and grasslands. PNNL therefore developed reference and advanced technology assumptions for each of these. The soils and grasslands analyses used MiniCAM model results as inputs but were conducted outside of the MiniCAM modeling framework.

By far the most extensive of the analyses is that of carbon sequestration in agricultural soils. This analysis breaks new ground in the development of global estimates of soil carbon sequestration potential. Forestry and grassland carbon sequestration are also potentially substantial and might receive more detailed treatment in future analyses.

### 3.6.1 Carbon Sequestration in Agricultural Soils

Soil carbon sequestration refers to the purposeful management of soils that, in addition to meeting production or conservation objectives, succeed in augmenting soil carbon stocks. For these scenarios, a methodology was developed to estimate gridded values of soil carbon sequestration at the global scale and then combine these with MiniCAM output to obtain different scenarios of soil carbon sequestration.

In this analysis, soil carbon sequestration was calculated based on conversion of agricultural land to no-till practices.

The initial soil carbon stock of each region was determined by a Global Information System analysis using major United Nations Food and Agriculture Organization (FAO) soil orders (Batjes 2002) as classified globally into a gridded dataset by Zobler et al. (1986) (Fig. 3.1) and adjusted for land use using the dataset of Ramankutty and Foley (1998). Changes in soil carbon over time were calculated by balancing additions to the soil and emissions from decomposition. Emissions were assumed to follow first-order kinetics—the decomposition of soil carbon is proportional to the first power of the carbon content in soil. Since the decomposition rate of soil carbon compounds is not homogenous, the soil was divided into three layers: crop and/or root residues, the active layer, and the passive layer. Additions of carbon to the soil were calculated based on crop yield data for each region for wheat, millet, corn, and soybean (FAO 2005). Key assumptions used to represent soil kinetics are shown in Table 3.18.

**Table 3.18**. Initial allocation of soil carbon, allocation of carbon additions, decay rate, and associated mean residence time

| | **Crop / Root Residues** | **Active** | **Passive** | **Whole Soil** |
|---|---|---|---|---|
| **Initial Allocation of Carbon (fraction)** | 0.05 | 0.45 | 0.50 | 1.0 |
| **Allocation of Carbon Additions (fraction)** | 0.85 | 0.10 | 0.05 | 1.0 |
| **Decay Rate ($yr^{-1}$)** | 0.2 | 0.01 | 0.002 | 0.016 |
| **Mean Residence Time (yr)** | 5 | 100 | 500 | 65 |

Results from the MiniCAM land-use module provided agricultural land area in each region. This was adjusted to exclude areas where no-till is not a likely alternative, including land in rice, root, and vegetable crops. The annual rate of carbon sequestration as a result of conversion to no-till agriculture was then calculated and aggregated to produce an estimate of total potential soil carbon sequestration for each MiniCAM region over the next century.

The total potential for carbon sequestration in soils was then adjusted for economic influence on the adoption of no-till agriculture using the carbon price set in MiniCAM simulations using the assumptions that a higher carbon price will increase the rate and maximum fraction of land area of adoption. The adoption of no-till over all agricultural lands worldwide is not likely due to the heterogeneity of soil properties, the availability of knowledge and equipment, and potential changes in crop production. Therefore, the maximum adoption level for no-till was adjusted based on the marginal abatement cost curves for the economic potential of soil carbon sequestration as reported in McCarl and Sands (2006).

Many actions that might be taken to reduce greenhouse gas emissions or sequester carbon in terrestrial systems will only be implemented if policies are put in place to encourage these actions. For example, carbon capture and storage adds costs to electricity production and is, therefore, not a viable option absent concerted efforts to address climate change. Some actions, on the other hand, are viable to some degree even without concerted climate policy. It was assumed that agricultural practices, such as no-till agriculture, that can lead to carbon sequestration in agricultural soils have some economic benefits irrespective of climate change, including improved soil quality and reduction of energy used in agricultural production. These practices are in use to varying degrees today and are, therefore, a component of the Reference Case. The stabilization scenarios include additional sequestration in agricultural soils based on the value of carbon that is associated with stabilization.

The advanced technology assumptions for soil carbon sequestration incorporate changes to two physical soil parameters. To reflect advances in crop production technologies, such as improved crop yields, increased fertilization, improved residue management practices, and the development of higher yielding crop varieties through biotechnology advances, a 30% increase was applied to the parameter representing additions of carbon to the soil. The other potential advanced technology impact is an increase in the maximum amount of carbon that can be stored in the soil with technologies such as deep carbon storage, soil amendments, or manipulations of soil microbial communities (Post et al. 2004). This was represented by a decrease of 10% in the decay rate coefficient, which increases the mean residence time of carbon in the soil and, therefore, increases the quantity of carbon in the soil at any given time.

### 3.6.2 Carbon Sequestration Through Reforestation

As discussed above, MiniCAM contains a model of land use that produces estimates of managed crop, forest, and pasture lands in each region. Deforestation and reversion to previously forested lands is, therefore, taken into account endogenously by MiniCAM. Consideration of terrestrial sequestration through reforestation must be done in a manner that does not double count carbon flows or stocks. For the scenarios in this report, additional analysis exogenous to the integrated assessment model was conducted to construct scenarios for terrestrial carbon sequestration through reforestation.

The options for enhancing the carbon content of forests can be broadly divided into two types: those that promote the growth of forests on land that is not forested now and those that promote greater carbon content of current forests, largely managed forests. Comprehensive data on productivity increases in managed forests is not available, so this parameter was not further adjusted in the model scenarios. For these scenarios, an analysis was conducted of potential reforestation of lands not otherwise used for crops, timber, pasture, or buildings.

The amount of land that could be potentially reforested was estimated by determining the extent of lands that are not currently forested or managed for other uses but where forest cover could naturally occur. To estimate this, a number of gridded data sets were used. Current forest cover was taken from DeFries et al. (2000), potential forest cover and current arable land from Ramankutty and Foley (1999), and pasture and built-up land area from Foley et al. (2003).

The primary calculation of the fraction of area of potential reforestation was performed on a 0.5° grid. Potential vegetation and forest cover data sets were aggregated up from five minute data. The forest cover data set has a maximum value of 80%, evidently due to limits in the satellite data processing algorithm. Because these areas could be maximally forested at present, areas with aggregated (0.5°) forest coverage of 75% or greater are excluded from the reforestation calculation. (These areas are primarily in South America and Africa).

In order to produce a conservative estimate, arable land, pasture land, and currently built-up land are not considered for reforestation. Due to inconsistencies in data, boreal regions were also removed from the calculation. Boreal regions were determined from the Global Agro-Ecological Zones reported in Lee et al. (2005). The result of the calculation is shown in Figure 3.1.

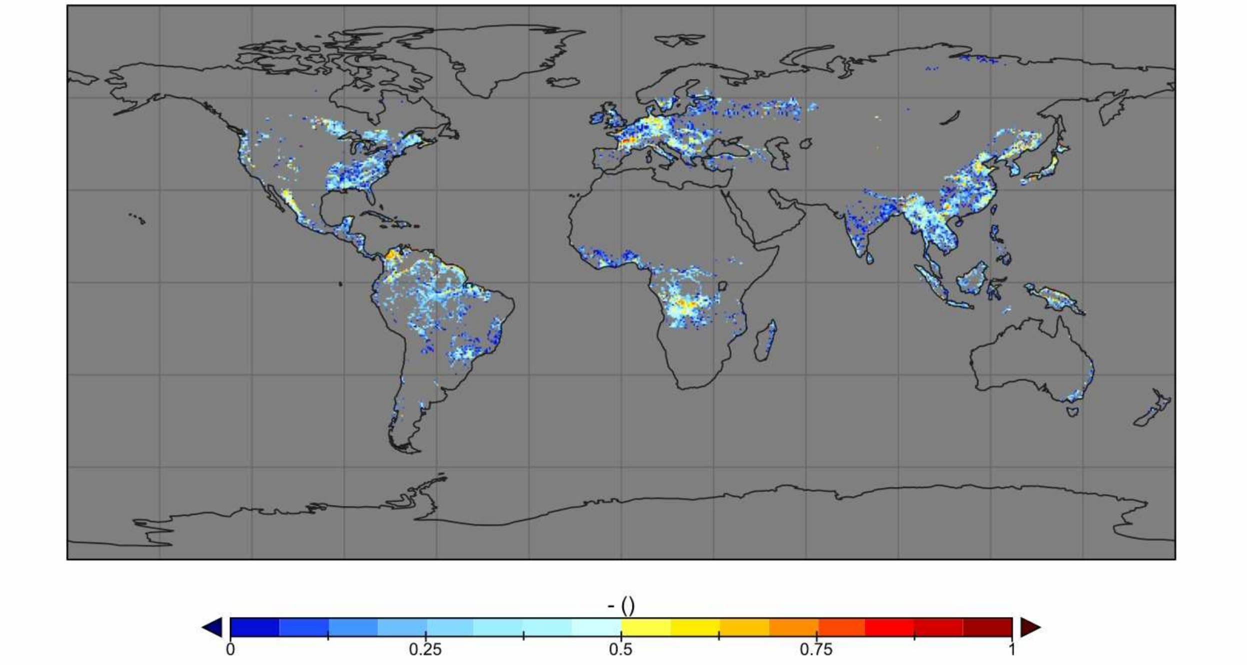


**Figure 3.1**. Global areas of potential reforestation (fraction of area that could be reforested)

To translate reforested area into terrestrial carbon sequestration scenarios, we use aboveground forest carbon content and regrowth rates from Houghton and Hackler (2001). The areas of potential reforestation determined above were further reduced by the amount of regional forest area in the MiniCAM simulations, (which reflects potential conversion of these areas to other uses). This adjustment reduced areas by an average of 35% globally. Additionally, increases in population were assumed to also encroach into potentially forested areas due to expansion of urban lands, although this adjustment is small globally (4%).

The total area available for reforestation was estimated to be 570 million hectares. The reference technology assumption is that one third of this area can be reforested. The remaining areas are assumed to be valued for other purposes or somehow unsuitable or degraded. For the advanced technology assumptions, this fraction is increased to 40%.

Reforestation only occurs in the stabilization scenarios. It was assumed that no reforestation occurs in the Reference Case because of the absence of constraints on carbon emissions. In the stabilization scenarios, the reforested area in each region was assumed to be planted over a thirty-year period, with trees reaching their maximum carbon content using the time scales from Houghton and Hackler (2001). The stabilization scenarios differ in terms of when the planting is initiated. It was assumed that reforestation begins when the value of carbon reaches roughly $10/tC. Hence, the more stringent the carbon constraint, the earlier reforestation begins.

### 3.6.3 Carbon Enhancement in Pasture Land

Terrestrial carbon sequestration options for grasslands include converting grasslands to forest or increasing the productivity and/or carbon content of managed grasslands (Conant et al. 2001, Post 2000). Changes in management practices for lands used for pasture (grazing) were considered in these scenarios;

alterations in other grasslands were not considered. A review of the literature indicates a wide range of potential enhancements. A substantial uncertainty exists in the amount of pasture land to which carbon enhancements could be applied. Some of these options, however, involve management changes such as fertilizer addition which might have greenhouse gas emissions consequences that would offset some of the additional soil carbon sequestration.

The pasture land areas as used in the MiniCAM model (derived from FAO data) were used as the basis for pasture land carbon sequestration. These data represent permanent pasture, which is presumably already under management, amounting to 1500 million hectares globally. A total century-scale potential for terrestrial sequestration in pastures was developed associated with the Level 2 stabilization level (roughly 550 ppmv). For the remaining three stabilization levels, this total was adjusted based on the percentage variations in the totals associated with agricultural soils. The time path was also assumed to follow that for agricultural soils. Terrestrial sequestration in pasture lands differs from that in agricultural soils, however, in that no sequestration is assumed in the Reference Case for pasture lands. Recall that sequestration in agricultural soils occurs without constraints on carbon emissions.

For reference technology a conservative estimate of 0.2 tonnes of carbon per hectare over 40 years (or 8 tonnes C/Ha) was assumed to be applied to 40% of pasture land for the Level 2 stabilization scenarios. This value is on the lower end of the range, note that this represents is the net effect of the management changes in terms of carbon emissions, with any offsetting emissions subtracted, such as those from fertilizer application. The total global carbon sequestration is 4.7 GtC, with management changes assumed to be adopted at the same rate as agricultural soil sequestration practices. For advanced technology, the carbon addition was taken to be 0.3 Tonnes C/Ha per year, again over 40 years (12 T/Ha), but applied over 60% of pasture lands. The outcome is 10.6 GtC sequestered over the century for the Level 2 scenarios. Further research would be required to better understand, and bound, the potential carbon sequestration potential of pasture lands.

## 3.7 Non-$CO_2$ Greenhouse Gases

MiniCAM calculates emissions of $CH_4$, $N_2O$, and seven categories of industrial sources for HFCFCs, HFCs, PFCs, and $SF_6$. Emissions are also calculated for other radiatively important substances, such as ozone, aerosols, and aerosol precursor compounds, but these were not considered in this study because the forcing targets were defined in terms of greenhouse gas forcings only. Emissions are determined for over 30 sectors, including fossil fuel production, transformation, and combustion; industrial processes; land use and land-use change; and urban emissions. Emissions are proportional to driving factors appropriate for each sector, with emissions factors in many sectors decreasing over time according to an income-driven logistic formulation.

Marginal abatement cost (MAC) curves are used to represent the opportunities for greenhouse gas emissions reductions, and they include shifts in the curves for methane due to changes in natural gas prices. In all the stabilization scenarios, the values of non-$CO_2$ greenhouse gases used to determine abatement levels are based on the value of carbon adjusted by the global warming potential for each gas. The values of non-$CO_2$ greenhouse gases and carbon, therefore, move in concert. MAC values that are less than zero for a zero carbon price are assumed to be phased in over a period of several decades. Due to this assumption, significant economically driven reductions in non-$CO_2$ greenhouse gases take place even in the Reference Case. Some of these economically driven reductions are the result of technological advances over time. The marginal abatement cost curves from the EMF-21 exercise as supplied by the Environmental Protection Agency and its collaborators were used for this exercise.

For these scenarios, two sets of MACs were developed: reference technology and advanced technology. The marginal abatement cost curves have the same structure for both reference and advanced technology, but with different levels assumed for technological change. In order to treat non-$CO_2$ emissions mitigation in a comparable manner to energy system reductions, technological change is assumed to enhance the opportunities for reductions over the next century. Technological change was incorporated by assuming that the maximum possible amount of mitigation for each sector and gas increases over the next century.

Table 3.19 presents the reference and advanced technology assumptions for mitigation in the U.S. by gas and source sector. The scenario values in the table were selected by a combination of expert judgment and consistency across sectors and gases. The base case values from the EMF-21 curves, as applied for near-term technology, are also shown for reference.

**Table 3.19**. U.S. non-$CO_2$ greenhouse gas reductions (%)

| Gas | Sector | EMF-21 base | Ref Tech | Adv Tech |
|---|---|---|---|---|
| $CH_4$ | Coal Mining | 85 | 85 | 85 |
| $CH_4$ | Natural Gas Systems | 35 | 60 | 80 |
| $CH_4$ | Petroleum Systems | 20 | 25 | 40 |
| $CH_4$ | Landfills | 85 | 85 | 85 |
| $CH_4$ | Enteric Fermentation | 20 | 35 | 50 |
| $CH_4$ | Manure Management | 10 | 60 | 85 |
| $N_2O$ | Adipic Acid Production | 95 | 95 | 95 |
| $N_2O$ | Nitric Acid Production | 90 | 90 | 90 |
| $N_2O$ | Agricultural Soils | 10 | 20 | 35 |
| HFC-245fa | Foams | 30 | 40 | 55 |
| HFC-134a | Aerosols | 20 | 30 | 40 |
| HFC-134a | Solvents | 80 | 85 | 90 |
| HFC-134a | Mobile Air Conditioning | 70 | 75 | 80 |
| HFC-134a | Commercial Building AC | 70 | 75 | 80 |
| HFC125(227ea) | Fire Extinguishing Systems | 30 | 45 | 60 |
| HFC125(227ea) | Commercial Building AC | 70 | 70 | 70 |
| HFC125(227ea) | Residential Building AC | 70 | 70 | 70 |
| HFC125(227ea) | Food Distribution and Appliances | 70 | 75 | 80 |
| $SF_6$ | Electric T&D | 30 | 45 | 60 |
| $C_2F_6$ | Semiconductor Manufacture | 10 | 15 | 20 |
| $CF_4$ | Al and Mg Manufacturing | 40 | 55 | 65 |
| $CF_4$ | Solvents | 80 | 85 | 90 |

# 4.0 The Reference Case

## 4.1 Introduction to the Reference Case

This chapter describes the Reference Case, a scenario in which technology evolves over the century according to the reference technology assumptions (see Chapter 3) and in which no explicit actions are taken regionally, nationally, or globally to limit greenhouse gas emissions. The Reference Case is not a prediction. It is a plausible point of departure for analyses of stabilization and the role of advanced technology. A wide range of equally plausible reference cases could have been developed for this exercise. The $CO_2$ emissions from the Reference Case chosen for this analysis are near the middle of the range of reference case emissions from the scenarios published in the Intergovernmental Panel on Climate Change *Special Report on Emissions Scenarios* (IPCC 2000).

In addition to its role as a starting point for further scenario analysis, the Reference Case 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 Case are not predetermined; they are the result of the interactions between these various drivers over the 21st century.

The Reference Case does not assume that technology remains frozen at today's levels. Substantial advances occur in the Reference Case across virtually all of the relevant technological areas considered in the analysis: energy supply technologies, end-use technologies, agricultural technologies, and technologies for reducing the emissions of non-$CO_2$ greenhouse gases. The Advanced Technology Scenarios that will be the focus of Chapter 5 differ from the Reference Case in that they assume *additional* improvements in technology beyond those in the Reference Case.

The stabilization scenarios in Chapter 5 also differ from the Reference Case 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 Case is consistent with the role of the Reference Case 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 U.S. is committed to a greenhouse gas intensity goal and a number of other developed countries are participating in the Kyoto Protocol.

Beyond these two distinguishing characteristics, the Reference Case is identical to the stabilization cases in Chapter 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 Case 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 chapter explains the key characteristics of the Reference Case. 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 Case, 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 Case, 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 Case 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 these three factors modified by an energy-service price elasticity. Identical assumptions for these parameters are used in all the scenarios considered in this study, including the stabilization scenarios. However, stabilization incurs economic costs, which are 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 differ from the Reference Case, but the underlying economic and demographic forces do not.

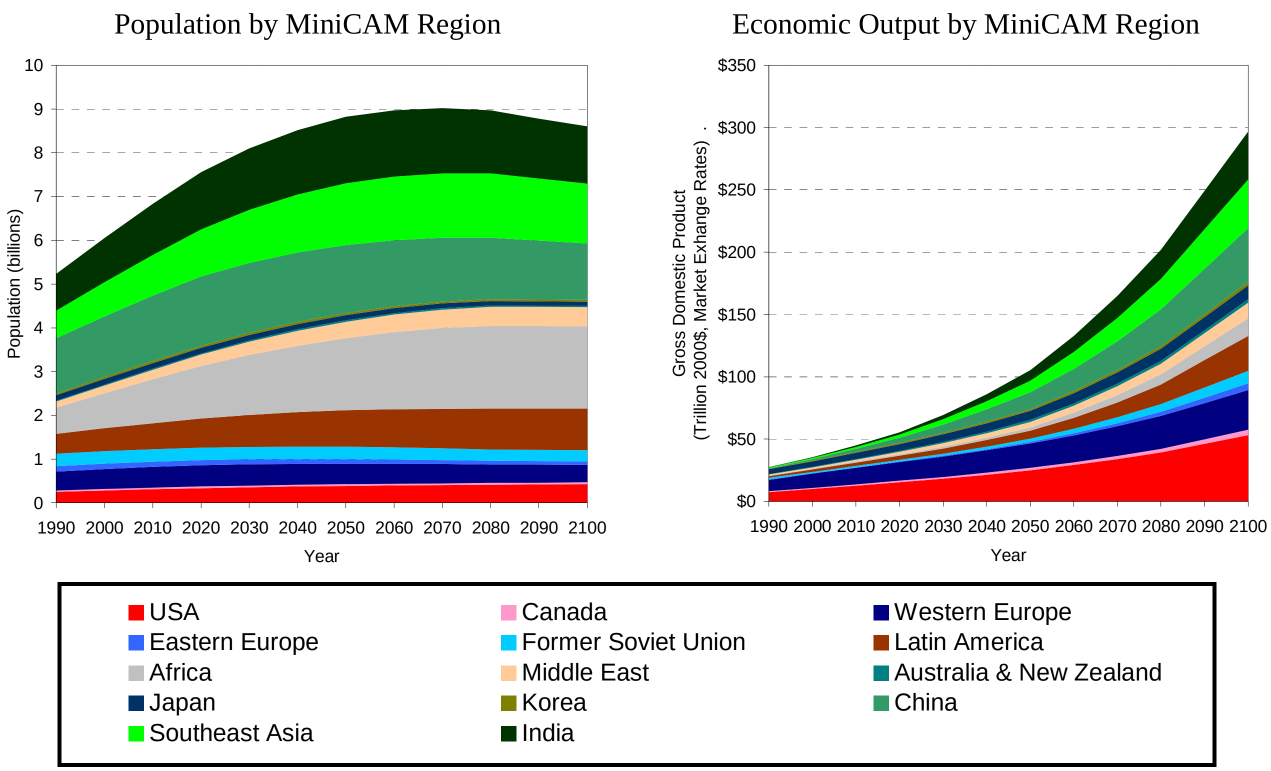
The population assumptions used in these scenarios are based on a combined analysis of the median scenario by the United Nations (UN 2005) and a Millennium Ecosystem Assessment (MEA 2005) Techno-Garden Scenario from the International Institute for Applied Systems Analysis. Starting with the underlying 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 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 Case 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. However, 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% 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. The result is growth in global gross domestic product (GDP) from roughly 35 trillion dollars in 2000 to over 250 trillion dollars (in constant 2000 dollars) by the end of the century, with China, India, and Southeast Asia producing over 100 trillion dollars combined.

## 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 Case. 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.


Population by MiniCAM Region

Economic Output by MiniCAM Region

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

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 primary 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 Chapter 3, the Reference Case assumes roughly 0.5% growth annually in the efficiency of end-use technologies. This reduces the rate of growth of final energy consumption.

Finally, the Reference Case 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.

Another important characteristic of the Reference Case is disproportionate growth in the consumption of transportation services, which leads to disproportionate growth in the demand for liquid fuels, as shown in Figure 4.2. This growth in transportation demands is largely driven by rapid expansion in transportation in the developing economies of the globe during their early periods of economic expansion.

As discussed in Chapter 3, detailed models of the U.S. buildings and transportation sectors were also used in this analysis. As shown in Figure 4.3, an important trend in the building sector is increasing demands for appliance, information technology, and other predominantly electric demands, which are included in the “other residential” and “other commercial” categories. At

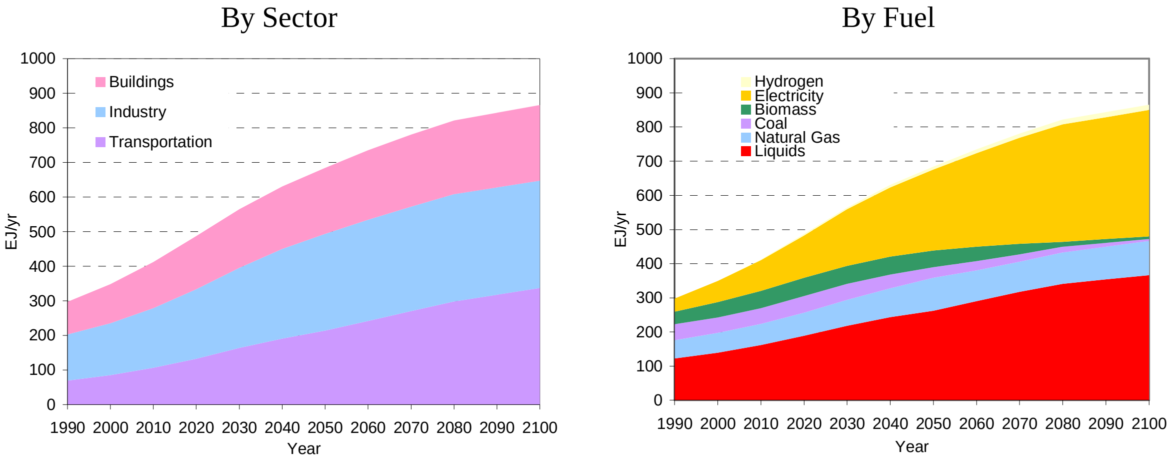


**Figure 4.2**. Global final energy by sector and fuel

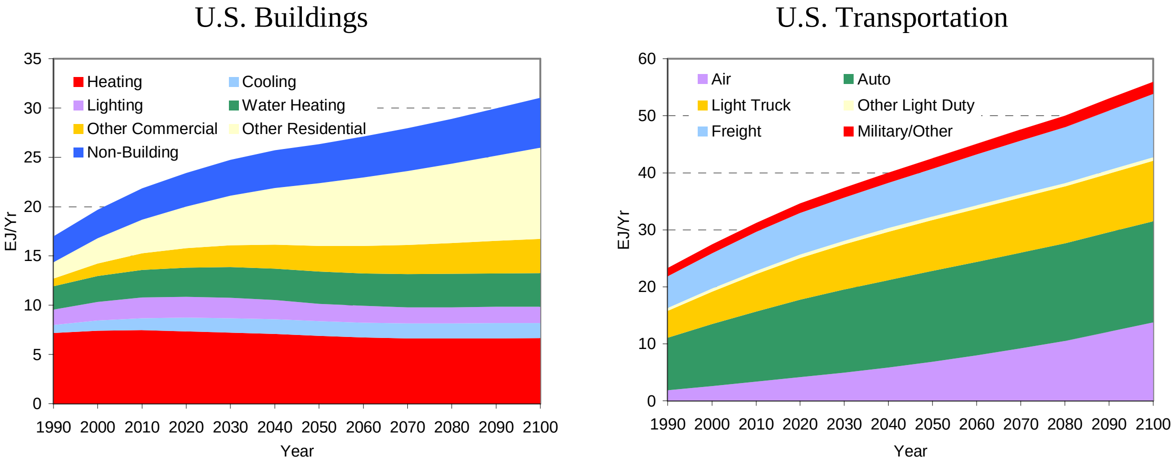


**Figure 4.3**. Delivered energy by end use in the U.S. buildings and transportation sectors[5]

present, heating is the largest single demand for final energy in the buildings sector, but the relative importance of heating decreases over time because of the increasing penetration of high-efficiency, electric heat pumps along with the increasing internal gains (heat given off by other end-use devices) from those other technologies. In the transportation sector, passenger transportation continues as the dominant demand for liquid fuels, and there is a substantial expansion in the demand for air travel.

Increasing consumption of final energy leads to a roughly commensurate increase in the production of energy. Figure 4.4 shows global primary energy consumption by fuel in the Reference Case. 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.

Of particular note, carbon-free energy sources, such as renewable energy, commercial biomass, and nuclear power, experience substantial growth in this future. Spurred on by the substantial improvements in costs and performance that were described in Chapter 3, these energy sources 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.

Despite the growth in carbon-free energy sources, however, 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 Case 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

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[5] Note that non-building refers to end uses that are classified as commercial for the purposes of national accounting, but refer to non-building energy uses, such as parking garages.

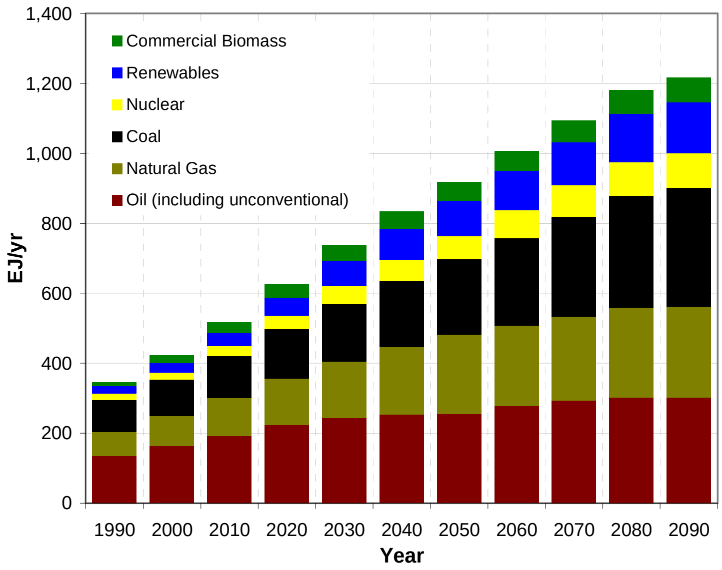

**Figure 4.4**. Global primary energy in the Reference Case

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.

## 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 Case, 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 Case, as shown in Figure 4.5.

As the century unfolds, growth in croplands and pasture lands impinge on currently unmanaged lands. The amount of land dedicated to crops expands to meet increased demands. The conversion of unmanaged lands to cropland, and the conversion of forested lands in particular, results in carbon emissions through deforestation.

It is important to note that the growth in agricultural lands arises despite the increasing agricultural productivity. Agricultural productivity, including biomass crops, is assumed increase by 1% per year from 1990 to 2035 and 0.5% per year thereafter. Productivity in managed forests is assumed to increase by 0.5% per year throughout. Without this growth in agricultural productivity, the displacement of unmanaged lands would be much larger.

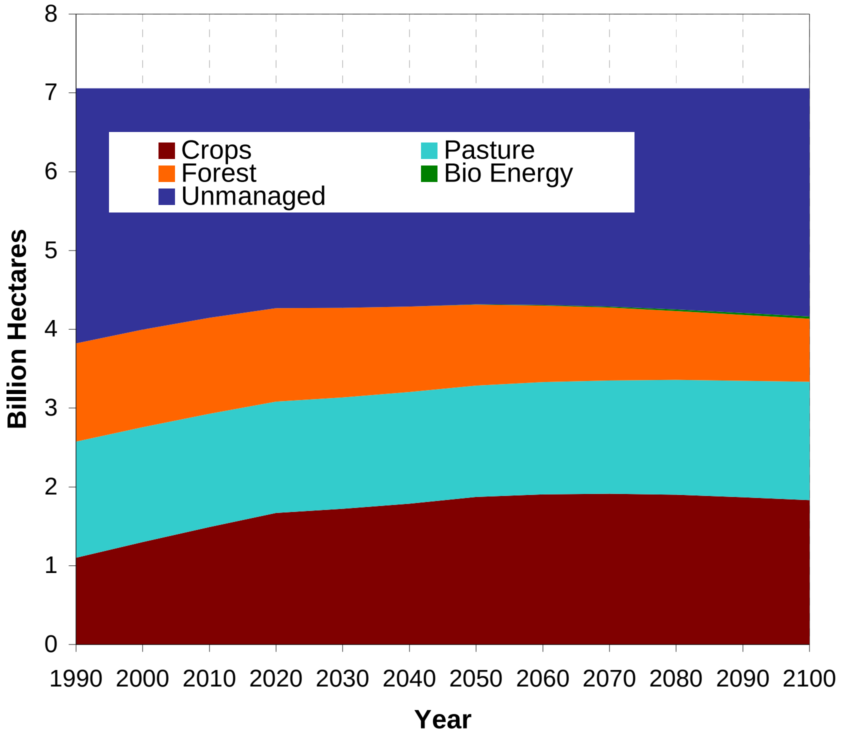

**Figure 4.5**. Global distribution of land in the Reference Case[6]

### 4.4.2 Terrestrial Sequestration

As discussed in Chapter 3, many actions that might be taken to reduce greenhouse gas emissions or sequester $CO_2$ in terrestrial systems will only be implemented if policies are put in place to encourage these actions. Some actions, on the other hand, are viable to some degree even without concerted climate policy. The terrestrial sequestration options considered in these scenarios—soil carbon sequestration, reforestation, and carbon sequestration in pasture lands—are assumed to include both actions that are only viable with policies and those that might occur without policies. The Reference Case assumes no explicit actions to reforest previously forested lands or to sequester carbon in pasture lands. Conversely, the Reference Case assumes that the agricultural practices such as no-till agriculture, which can lead to carbon sequestration in agricultural soils, have some economic benefits irrespective of climate change, including improved soil quality, reduced runoff, and reduction of energy used in agricultural production.

The soil carbon sequestration results in the Reference Case are shown in Figure 4.6. Rates peak after several decades and then decline because the remaining opportunities to convert to soil management practices that are economic in the Reference Case are undertaken over the first half of the century. These soils continue to take up carbon, but at a decreasing rate.

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[6] Note that land for bioenergy is positive in the Reference Case but is small enough to only show up marginally in Figure 4.5**.**

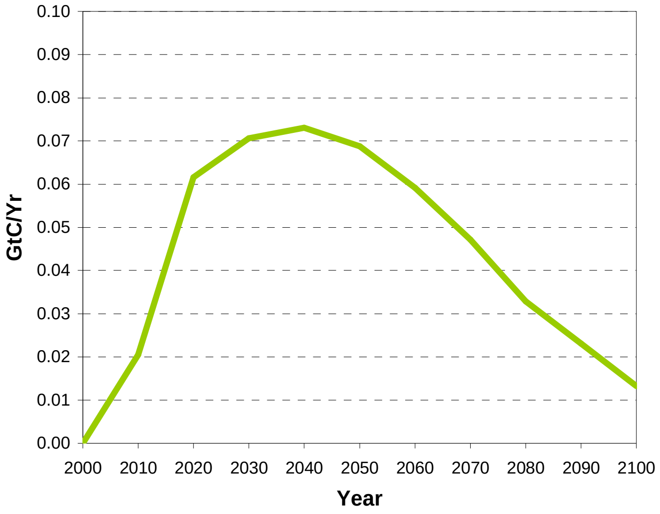


**Figure 4.6**. Soil carbon sequestration rates in the Reference Case

## 4.5 Emissions, Concentrations, and Radiative Forcing

One outcome of population and economic growth is increasing $CO_2$ emissions throughout the century. The left panel in Figure 4.7 shows the $CO_2$ emissions in the Reference Case from fossil and other industrial (cement) sources. $CO_2$ emissions are projected to rise over threefold, from about 6.5 GtC/yr in 2000 to slightly over 21 GtC/yr in 2100. This is roughly commensurate with threefold growth in primary energy consumption in the Reference Case. The cumulative result is increasing atmospheric concentrations of $CO_2$, as shown in the right panel of Figure 4.7. 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.

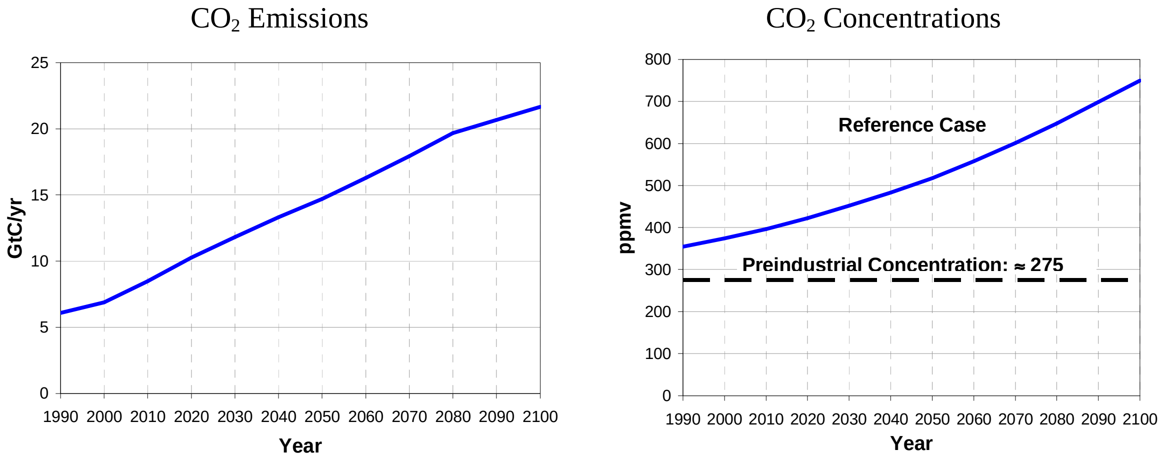
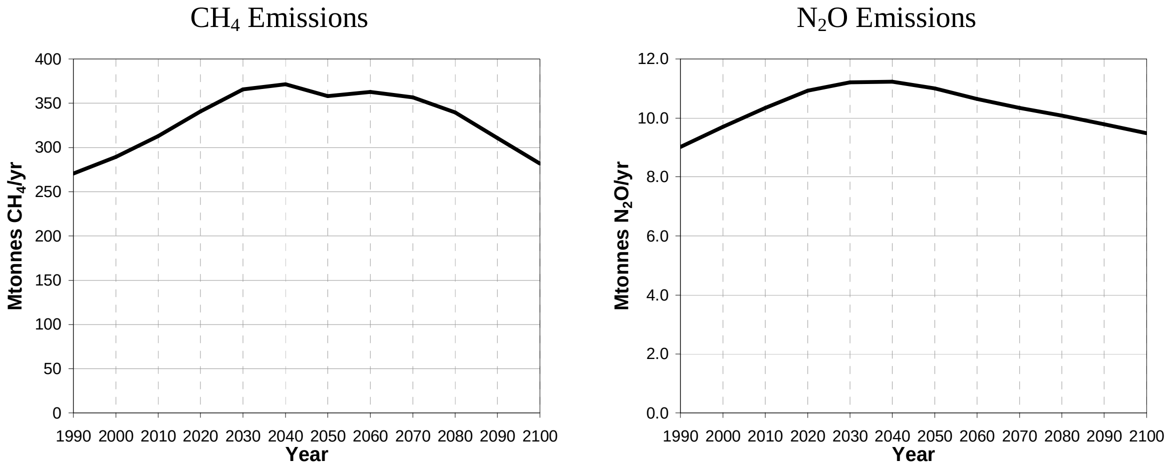


**Figure 4.7**. $CO_2$ emissions from fossil and other industrial (cement) sources and $CO_2$ concentrations in the Reference Case

$CH_4$ and $N_2O$ emissions both exhibit a gradual peak and decline in the Reference Case, as shown in Figure 4.8. The eventual decline in these non-$CO_2$ greenhouse gases is caused by assumptions about the viability of zero-cost options for mitigation. As discussed in Chapter 3, these options are assumed to be phased in and exploited gradually.

Increased greenhouse gas emissions and resulting concentrations lead to increasing radiative forcing from these gases. Figure 4.9 shows the radiative forcing from the greenhouse gases considered in this study. These results highlight two important themes that will be important in the stabilization scenarios in Chapter 5. First, $CO_2$ becomes an increasingly dominant source of increased radiative forcing; it is the most important greenhouse gas to control. Second, substantial reductions need to be made in the emissions of non-$CO_2$ greenhouse gases if stabilization is to be achieved. The non-$CO_2$ greenhouse gases do not have as large a footprint as $CO_2$, but their control has important impacts on the costs of stabilization, as will be discussed in more detail in Chapter 5.



$CH_4$ Emissions

$N_2O$ Emissions

**Figure 4.8**. Emissions of $CH_4$ and $N_2O$ in the Reference Case

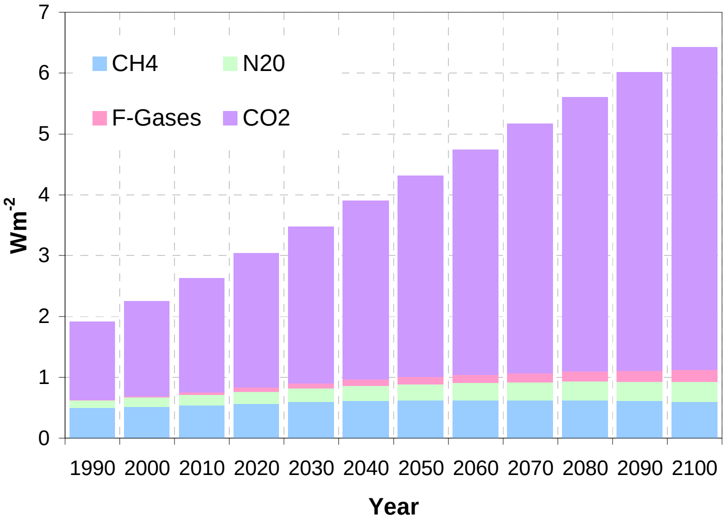


**Figure 4.9**. Radiative forcing by gas in the Reference Case

# 5.0 The Stabilization Scenarios

## 5.1 Introduction to the Stabilization Scenarios

This chapter 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. The scenarios discussed in this chapter differ from the Reference Case discussed in Chapter 4 in two ways. First, most of the scenarios discussed here include advances in technology beyond those that were assumed in the Reference Case. Three different suites of advanced technology assumptions were used, as discussed in Chapter 2 and Chapter 3: Closing the Loop on Carbon, New Energy Backbone, and Beyond the Standard Suite. 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. Four hypothetical emissions trajectories were examined in the study, corresponding to the four radiative forcing levels discussed in Chapter 2. These four radiative forcing levels were designed so that the associated $CO_2$ concentrations would be 450 ppmv (Level 1), 550 ppmv (Level 2), 650 ppmv (Level 3), and 750 ppmv (Level 4). Conversely, the Reference Case assumes no explicit actions are taken in the future to mitigate greenhouse gas emissions.

There are twelve stabilization scenarios with advanced technology, created by combining the three sets of advanced technology assumptions with the four radiative forcing stabilization levels. In addition, the analysis included four Baseline Scenarios, which achieve the same four stabilization levels with reference technology instead of advanced technology. The comparison of the costs associated with the Baseline Scenarios to those associated with the Advanced Technology Scenarios helps assess the economic benefits that advanced technologies might generate.

Emissions and concentrations are nearly identical across the Advanced Technology Scenarios because they are all based on the same radiative forcing and greenhouse gas emissions levels. However, the means of achieving these reductions differ substantially across the Advanced Technology Scenarios. In the Closing the Loop on Carbon scenarios, a large amount of electricity is generated from power plants equipped with carbon capture and storage equipment; in the New Energy Backbone scenarios, greater amounts of renewable and nuclear energy are generated; in the Beyond the Standard Suite scenarios, significant quantities of energy come from breakthrough technologies in the latter half of the century.

The costs of meeting the various stabilization levels are also similar across the three sets of advanced technology assumptions. This is an outcome of the assumptions behind the technology scenarios. From within the wide range of plausible assumptions that could have been used in each technology area, the advanced technology assumptions were chosen to be reasonable, given our state of knowledge about how technologies might advance, but also to achieve relative consistency in costs across the three technology scenarios. Comparing across technology assumptions, therefore, provides insight into what sorts of advances in cost and performance would need to happen, in three very different energy supply technology areas, to lead to a similar end point. Although experts may differ on the likelihood of each of these sets of technological advances occurring, the scenarios show that each one, if it were to be achieved, could bring dramatic cost benefits to the goal of achieving stabilization.

Ultimately, the role of technology in stabilization is to reduce the costs of achieving stabilization. Although they differ in terms of their energy supply characteristics, the additional technological advances assumed in the Advanced Technology Scenarios more than halve the costs of stabilization across stabilization levels. And these costs are substantial; cumulative discounted costs over the century could be tens of trillions of dollars.

The stabilization scenarios demonstrate that a range of technologies can 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.

The remainder of this chapter 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 and Section 5.6 provide closing observations on the role of technology in stabilization. Section 5.5 explores the relative contributions of different technologies to emissions reductions and demonstrates that various types of technological advances can be important contributors to stabilization. Section 5.6 compares the costs of stabilization under the advanced technology assumptions with the costs based on reference technology.

## 5.2 Emissions, Radiative Forcing, and Concentrations

Stabilization in these scenarios is defined in terms of radiative forcing from the suite of greenhouse gases discussed in Chapter 2. Stabilizing radiative forcing from these gases has implications for their concentrations and, therefore, their emissions over time. For greenhouse gases, stabilizing radiative forcing is equivalent to stabilizing atmospheric concentrations, because radiative forcing from each greenhouse gas depends primarily on its concentration in the atmosphere. Stabilizing greenhouse gas concentrations, in turn, requires that emissions be equally balanced by the processes that remove greenhouse gases from the atmosphere, so that there are no net additions to the atmosphere.

$CO_2$ 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. This is true of all the stabilization levels considered in this study.

In contrast to $CO_2$, all of the non-$CO_2$ greenhouse gases are destroyed by chemical or photochemical processes in the atmosphere. The destruction rates increase with the concentrations of these greenhouse gases. For this reason, if emissions were kept constant for any of these greenhouse gases, the rates at which they are destroyed would increase and eventually come into balance with the rates at which they are emitted. Hence, concentrations would be stabilized. The timeframes for this process vary among the gases because of their differing atmospheric lifetimes, but for all of these non-$CO_2$ gases, stabilizing concentrations is synonymous with stabilizing emissions. The final concentration level determines the final level at which emissions must be stabilized.

Figure 5.1 shows the radiative forcing trajectories for the four stabilization levels.[7] The timing of stabilization differs among the stabilization levels. The more stringent the stabilization goal, the more quickly it will need to be reached to achieve and maintain it. For the two least stringent levels, Level 3 and Level 4, stabilization is not achieved until well into the next century or perhaps beyond for Level 4. For this reason, in both of these scenarios, radiative forcing is still increasing and is well below the target level in 2100. In contrast, radiative forcing is approaching its stabilized level at the end of the century in Level 2, and stabilization is achieved in this century for Level 1.

Figure 5.2 shows radiative forcing across the stabilization levels at the end of the century along with radiative forcing in 2000. Together Figure 5.1 and Figure 5.2 illuminate the relative roles of different greenhouse gases in stabilization. $CO_2$ is clearly the most important greenhouse gas to control. It represents the largest contribution to radiative forcing in the Reference Case, accounting for over 5.0 $Wm^{-2}$ out of a total of roughly 6.5 $Wm^{-2}$ in 2100. The most stringent stabilization goal, Level 1, requires a reduction in radiative forcing from $CO_2$ on the order of 3.0 $Wm^{-2}$ in 2100. In contrast, non-$CO_2$ greenhouse gases represent slightly above 1.0 $Wm^{-2}$ in the Reference Case, and reductions under the most stringent stabilization goal are approximately 0.5 $Wm^{-2}$.

At the same time, a simple comparison of radiative forcing reduction amounts does not fully illuminate the importance of controlling emissions of the non-$CO_2$ greenhouse gases. Reductions in non-$CO_2$ greenhouse gas emissions are worth substantially more from a cost perspective than a simple comparison of emissions reductions might indicate. Emissions reductions in every gas are assumed to occur in order of cost. The most cost-effective reductions are taken first; the greater the requisite reductions in emissions, the higher the cost of eliminating the final unit of emissions. In economic terminology, the marginal costs of emissions reductions increase as the level of abatement increases. The reductions in radiative forcing from non-$CO_2$ greenhouse gases may be smaller than those for $CO_2$, but they eliminate the $CO_2$ emissions reductions with the highest marginal costs. For this reason, the lowest-cost approach to climate change must be a comprehensive one that includes the non-$CO_2$ greenhouse gases.

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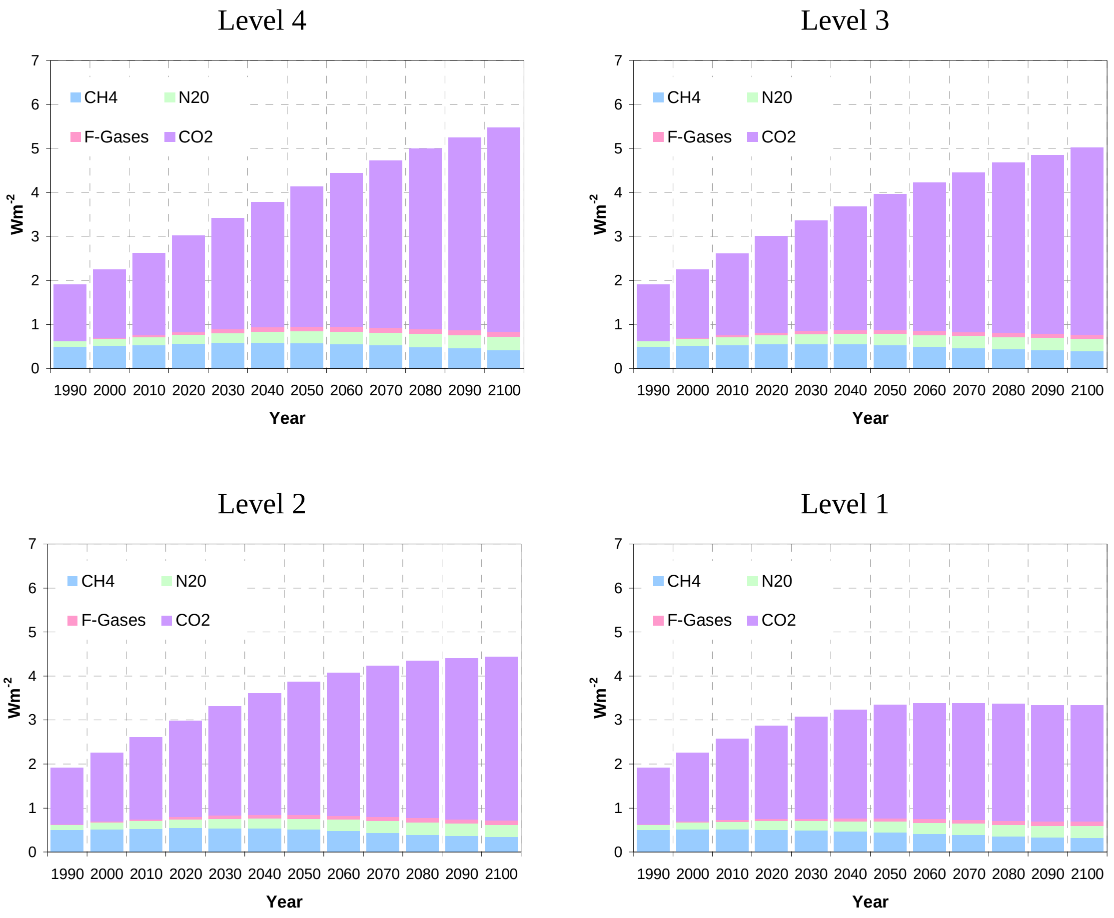
[7] The figure shows the radiative forcing trajectories for the Closing the Loop on Carbon scenarios. The radiative forcing trajectories do not differ significantly across the different Advanced Technology Scenarios. The baseline scenarios—stabilization scenarios with reference technology—do differ slightly in the relative mix of $CO_2$ to the non-$CO_2$ greenhouse gases. Less advanced technology in those scenarios leads to lower reductions in non-$CO_2$ greenhouse gases so that these gases contribute a greater share to total radiative forcing. The total, however, does not differ between the advanced technology and baseline scenarios.



Level 4

Level 3

Level 2

Level 1

**Figure 5.1**. Radiative forcing by gas by stabilization level[8]

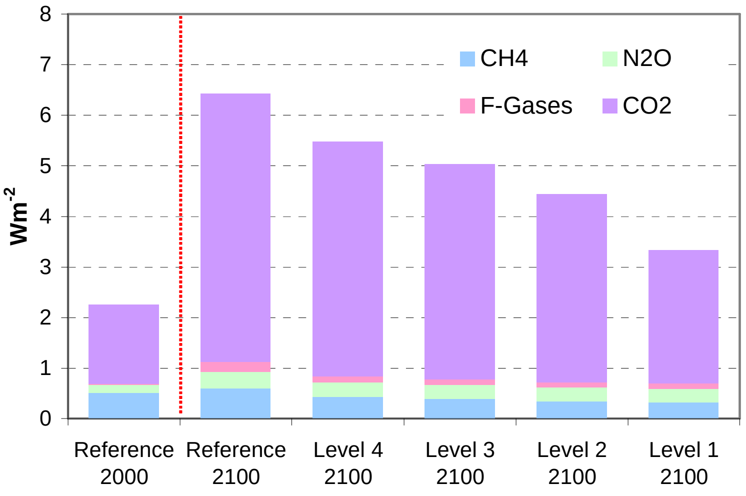


**Figure 5.2**. Radiative forcing in 2000 and in 2100 across stabilization levels[9]

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[8] See Footnote 7.

Just as substantial improvements in energy technologies are included in the Reference Case, the processes that result in emissions of non-$CO_2$ greenhouse gases also exhibit improvements over time even in the Reference Case. For example, as the price of natural gas (methane) increases over time, so does the incentive to reduce leaks of natural gas from pipeline systems. If these actions were not taken in the Reference Case, the non-$CO_2$ greenhouse gas emissions would be higher in the Reference Case, and the potential for reductions would also be higher.

$CO_2$ concentration trajectories, shown in Figure 5.3, mimic those of radiative forcing, because radiative forcing is primarily a function of greenhouse gas concentrations. Concentrations are rising at the end of the century for Level 3 and Level 4; concentrations are approaching their stabilized levels in 2100 for Level 2; and stabilization is achieved in this century for Level 1. Per the design of these scenarios, the long-term $CO_2$ concentrations associated with the four stabilization levels roughly mimic a set of concentrations that have been frequently cited in previous scenario exercises: 450 ppmv (Level 1), 550 ppmv (Level 2), 650 ppmv (Level 3), and 750 ppmv (Level 4).

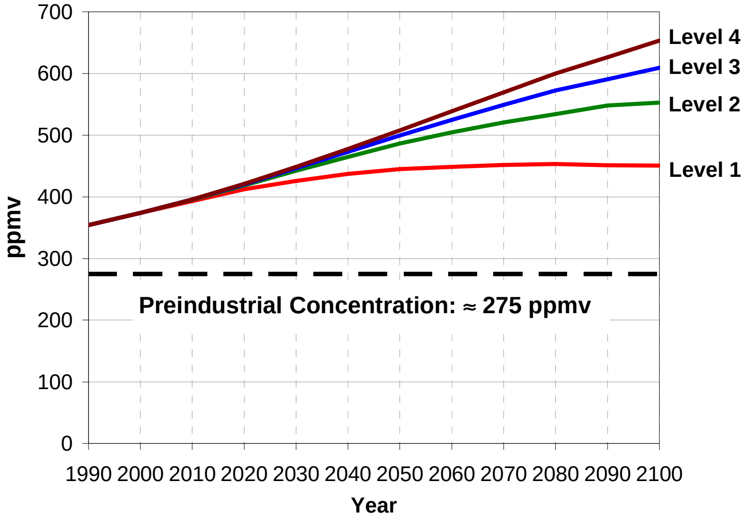

**Figure 5.3**. $CO_2$ concentrations across stabilization levels[10]

Figure 5.4 shows the emissions trajectories for $CO_2$, $CH_4$, and $N_2O$ across stabilization levels in the Advanced Technology Scenarios. The degree to which emissions must be constrained to achieve stabilization varies substantially over the four stabilization levels. In stabilization at Level 4, for example, emissions of $CO_2$ at the end of the century are over twice that of today. In contrast, in Level 2, emissions by the end of the century are at roughly today's levels. For Level 1, emissions at the end of the century are roughly half that of today. Likewise, the tighter the constraint, the sooner $CO_2$ emissions must peak, and the sooner they must reach levels at which there are no net additions to the atmosphere. $CO_2$ emissions do not peak until late in the century for Level 4. In contrast, emissions peak and begin their decline in a matter of decades for Level 1.

Across the stabilization levels, reductions in emissions relative to the Reference Case begin immediately and increase over time, which is a general characteristic of cost-minimizing emissions trajectories. Over

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[9] See footnote 7.

[10] See footnote 2.

the full century, cumulative reductions in $CO_2$ emissions from the Reference Case are on the order of 300 GtC to 1,000 GtC across the four stabilization levels. Figure 5.5 shows an illustrative example of the emissions reductions required to reach Level 2, corresponding to 550 ppmv $CO_2$. The relative contributions of different technologies toward achieving these reductions will be explored in Section 5.5.

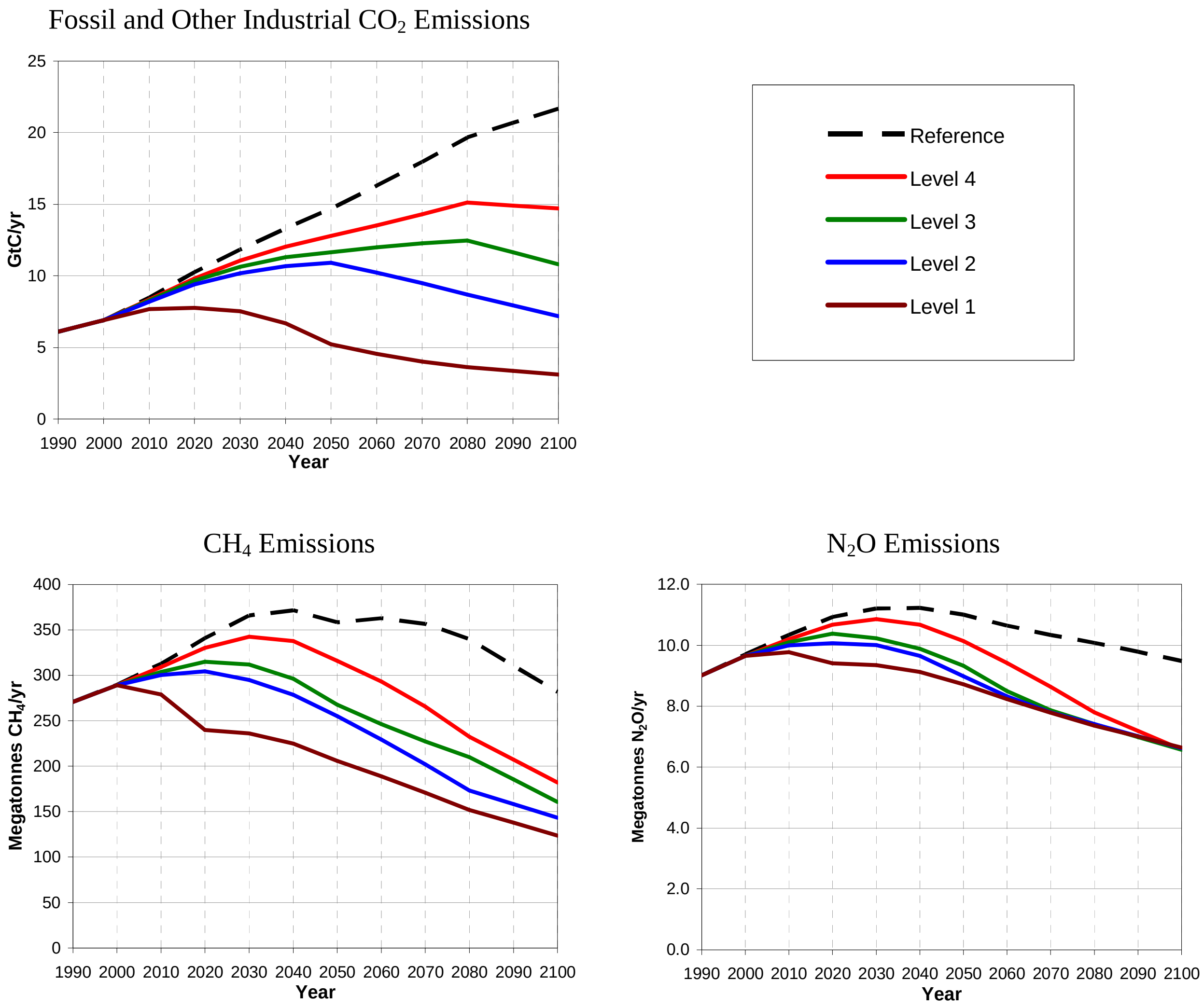

**Figure 5.4**. $CO_2$, $CH_4$, and $N_2O$ emissions across stabilization levels[11]

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[11] Shown for Closing the Loop on Carbon, but variations among Advanced Technology Scenarios are negligible.

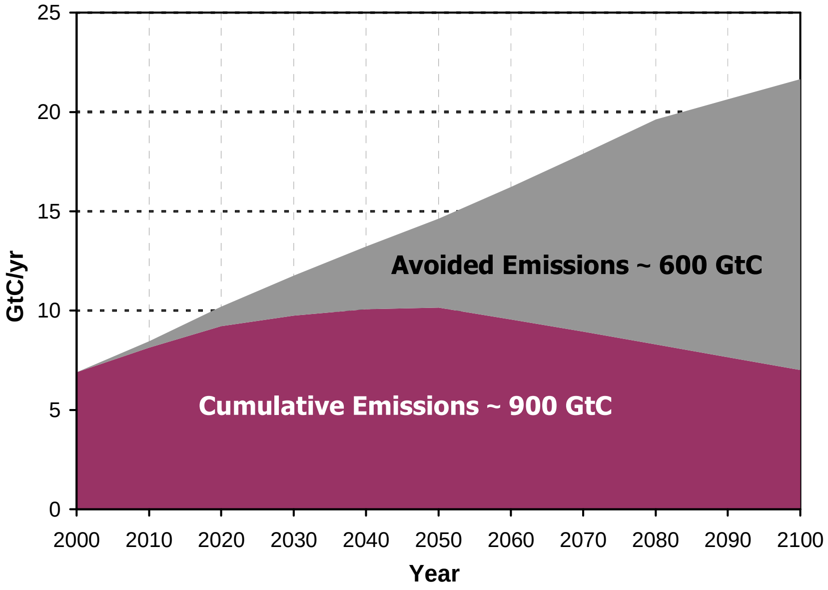


**Figure 5.5**. Potential scale of $CO_2$ emissions reductions to stabilize greenhouse gas concentrations

## 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.

Figure 5.6 shows primary energy consumption over time across the Advanced Technology Scenarios and the Reference Case. Changes in the energy sector (compared to the Reference Case) 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 are captured in the sections of the bars entitled “end-use reduction”. The mix of energy supply technologies is shown in the remaining sections of the bars.

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. The assumed technological gains in energy end-use efficiency do not vary among the Advanced Technology Scenarios. Increased end-use energy efficiency leads to reductions in energy demand by the end of the century on the order of 10% from the Reference Case across the Advanced Technology Scenarios. In the Level 4 scenario, these end-use efficiency gains are the primary source of end-use energy reductions. At more stringent stabilization levels, additional reductions are primarily due to a 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.

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. Switching to hydrogen or biofuels in transportation provides similar benefits, if hydrogen can be generated from fossil fuels with carbon capture and storage technology 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. Hence, the role of end-use technologies in achieving greenhouse gas stabilization goes beyond end-use energy reduction.

The relative roles of different supply technologies, shown in Figure 5.6, change as the emissions limits become more stringent, when freely emitting fossil energy (fossil fuels without carbon capture and storage) is replaced by low- or non-emitting sources such as fossil energy with carbon capture and storage, bioenergy, nuclear power, other renewables, and breakthrough technologies. In the Level 2 scenarios, energy from freely emitting fossil fuels is at roughly today's levels at the end of the century, after a peak prior to 2050 and then a long decline, while energy from low- or zero-emissions sources at the end of the century exceeds global energy production today. This represents a dramatic expansion of these low- or zero-emitting sources. In the Level 1 scenarios, freely emitting fossil energy in 2100 is roughly half of that today, and energy from alternative sources in 2100 is on the order of one-and-one-half times the size of the global energy system today. Despite these shifts, freely emitting fossil fuels continue to be the largest source of energy for the first half of the coming century in all scenarios, and for most of the 21st century for the less stringent scenarios. Hence, stabilization does not imply a near-term phase out of fossil fuels. This is particularly true in the Closing the Loop on Carbon scenarios, because the presence of competitive carbon capture and storage technologies allows for fossil fuels to participate in the energy sector as a low-emitting energy source.

In addition to the shift toward low- or zero-emitting energy sources, all of the stabilization scenarios exhibit a shift within the fossil fuels toward those that result in less carbon per unit of energy. Coal and unconventional fossil sources such as tar sands and shale oil result in greater emissions per unit of energy than conventional crude oil or natural gas. Natural gas produces the lowest emissions per unit of energy of the fossil fuels. So, an important response to emission constraints is to shift toward natural gas and away from coal and unconventional sources. This dynamic in the fossil supply mix is manifest in all of the scenarios, although it is less dramatic in the Closing the Loop on Carbon scenarios, because of the viability of carbon capture and storage technology to turn coal-fired power plants into low-emissions technologies.

As was discussed in Chapter 2, the primary distinction between the different advanced technology assumptions is in the supply of primary energy. As shown in Figure 5.6, each class of Advanced Technology Scenarios exhibits its own unique change in the energy mix as the $CO_2$ emissions constraint is tightened from Level 4 to Level 1. In the Closing the Loop on Carbon (CLC) scenarios, the shift is toward more carbon capture and storage and other advanced fossil-based energy technologies as emissions become more constrained. In the New Energy Backbone (NEB) scenarios, the role of nuclear and renewable energy increases as the constraint is tightened, because they are assumed to exhibit a high level of technical progress and become relatively cost-effective compared to other technologies. In addition, constraints on, and higher costs of, carbon storage limit its effectiveness in reducing carbon emissions in this scenario, compared to Closing the Loop on Carbon. So, in the NEB scenarios, carbon capture and storage is projected to continue playing a role, but not as large as that projected in the CLC scenarios. In the Beyond the Standard Suite (BSS) scenarios, very advanced forms of energy supply and distribution become more important as constraints become tighter, because it is assumed that they make technological progress to the point that they can compete for market share in the latter part of the 21st century.

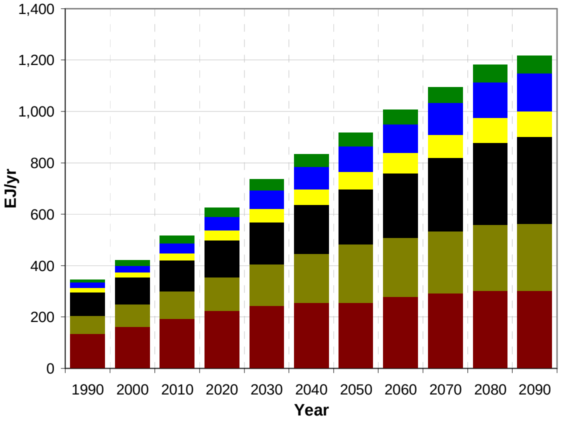
Despite these differences in emphasis, all of the scenarios exhibit a diverse portfolio of energy technologies at all points throughout the century. For example, the CLC scenarios include contributions from nuclear and renewables well above those of today, which represent a dramatic expansion in production, particularly from the renewable sources. Similarly, some carbon capture and storage is deployed in the NEB scenarios. In the BSS scenarios, the breakthrough technologies don't emerge until the second half of the century. Even after they emerge, they do not dominate the energy system, but their emergence is enough to substantially lower the costs of stabilization.

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. It may be that particular technologies are the technology of choice for particular applications for years or 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.

Just as the reduction in emissions from the Reference Case increases over time, so to does the degree of adjustment in the energy sector. The majority of the shift in the energy sector occurs in the second half of the century in all scenarios, but in all scenarios important shifts in the energy sector actions are also undertaken over the next few decades. This can be seen by a comparison of the stabilization scenarios in Figure 5.6 with the Reference Case. The shift is larger when the stabilization level is more stringent. For example, in the CLC scenarios, carbon capture and storage technology does not see substantial deployment until well into the second half of the century for Level 4, but meaningful quantities of electricity from power plants with carbon capture and storage are online by 2020 in the Level 1 scenario.

Behind these explicit shifts in the mix 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 Chapter 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.

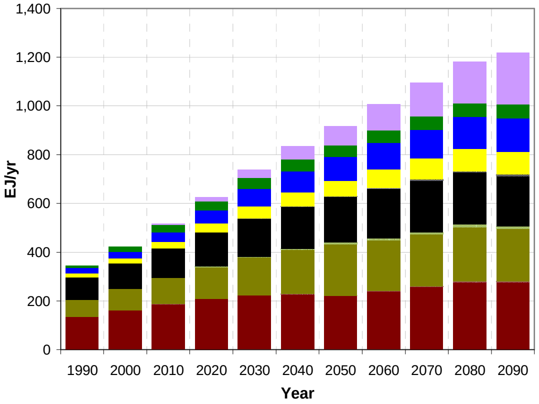
**Reference Case**



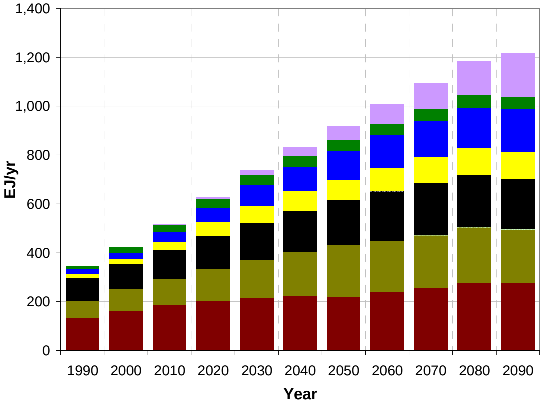
- 🟥 Oil w/o CCS
- 🟫 Natural Gas w/o CCS
- ■ Coal w/o CCS
- 🟨 Nuclear
- 🟩 Commercial Biomass
- 🟪 Energy Use Reduction
- 🟫 Oil w/CCS
- 🟩 Natural Gas w/CCS
- ■ Coal w/CCS
- 🟦 Renewables
- 🟥 Breakthrough Technology

**Level 4**

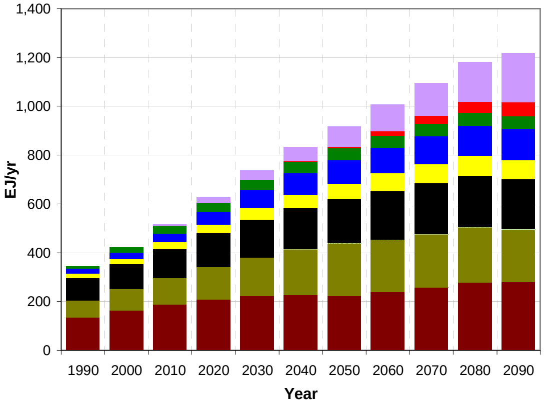
**Closing the Loop on Carbon**

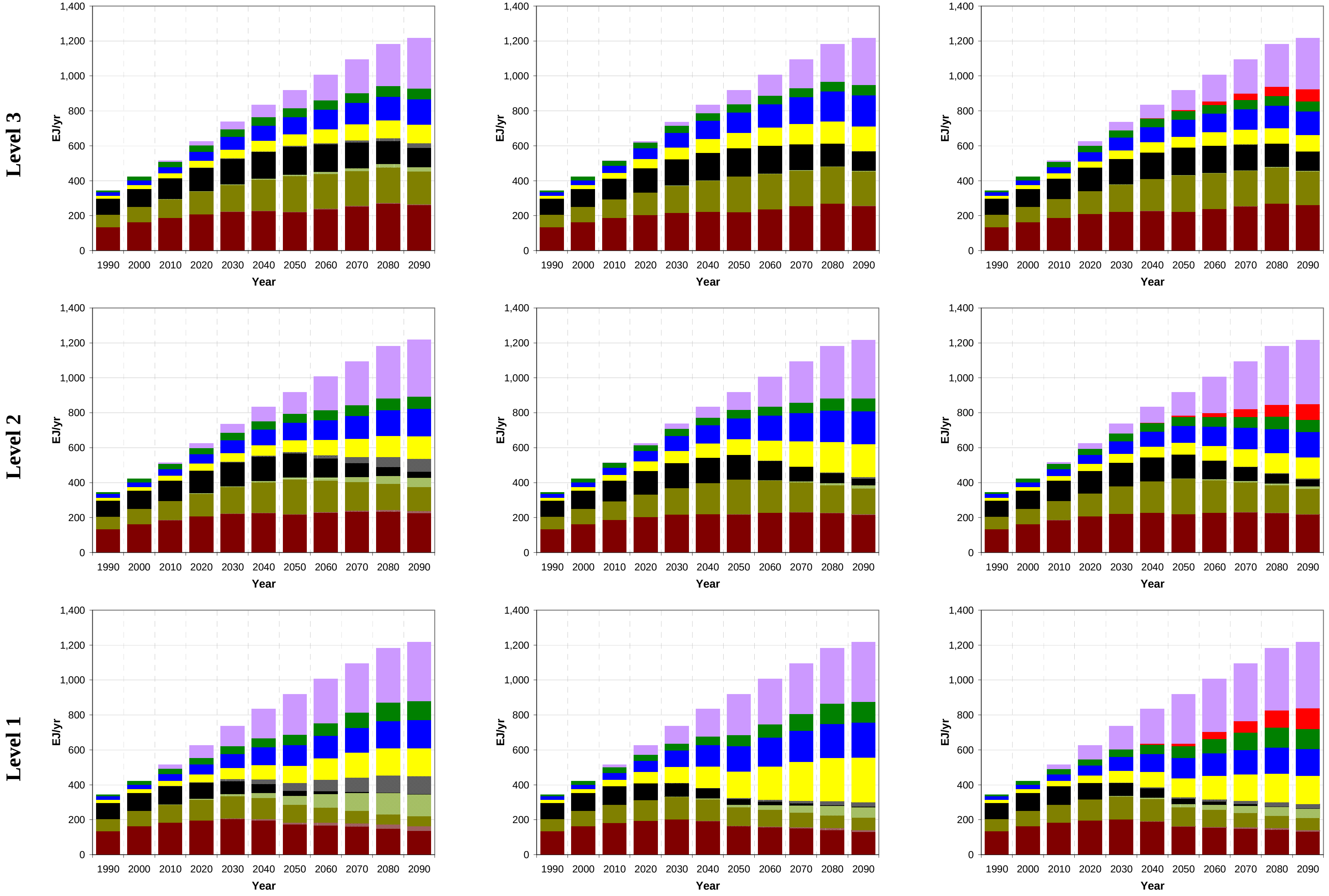


**New Energy Backbone**



**Beyond the Standard Suite**





**Closing the Loop on Carbon** **New Energy Backbone** **Beyond the Standard Suite**

**Figure 5.6**. Global primary energy consumption across stabilization scenarios

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

### 5.4.1 Land Use and Land-Use Change

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, 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. 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 Chapter 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).

Figure 5.7 shows the distribution of land uses for the Level 1 scenarios (roughly 450 ppmv) with reference technology and advanced technology. In the Advanced Technology Scenario, the land dedicated to bioenergy crops (roughly 100 million hectares globally) is larger than in the Reference Case (roughly 25 million hectares globally). The land for bioenergy is not larger than this for several reasons. For one, the Advanced Technology Scenarios include assumptions for hydrogen production and use that make it a viable alternative transportation fuel for at least some portion of the transportation system. This dampens the demand for bio-based oil substitutes. The Advanced Technology Scenarios also incorporate a decrease in all energy demands, including transportation demand, of roughly 10% by the end of the century due to increase end-use efficiency. There are also more cost-effective options for reducing carbon emissions from electricity in the Advanced Technology Scenarios, so more carbon can be cost-effectively removed from electricity production in these scenarios, reducing the need for low-carbon alternatives in transportation applications. For all of these reasons, along with the increasing value of carbon, the land required for bioenergy does not impinge on other land uses in the Advanced Technology Scenarios, even under the most stringent stabilization level.

The Level 1 Baseline Scenario (i.e., with reference technology) provides a different perspective. With reference technology, hydrogen is not as viable an option; energy-efficiency improvements are lower in all sectors, which drives up the associated energy demands; and there are fewer alternatives for reducing emissions from electricity production. These factors taken together lead to increased production of bioenergy, particularly in the second half of the century. This increased production is supplied by converting unmanaged lands and managed forests to bioenergy crops, which leads to a net release of carbon to the atmosphere. This, in turn, necessitates greater reductions in carbon emissions from fossil and industrial sources to meet the same carbon constraint.

At the same time, it is important to note that the land requirements for bioenergy in the Advanced Technology Scenarios, as well as the Baseline Scenarios, extend beyond dedicated biomass crops. Although energy crops are not as widely used in the Advanced Technology Scenarios as in the Baseline Scenarios, biomass from residue and waste sources is still used for energy purposes in these scenarios as it has fewer land-use implications. The specific assumptions used in this study tend to limit the use of biomass crops in the Advanced Technology Scenarios; a different set of assumptions, particularly those for biomass crop production and biomass conversion technologies, could result in a different outcome for biomass crops.

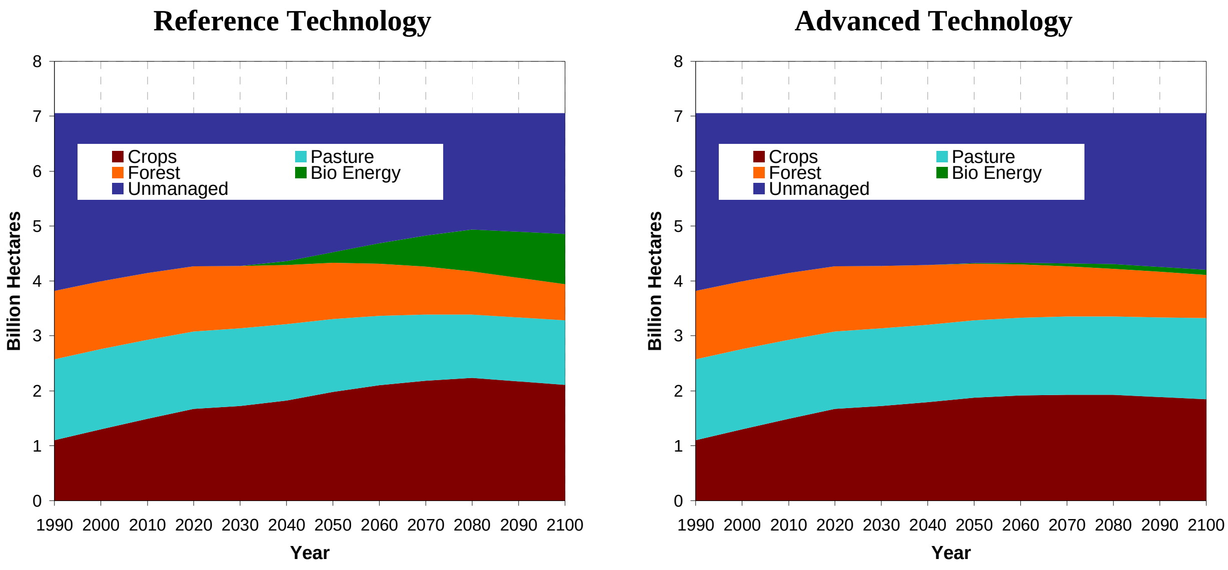


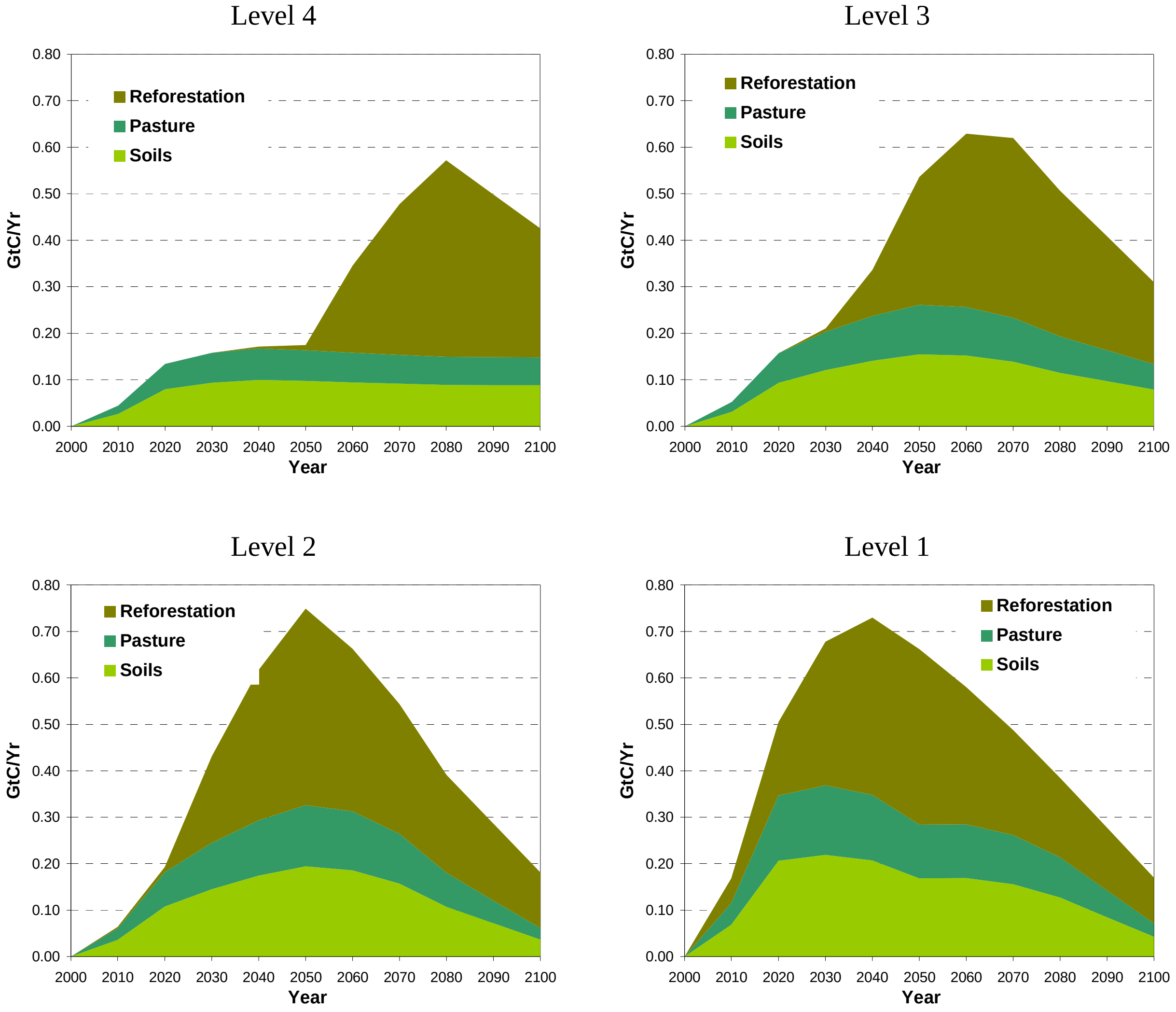
**Figure 5.7**. Global distribution of land uses for Level 1 stabilization (450 ppmv) with reference technology and advanced technology

## 5.4.2 Terrestrial Sequestration

Terrestrial carbon sequestration in the Advanced Technology Scenarios differs from the Reference Case along two dimensions: the total quantity of terrestrial sequestration over the century and its timing. Total potential carbon sequestration from the terrestrial options ranges from 0 to 0.8 GtC per year with approximately half of terrestrial carbon sequestration attributed to reforestation. Terrestrial sequestration characteristics of the Advanced Technology Scenarios are shown in Figure 5.8.

As discussed in Chapter 3, sequestration in agricultural soils and pasture land follow identical time paths, with differing totals. In Level 1, sequestration activities are larger and more focused on the near term. Much of the potential is exploited over the next several decades. Over the remainder of the century, additional sequestration includes the declining uptake from lands that already converted to higher carbon content applications, as well as additional applications that become economically viable as the value of carbon increases. In contrast, sequestration in soils and pasture is more stable under the least stringent constraint, Level 4. The lower value of carbon leads to steadier turnover of lands to carbon sequestering processes over the century.

Reforestation is initiated only when the value of carbon reaches $10 per tonne. This is a larger price signal than is required for sequestration in agricultural soils and pasture, because of the economic benefits associated with soil sequestration even without constraints on carbon. This means that reforestation begins later than the other two terrestrial sequestration options, except under the most stringent constraint, where all options are exercised quickly. In the Level 4 scenarios, reforestation does not begin in earnest until after mid-century. Reforestation sequestration also attenuates more rapidly from its peak than sequestration in agricultural soils and pasture.


Level 4

Level 3

Level 2

Level 1

**Figure 5.8**. Terrestrial sequestration in the Advanced Technology Scenarios

Note that reforestation in the results presented in this report refers to deliberate reforestation of areas not otherwise used for agriculture. Avoided deforestation is often also accounted for under the term reforestation, but this is not the case here. Avoided deforestation is deforestation that would occur in the Reference Case but does not happen in a policy case due to consideration of the value of standing carbon stocks. In this analysis, the portion of avoided deforestation that occurs due to the expansion of land for biomass crops is accounted for as described in Section 5.4.1. This is not shown in the graphs below.

## 5.5 Technology Contributions to Emissions Reduction

Section 5.3 discussed how a diverse range of energy technologies contribute to the shifting energy system portfolio necessary to achieve stabilization. This diversity is part of every scenario, across stabilization levels and technology assumptions. A similar theme emerges when examining the contributions of different technologies, including terrestrial sequestration and technologies for reducing non-$CO_2$ greenhouse gas emissions, to emission reductions and stabilization.

One approach to comparing contributions of the various technologies is to allocate cumulative carbon emissions reductions based on changes in the deployment or use of technologies relative to the Reference Case. The results of such an exercise are shown in Figure 5.9 and Figure 5.10. Figure 5.9 shows the contributions of different energy technologies and of terrestrial sequestration over the century in reducing $CO_2$ emissions. The bottom wedge represents the vented emissions of $CO_2$ in the scenario, and the wedges above show the reductions in $CO_2$ emissions from the Reference Case, allocated to technology areas. Figure 5.10 shows the cumulative $CO_2$ emissions reductions over the century, and it also incorporates the contributions of reductions in non-$CO_2$ greenhouse gas emissions, converted into $CO_2$-equivalent terms.[12]

These figures are valuable tools for conveying the relative importance of different technologies, but an important aspect of these representations should be kept in mind. The figures are based on the changes in technology contributions *relative to the Reference Case*. Hence, if a technology is deployed substantially in the Reference Case and its deployment does not increase dramatically in the stabilization case, then its allocation of emissions reductions will not be fully representative of its actual deployment and associated importance in stabilization. For example, solar and wind power, nuclear power, biomass energy, and terrestrial sequestration are all deployed to levels well above those of today in the Reference Case. Such deployment is not reflected in the carbon emissions reductions allocations shown in the figures. Conversely, carbon capture and storage technology is only deployed in the stabilization cases, so its allocation is representative of its full deployment in any scenario. A second caveat is that there is no single way to develop an appropriate accounting of the contributions of different technologies, and different methodologies will yield different relative roles of different technologies. For both of these reasons, the allocations should be taken as indicative of important themes and dynamics, but literal interpretation of precise emissions reductions by technology is inappropriate

Nevertheless, the figures effectively illustrate one of the most important characteristics of the stabilization scenarios. As is the case with the energy system, stabilization is not a result of a single technology. Stabilization is achieved through the cumulative contributions from a range of technologies and technology areas. For the least stringent scenarios—that is, the Level 4 scenarios—lower-cost actions to reduce emissions through control of non-$CO_2$ greenhouse gases, energy end-use reductions, terrestrial sequestration, and adjustments in the mix of fossil fuels are largely sufficient actions to take in this century to put emissions on a course toward stabilization in some time period after the 21st century. But the more stringent the stabilization level, the more these lower-cost actions must be supplemented by increased deployment of low- or zero-carbon energy sources. The mix of these sources varies by the scenario, because the underlying technology assumptions vary.

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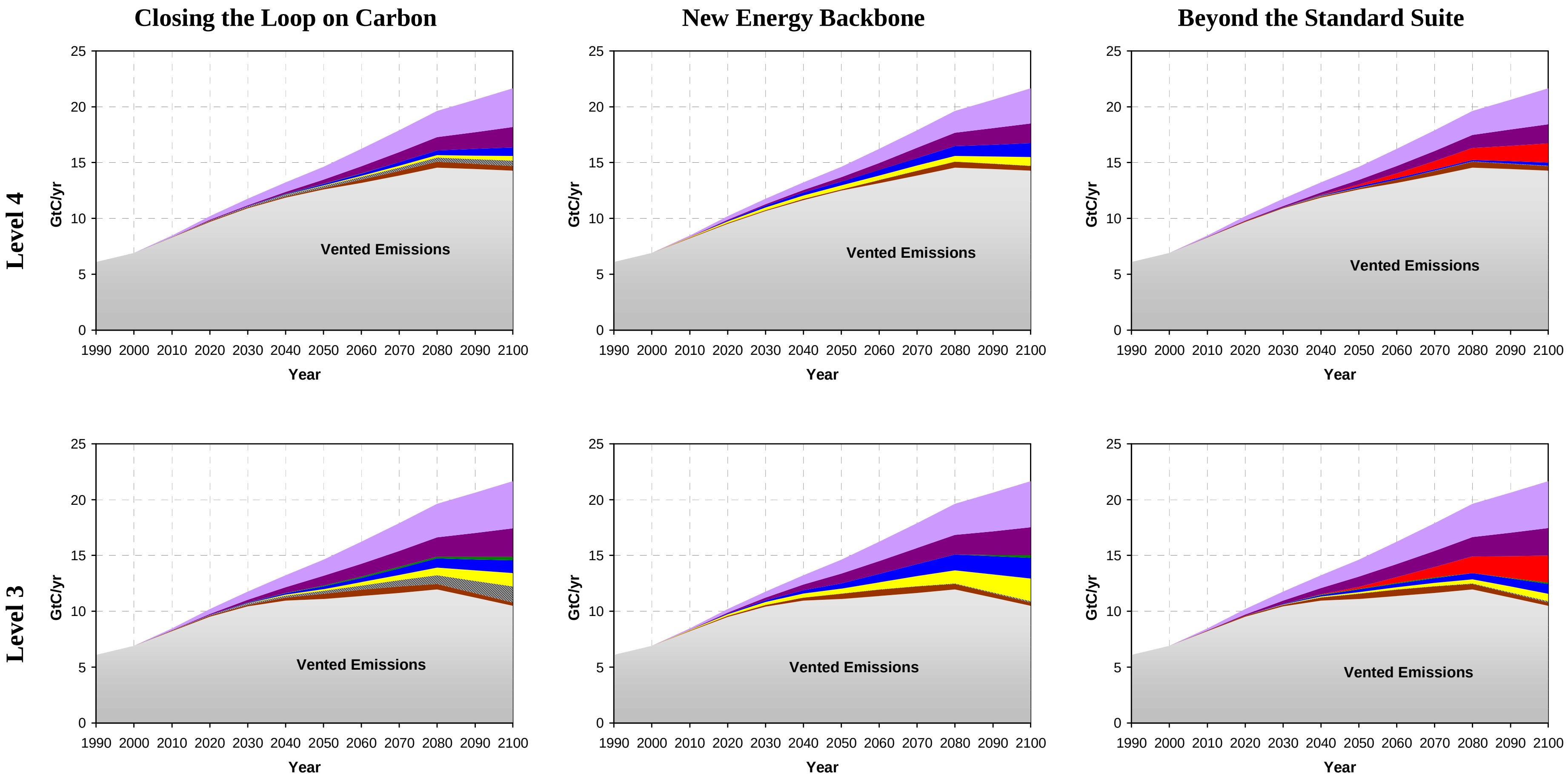
[12] The non-$CO_2$ greenhouse gas contributions were converted to $CO_2$ equivalents based on the radiative forcing reductions in the non-$CO_2$ greenhouse gases relative to the reference. First, the radiative forcing reductions in 2100 for non-$CO_2$ greenhouse gases relative to the reference case (reference technology and no policy) were determined for each scenario. Next, a range of MiniCAM runs was conducted to ascertain the relationship between cumulative $CO_2$ emissions over the century and radiative forcing from $CO_2$ at the end of the century in these scenarios. Finally, this relationship was combined with the radiative forcing benefits from non-$CO_2$ greenhouse gas reductions to obtain a cumulative $CO_2$-equivalent reduction in non-$CO_2$ greenhouse gases. This approach provides a more accurate appraisal of the $CO_2$-equivalent contribution of the non-$CO_2$ greenhouse gases than does the use of global warming potentials. (Note this is different than the approach that was used to obtain non-$CO_2$ greenhouse gas emissions reductions)


Closing the Loop on Carbon
New Energy Backbone
Beyond the Standard Suite
Level 4
Level 3
GtC/yr
0
5
10
15
20
25
1990
2000
2010
2020
2030
2040
2050
2060
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2090
2100
Year
Vented Emissions

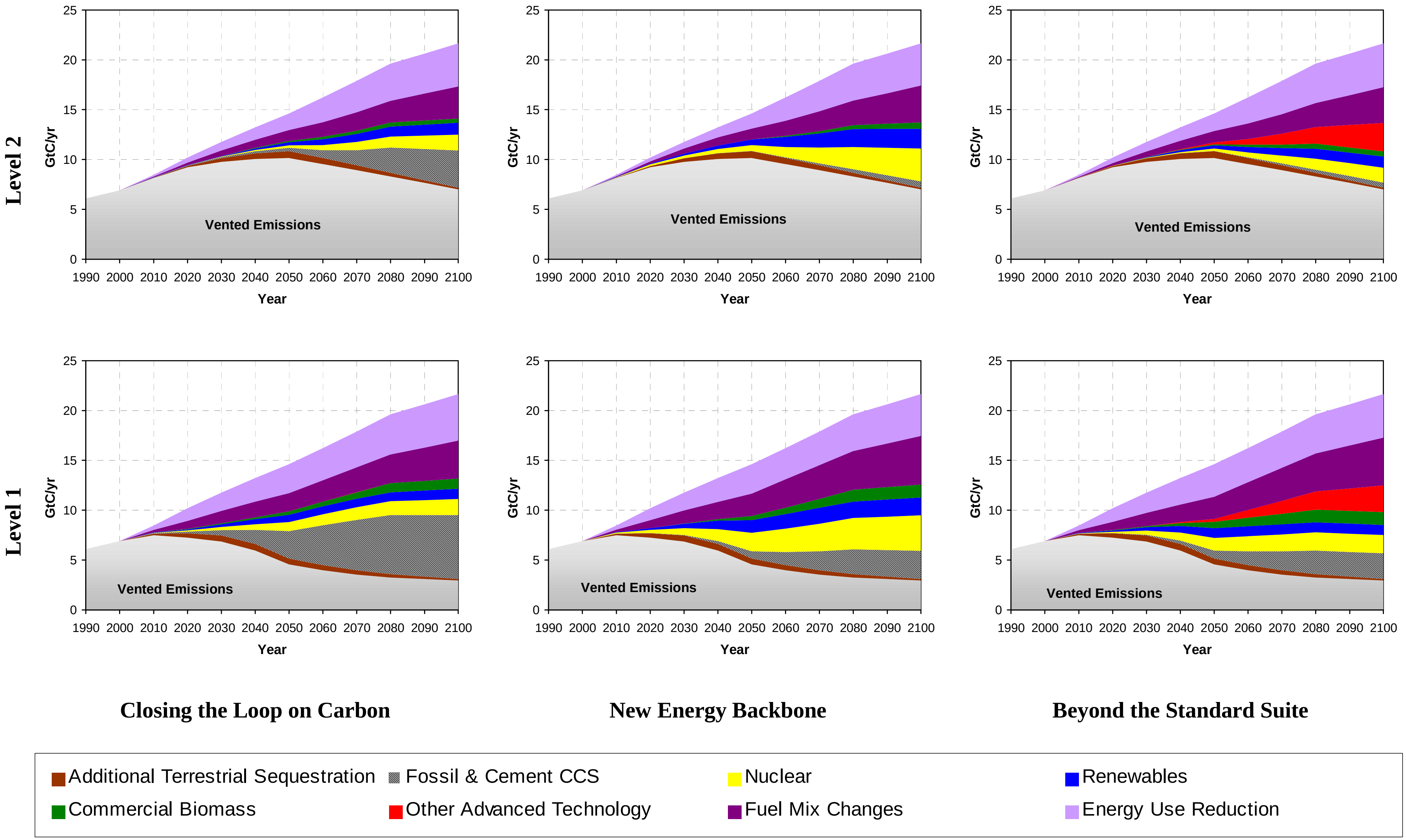


**Figure 5.9**. Contributions to $CO_2$ emissions reductions across stabilization scenarios

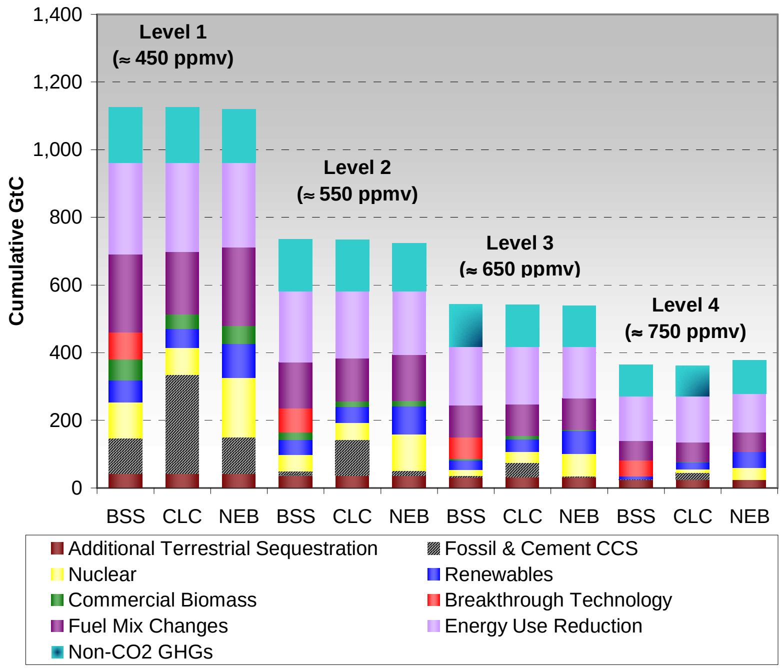


**Figure 5.10**. Cumulative emissions reductions by source, 2000-2100

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. As discussed above, this diversity arises both because there are options for reductions in a range of technology areas and because it is very difficult for any single technology, by itself, to accomplish all the necessary reductions. For example, carbon capture and storage is potentially an enormously valuable technology for limiting $CO_2$ emissions, but it will probably be used primarily in electricity generation. There are a range of energy uses for which electricity may not be a viable alternative, including portions of the transportation system, such as air travel, light-duty vehicles (absent substantial advances in battery technology), and many industrial applications that require very high temperature process heat that is more effectively generated by direct combustion instead of electricity-powered heating processes. These scenarios cannot prove that there will not be a single, silver-bullet technology that addresses climate change, but they do show the powerful logic that supports a diversified technology approach.

## 5.6 Advanced Technology and the Costs of Stabilization

To illustrate the economic benefits of the Advanced Technology Scenarios, the annual and cumulative costs of emissions reductions were estimated for each scenario by comparing the costs in the Advanced Technology Scenarios to those associated with the Baseline Scenarios that achieved the same level of emissions reductions but without advanced technology (i.e., with reference technology assumptions). The comparison suggests the extent to which advanced technology could reduce the costs, should the technologies advance as assumed.

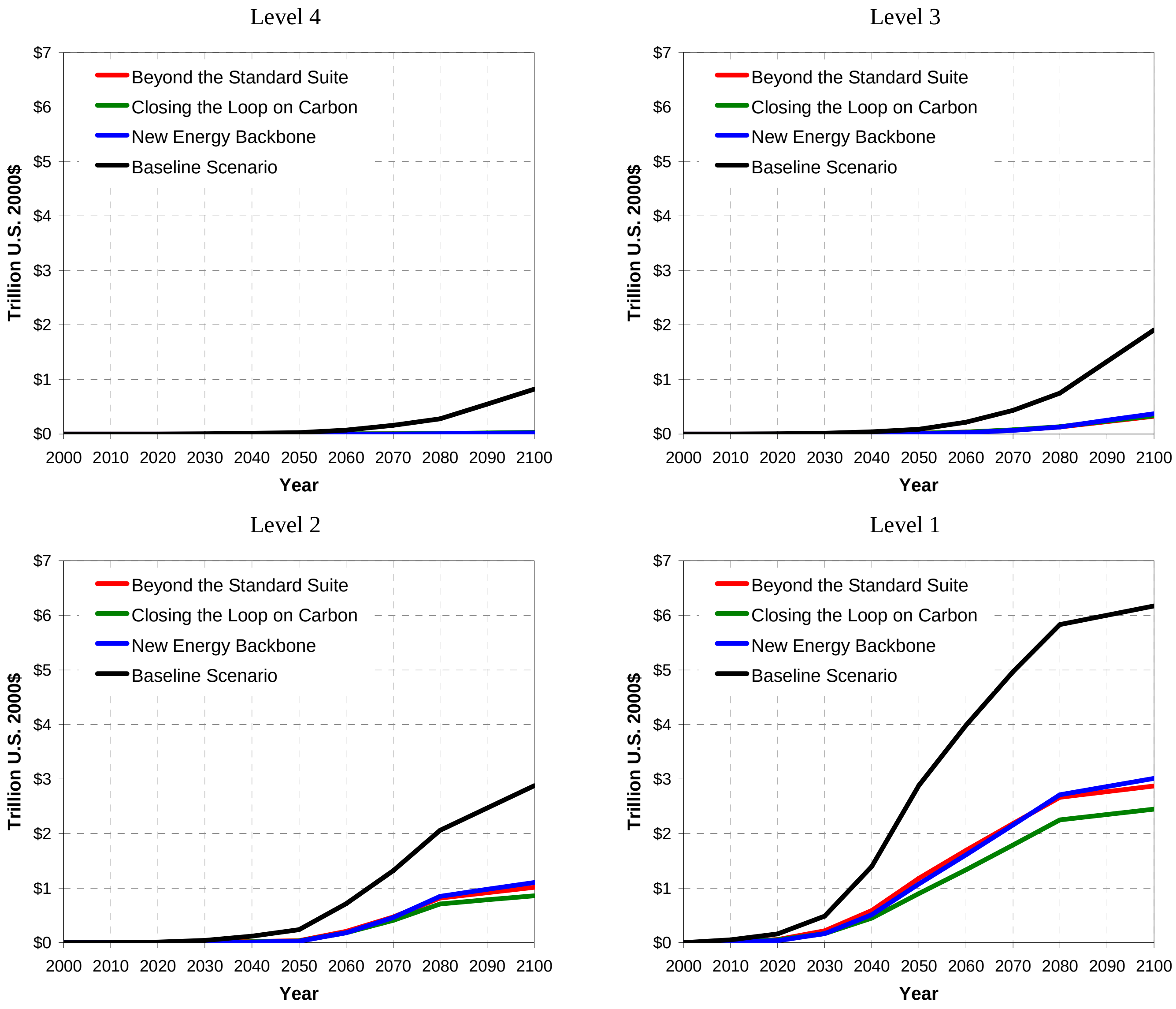


**Figure 5.11**. Total annual global costs of constraining carbon emissions across scenarios (undiscounted in 2000$)

Figure 5.11, Figure 5.12, and Figure 5.13 provide costs results from the scenarios. Figure 5.11 shows the annual costs, over the 21st century, of reducing carbon emissions in the Baseline Scenarios (using reference technology) and in the three Advanced Technology Scenarios. Figure 5.12 and Figure 5.13 show the cumulative costs over the century, plotted against the level of emissions reduction, using different discount rates. Figure 5.12 sums costs over time using a 5% discount rate. The positive discount rate in Figure 5.12 accounts for the fact that mitigation costs incurred at any point in time prevent investments in other parts of the economy, and these investments would have yielded benefits to society in excess of the amounts that were invested. This is a primary reason why many economic analyses use discounting to determine what is known as the present value of future income of cost streams. However, a range of rates are used for discounting investments, and, further, the enormously long timeframe associated with climate change raises a number of difficult issues associated with the appropriate choice of a discount rate that have never been satisfactorily resolved. To provide a benchmark, Figure 5.13 sums the annual costs with no discounting. Not surprisingly, it provides substantially higher cumulative cost values; however, the relative costs are similar across technology assumptions.

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, these cost results are not comprehensive in their accounting of mitigation costs, because they do not account for the costs of reducing non-$CO_2$ greenhouse gases nor do they account for any costs associated with implementing additional terrestrial sequestration. 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. In addition, differences in costs between the Advanced Technology Scenarios should not be emphasized, because the scenarios were constructed so that the costs would be relatively similar. The most appropriate comparison is that between the whole set of Advanced Technology Scenarios, on the one hand, and the Baseline Scenarios on the other.

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. And 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.

By far, the most important insight of the cost results is that technology advancement has serious implications for the costs of stabilization. The cost benefits of the additional technological advances in the Advanced Technology Scenarios, relative to the reference technology assumptions, reach into the trillions of dollars on an annual basis, and tens of trillions of dollars on a cumulative basis, when the discount rate is taken to be 5%. Without discounting, the importance of costs in the latter part of the century is magnified. In this case, the total cumulative cost savings can be as high as hundreds of trillions of dollars. In percentage terms, the advanced technology assumptions provide cost reductions of 60% or more over the course of the century across the scenarios. If all the technological advances are combined (see the line marked “All Advances” in Figure 5.12 and Figure 5.13), there are additional benefits beyond any of the three individual Advanced Technology Scenarios, but the benefits are not additive because many of the technologies are substitutes.

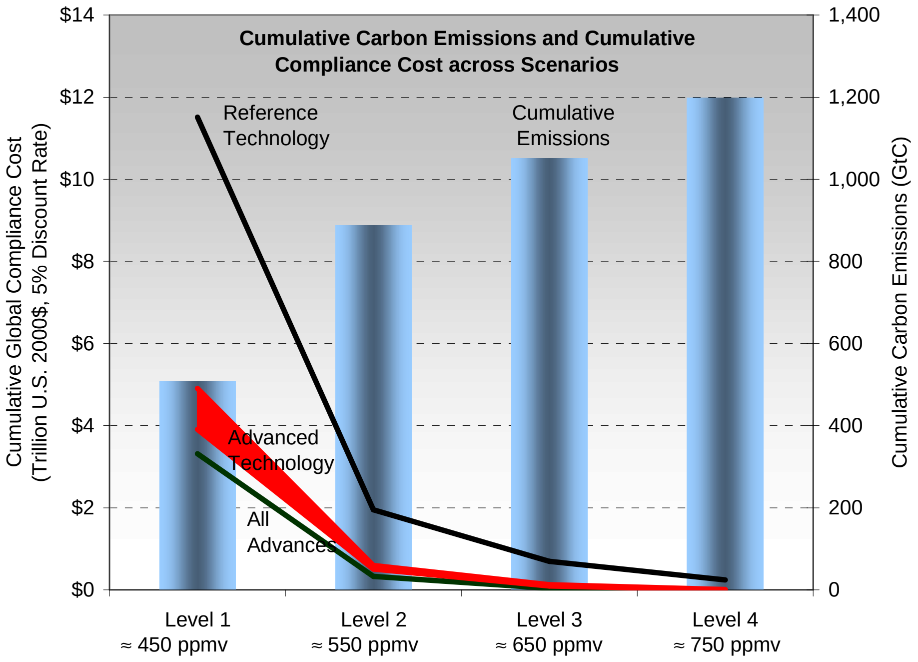


**Figure 5.12.** Cumulative global mitigation costs across scenarios, calculated using a 5% discount rate

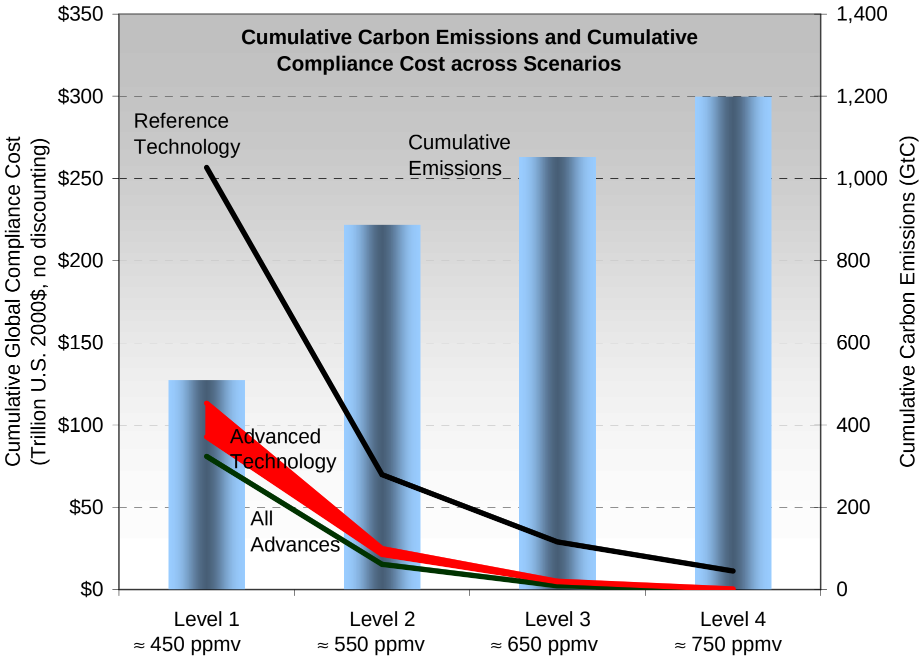


**Figure 5.13.** Cumulative global mitigation costs across scenarios, calculated using a 0% discount rate

# 6.0 Summary

This final chapter first summarizes the purpose of and approach to the scenario analysis presented in the previous chapters, and then concludes the report by placing the results of the scenario analysis into the context of the strategic goals of the U.S. Climate Change Technology Program (CCTP).

## 6.1 Summary of Purpose and Approach

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 concentrations of the greenhouse gases, which include carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$), and fluorinated gases such as halocarbons. Over the last century, global population and economic growth have been leading to increased emissions and concentrations of these 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.

To help in its strategic planning process, PNNL was asked by the CCTP to assist in a scenario analysis focused on the role of advanced technology. First, working closely with the CCTP, and aided by a review of published scenario analyses, PNNL conceived of three distinct classes of technology futures, referred to as Advanced Technology Scenarios, that could lead to lower greenhouse gas emissions. Then, working with CCTP Working Groups and technology experts, PNNL implemented illustrative examples of each of these general classes in the MiniCAM integrated assessment model by specifying a distinct set of underlying technology assumptions for each. These illustrative examples were used to illuminate the energy, economic, and emissions implications of each of the three technology futures, and of the role of technology in stabilization more generally.

Recognizing the uncertainties associated with the level of emissions reductions that might be needed to mitigate future climate-related impact, the scenario analysis was designed to examine each of the three Advanced Technology Scenarios under a range of radiative forcing and associated emissions constraints—from a constraint of 3.3 $Wm^{-2}$ (approximately equivalent to stabilization of $CO_2$ concentrations at 450 ppmv) to a constraint of 6.5 $Wm^{-2}$ (approximately equal to stabilization at 750 ppmv $CO_2$), as well as constraints of 4.5 $Wm^{-2}$ and 5.6 $Wm^{-2}$ that fell in between.

The Advanced Technology Scenarios were compared to a Reference Case—a hypothetical technological future without emissions constraints but with substantial advances in virtually all of the technological areas important for greenhouse gas emissions reductions: energy supply technologies, end-use technologies, agricultural technologies, and technologies for reducing the emissions of non-$CO_2$ greenhouse gases. Even when this technological progress is assumed to occur, energy demand and greenhouse gas emissions increase significantly by the end of the 21st century. The Reference Case provides an indication of the possible level of emissions that may occur in the absence of any actions aimed at greenhouse gas emissions mitigation and hence gives an indication of the scale of the challenge associated with stabilizing greenhouse gas concentrations. It also provides reference points to which the energy and emissions levels in the emissions-constrained scenarios can be compared.

To estimate cost savings associated with Advanced Technology Scenarios, the analysis also includes four Baseline Scenarios that simulate how the four levels of emissions constraints would be met using technologies from the Reference Case. Box 6-1 contains more detail on the 17 scenarios examined in the study (see Chapter 2 for additional information about the scenarios).

**Box 6-1**
**Scenarios Examined in the Study**

The 17 scenarios include the Reference Case and four sets of scenarios with greenhouse gas emissions constraints (each set has four different levels of emission constraint). One set of emissions-constrained scenarios (the Baseline Scenarios) assumes reference case technologies are available to meet the emissions constraints, and three sets of emissions-constrained scenarios assume advanced technologies become available. The scenarios are summarized as follows:

- A Reference Case scenario represents a hypothetical technological future, where greenhouse gas emissions are not constrained, but where significant technical improvements are achieved in a broad spectrum of currently known or available technologies for supplying and using energy. This scenario results in improvements in global greenhouse gas intensity over time, but emissions of many greenhouse gases, including $CO_2$, continue to rise over the century. This scenario provides a point of departure for exploration of the Advanced Technology Scenarios.
- A set of four Baseline Scenarios use the Reference Case technology assumptions but apply four hypothesized greenhouse gas emissions constraints. Because these scenarios require emission reductions from the Reference Case, low- or zero-emission technologies and other means to reduce greenhouse gas gases are deployed at higher rates in these baseline emission-constrained scenarios than in the Reference Case. The Baseline Scenarios provide energy and mitigation cost projections to which the energy mix and costs in the Advanced Technology Scenarios can be compared.
- Each of the three Advanced Technology Scenarios includes a distinct set of technology advancements, beyond those in the Reference Case. Each of these, in turn, is also applied under the four greenhouse gas emissions constraints (for a total of twelve Advanced Technology Scenarios). The Advanced Technology Scenarios include:

  **Closing the Loop on Carbon**, which assumes successful development of carbon capture and storage technologies for use in electricity, as well as in applications such as hydrogen and cement production.

  **New Energy Backbone**, which assumes additional technological improvement and cost reduction for carbon-free energy sources, such as wind power, solar energy systems, and nuclear power.

  **Beyond the Standard Suite**, which assumes major advances in breakthrough technologies, such as nuclear fusion, space-based solar power, or biotechnology, that can provide zero-carbon energy at competitive costs in the second half of this century.

  A number of features are common to all three Advanced Technology Scenarios, including:

    - Additional gains in energy efficiency beyond the Reference Case
    - Additional improvements in technologies for managing non-$CO_2$ greenhouse gases
    - Additional improvements in technologies for sequestering carbon in agricultural soils and pasture lands and for reforestation.

Under the assumptions used in this study, cumulative global emissions reductions over the course of the 21st century would have to be on the order of 300 GtC to 1000 GtC, including reductions in non-$CO_2$ greenhouse gases converted to equivalent units of $CO_2$, to stabilize radiative forcing from greenhouse gases at the four stabilization levels. These reductions (or avoidances) would be in addition to the emissions avoided by the substantial energy-efficiency improvements and $CO_2$-emission-free energy sources already assumed (embedded) in the Reference Case. Technology advancements could make such reductions much more feasible in the context of economic growth.

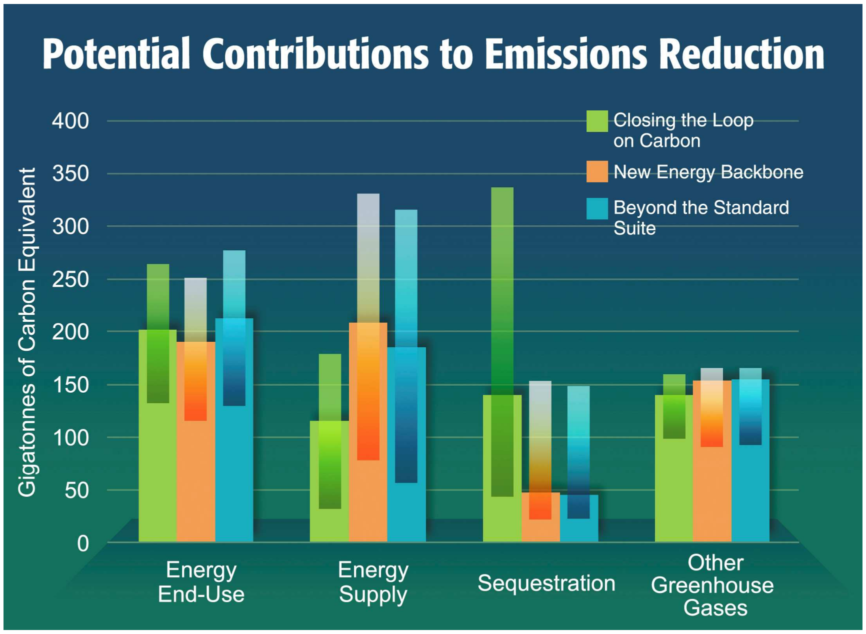
## 6.2 Scenario Results in the Context of CCTP Strategic Goals

Each of the Advanced Technology Scenarios assumes advances in particular classes of technology; however, all scenarios result in a mix of energy efficiency and energy supply technologies, as well as contributions to emissions reductions in non-$CO_2$ greenhouse gases and carbon sequestration in terrestrial systems. Given the scale of the challenge, no single technology or class of technology provides, by itself, the quantity of greenhouse gas emissions reductions needed to achieve stabilization of greenhouse gas concentrations or radiative forcing at the levels examined in this study. Instead, technological advances aimed at the following four broad areas, corresponding to four of the CCTP emissions-reduction goals (CCTP 2005), combine forces to provide the needed greenhouse gas emissions reductions:

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

Figure 6.1 and Table 6.1 show the contributions of four CCTP technology categories (directly linked to the four CCTP goals stated above) to cumulative greenhouse gas emissions reductions in the 21st century beyond the Reference Case. Based on the assumptions used in this set of scenarios, no one area was markedly more or less important than others. The cumulative 100-year emissions reductions associated with each of the four core technology areas range from 20 GtC to over 300 GtC. Note that Figure 6.1 reflects the potential reductions beyond the Reference Case, and the Reference Case already assumes significant improvements in end-use energy intensity and supply-side energy technology efficiency, including significant market penetration of carbon-free renewable and nuclear energy. This should be factored into the interpretation of the contributions shown in the figure.

Within Figure 6.1 and Table 6.1, “Energy End Use and Infrastructure” includes reductions in total primary energy use through efficiency improvements in both end-use technology (e.g., energy-consuming technology in buildings, industry, and other sectors) and energy supply (e.g., improvements in the efficiency of fossil-fueled power plants), as well as through price-induced energy conservation (i.e., as energy prices rise, energy users consume less energy). “Energy Supply” in the figure includes increases in the market penetration of carbon-free or near net-zero-emissions energy supply technologies, such as nuclear, wind, solar, and biomass, that lead to reductions in $CO_2$ emissions compared to those in the Reference Case. The “Sequestration” category includes terrestrial sequestration in forests and soils as well as carbon capture and storage. Finally, the “Other Greenhouse Gases” category includes reductions of non-$CO_2$ greenhouse gases. (Note that emissions reductions from changes in the fossil fuel mix are not included in the figure and table.)



*Note: The thick bars show the contribution in the scenarios that corresponds roughly to Level 2 (roughly 550 ppmv $CO_2$), and the thinner bars show the variation in the contribution between the most stringent constraint and the least stringent constraint.*

**Figure 6.1**. Contributions to cumulative emissions reduction between 2000 and 2100 in the Advanced Technology Scenarios corresponding to the four CCTP goals

**Table 6.1**. Contributions to cumulative emissions reduction between 2000 and 2100 in the Advanced Technology Scenarios corresponding to the four CCTP goals

| **CCTP Strategic Goal** | ***Most Stringent Constraint*: Level 1 (3.3 $Wm^{-2}$)** | **Level 2 (4.5 $Wm^{-2}$)** | **Level 3 (5.6 $Wm^{-2}$)** | ***Least Stringent Constraint*: Level 4 (6.5 $Wm^{-2}$)** |
|---|---|---|---|---|
| Goal #1. Reduce Emissions from Energy End Use & Infrastructure | 250 - 270 | 190 - 210 | 150 - 170 | 110 - 130 |
| Goal #2. Reduce Emissions from Energy Supply | 180 - 330 | 110 - 210 | 80 - 140 | 30 - 80 |
| Goal #3. Capture and Sequester Carbon Dioxide | 150 - 330 | 50 - 140 | 30 - 70 | 20 - 40 |
| Goal #4. Reduce Emissions of Non-$CO_2$ Greenhouse Gases | 160 - 170 | 140 - 150 | 120 - 130 | 90 - 100 |

An important implication of the scenarios is that substantial roles for each of these CCTP goals are plausible for a variety of technologies across a wide range of futures. Future technological advances cannot be predicted today, so any number of technologies may take on substantial future roles, depending on how well they progress. Furthermore, even if a single technology were to make dramatic leaps forward, the magnitude and complexity of the climate change challenge likely would allow for substantial contributions from a variety of technologies. For example, a future that includes significant penetration of $CO_2$ capture and storage does not necessarily imply a minimal role for nuclear and renewable energy, and a future that transitions to nuclear and/or renewable energy does not necessarily mean an end to the use of fossil fuels over the remainder of the century. Regardless of the primary energy mix, there are important opportunities to reduce energy consumption, directly sequester carbon from the atmosphere, and manage the emissions of the non-$CO_2$ greenhouse gases.

The Advanced Technology Scenarios also illustrate the strong contributions advanced technologies can make toward lowering greenhouse gas emissions and the associated costs. In fact, the specific cases modeled suggest that accelerated technology development offers the potential to reduce the cost of stabilization by hundreds of billions to trillions of dollars globally. This is illustrated in Figure 6.2, which presents the results of the comparative analysis of the cumulative, undiscounted costs of greenhouse gas mitigation over the course of the 21st century, with and without the accelerated advances in technology, across the range of Advanced Technology Scenarios and variously greenhouse gas emissions constraints. (Note: this figure is based on Figure 5.10 in Chapter 5.) The relative cost reductions are significant in all cases. As one would expect, the absolute cost reductions are more significant under the higher emissions constraints. (Note that cumulative costs have been added without discounting in the figure; see Chapter 5 for discussion of the costs under a 5% discount rate).

The analysis also provides insight into the potential requirements for the timing of commercial readiness of advanced technology to meet stabilization goals. A summary of the timing of the first GtC/yr of emissions reductions below the Reference Case, shown by CCTP strategic goal, is presented in Table 6.2. In general, the higher the emissions constraint, the sooner the advanced technologies are needed and deployed. Under the most stringent emissions constraint, emissions reductions occur within a matter of decades. Allowing for capital stock turnover and other inertia inherent in the global energy system and infrastructure, technologies with low or near-zero net emissions characteristics would need to be available and moving into the marketplace years before the periods shown on Table 6.2.

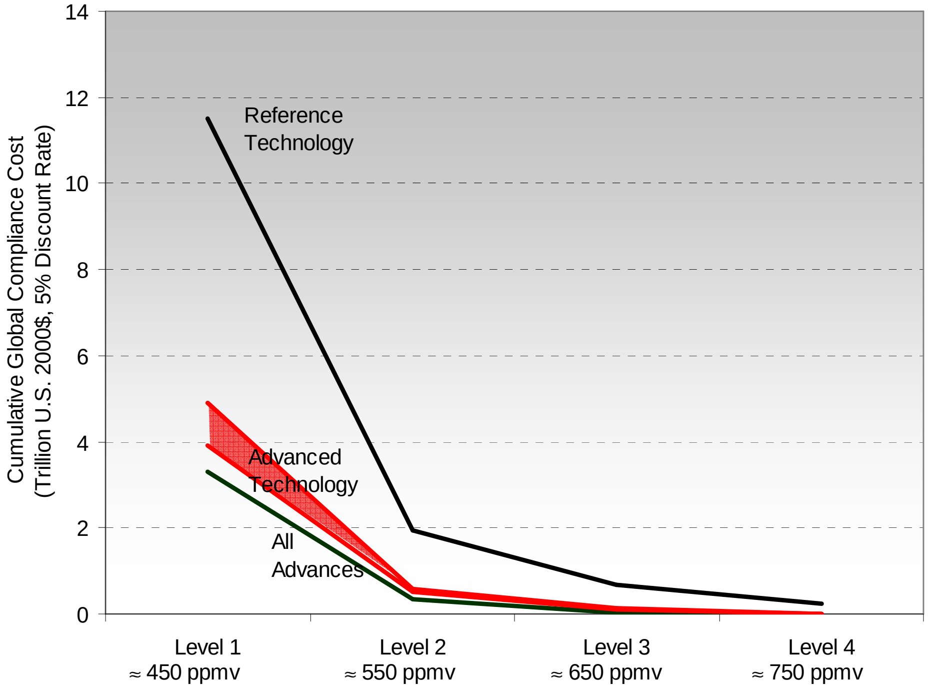


**Figure 6.2**. Cumulative costs of emissions reduction over the 21st Century with and without advanced technology

**Table 6.2**. Estimated timing of the first GtC/yr of avoided emissions for Advanced Technology Scenarios

| **CCTP Strategic Goal** | ***Most Strigent Constraint*: Level 1 (3.3 Wm$^{-2}$)** | **Level 2 (4.5 Wm$^{-2}$)** | **Level 3 (5.6 Wm$^{-2}$)** | ***Least Stringent Constraint*: Level 4 (6.5 Wm$^{-2}$)** |
|---|---|---|---|---|
| Goal #1. Reduce Emissions from Energy End Use & Infrastructure | 2010 - 2020 | 2030 - 2040 | 2030 - 2050 | 2040 - 2060 |
| Goal #2. Reduce Emissions from Energy Supply | 2020 -2040 | 2040 - 2060 | 2050 - 2070 | 2060 - 2100 |
| Goal #3. Capture and Sequester Carbon Dioxide | 2020 - 2050 | 2040 or Later | 2060 or Later | Beyond 2100 |
| Goal #4. Reduce Emissions of Non-$CO_2$ Greenhouse Gases | 2020 - 2030 | 2050 - 2060 | 2050 - 2060 | 2070 - 2080 |

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# Appendix A:  Supporting Figures

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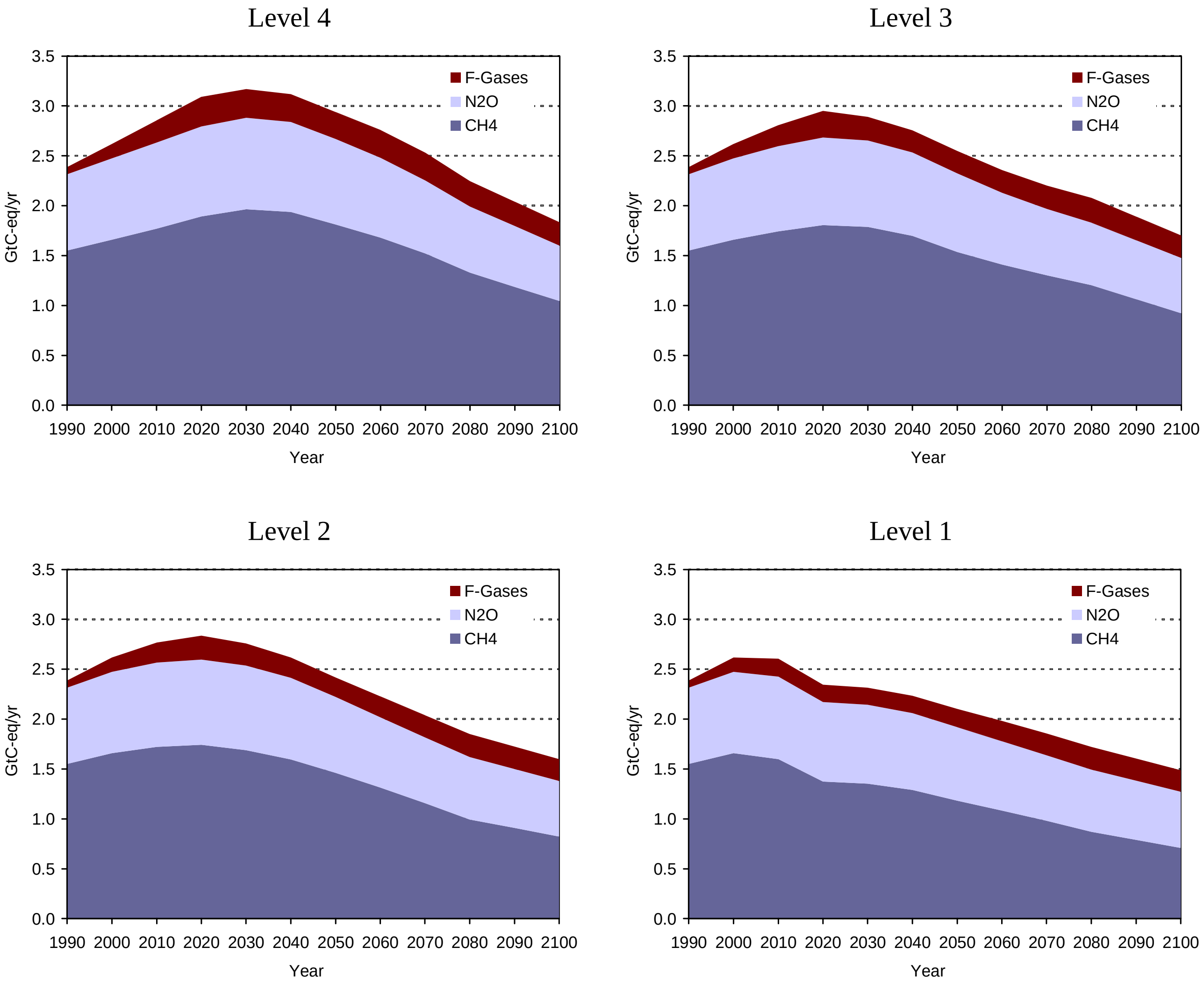

Level 4

Level 3

Level 2

Level 1

**Figure A.1**. Non-$CO_2$ greenhouse gas emissions by scenario, converted to carbon equivalents using global warming potentials

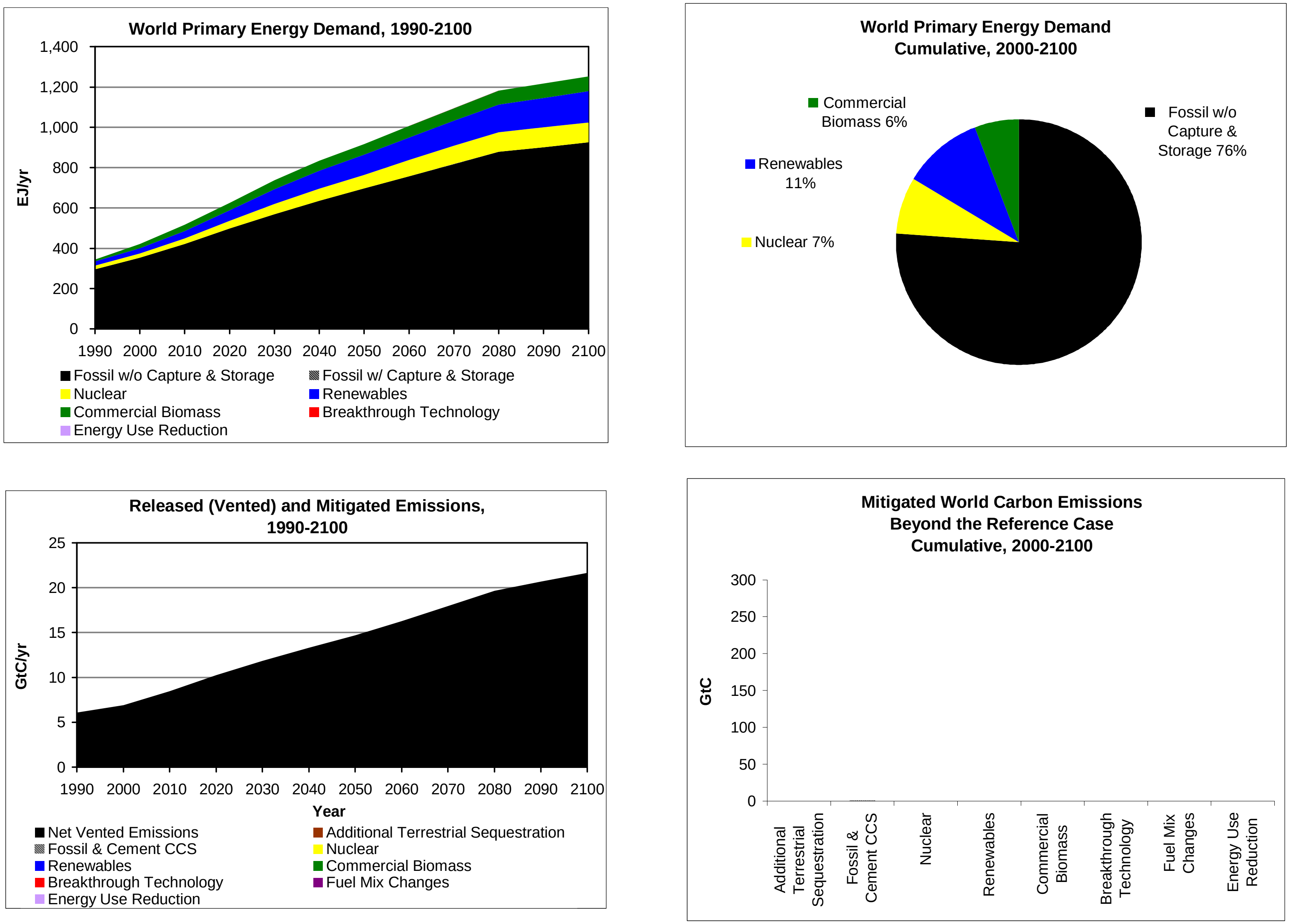


**Figure A.2**. The Reference Case

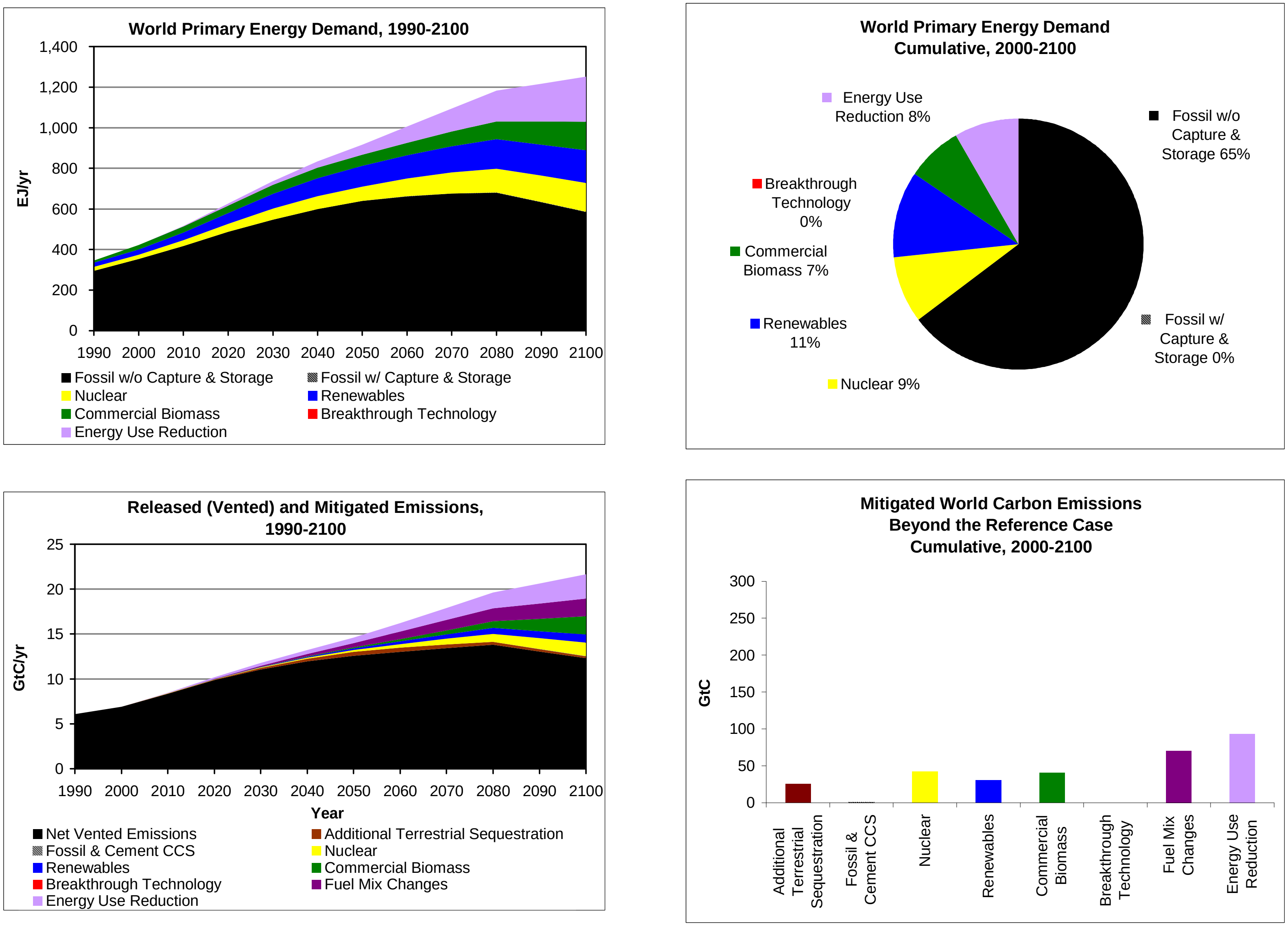


**Figure A.3**. Baseline Scenario, Level 4

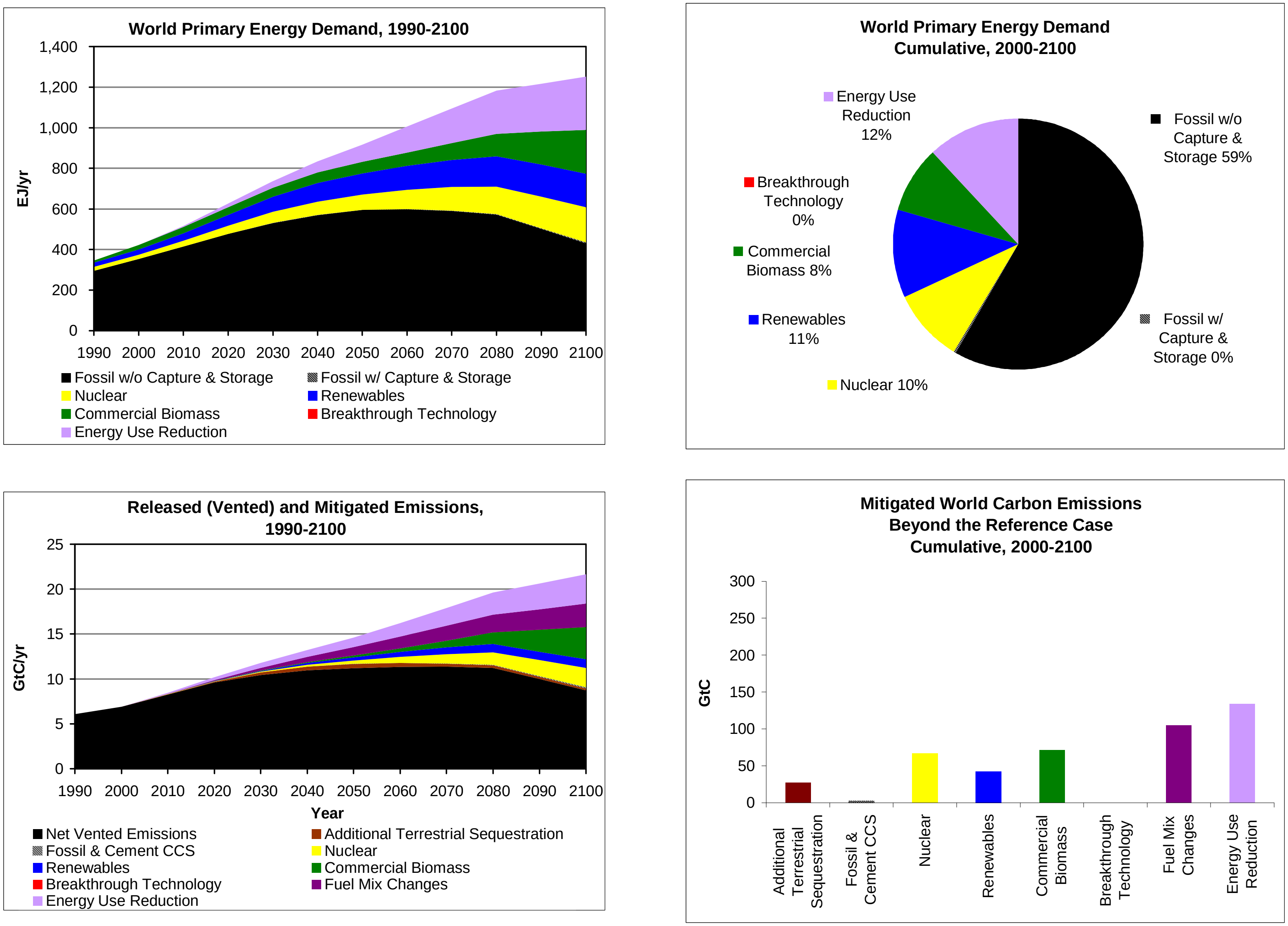


**Figure A.4**. Baseline Scenario, Level 3

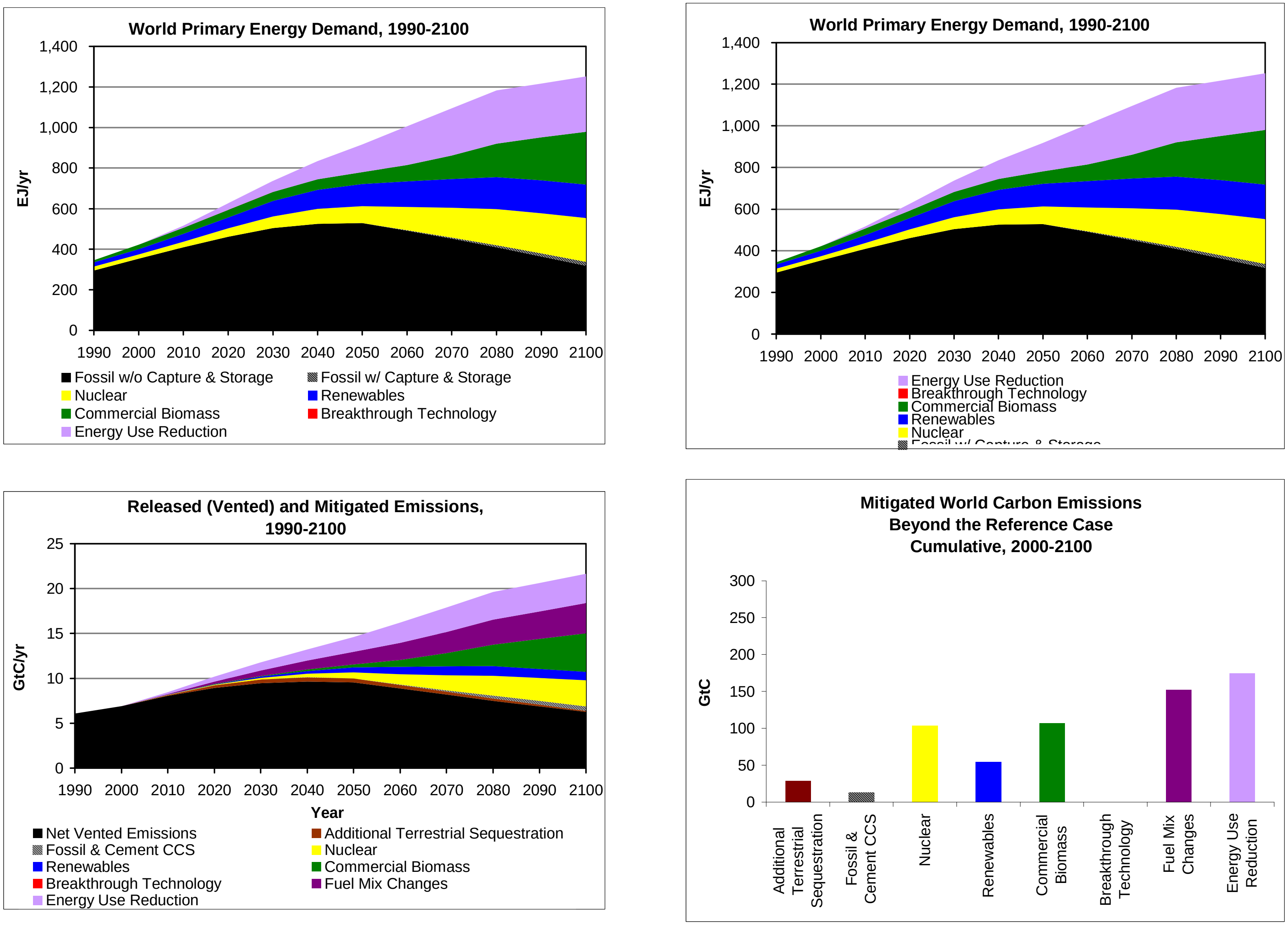


**Figure A.5.** Baseline Scenario, Level 2

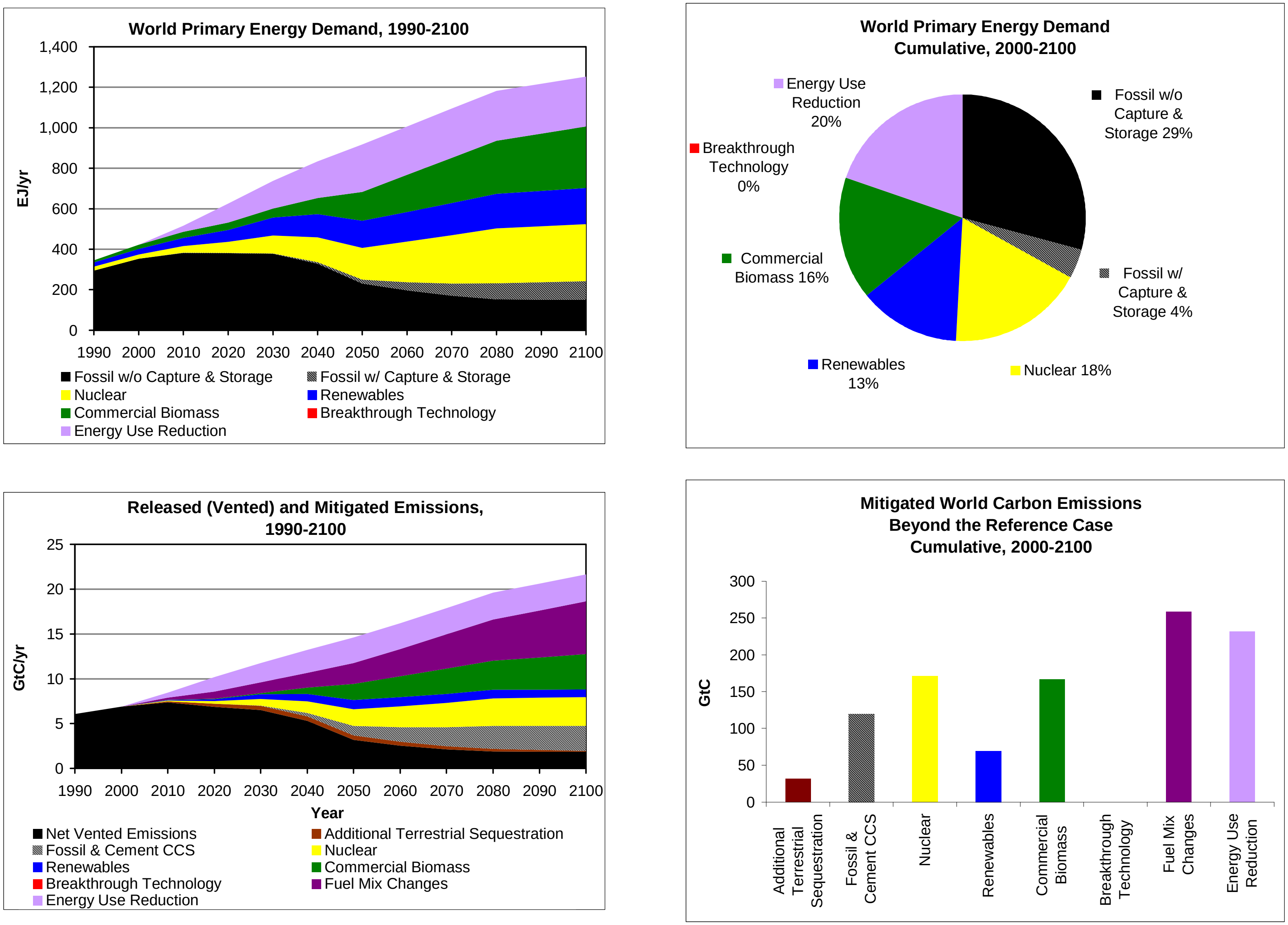


**Figure A.6.** Baseline Scenario, Level 1

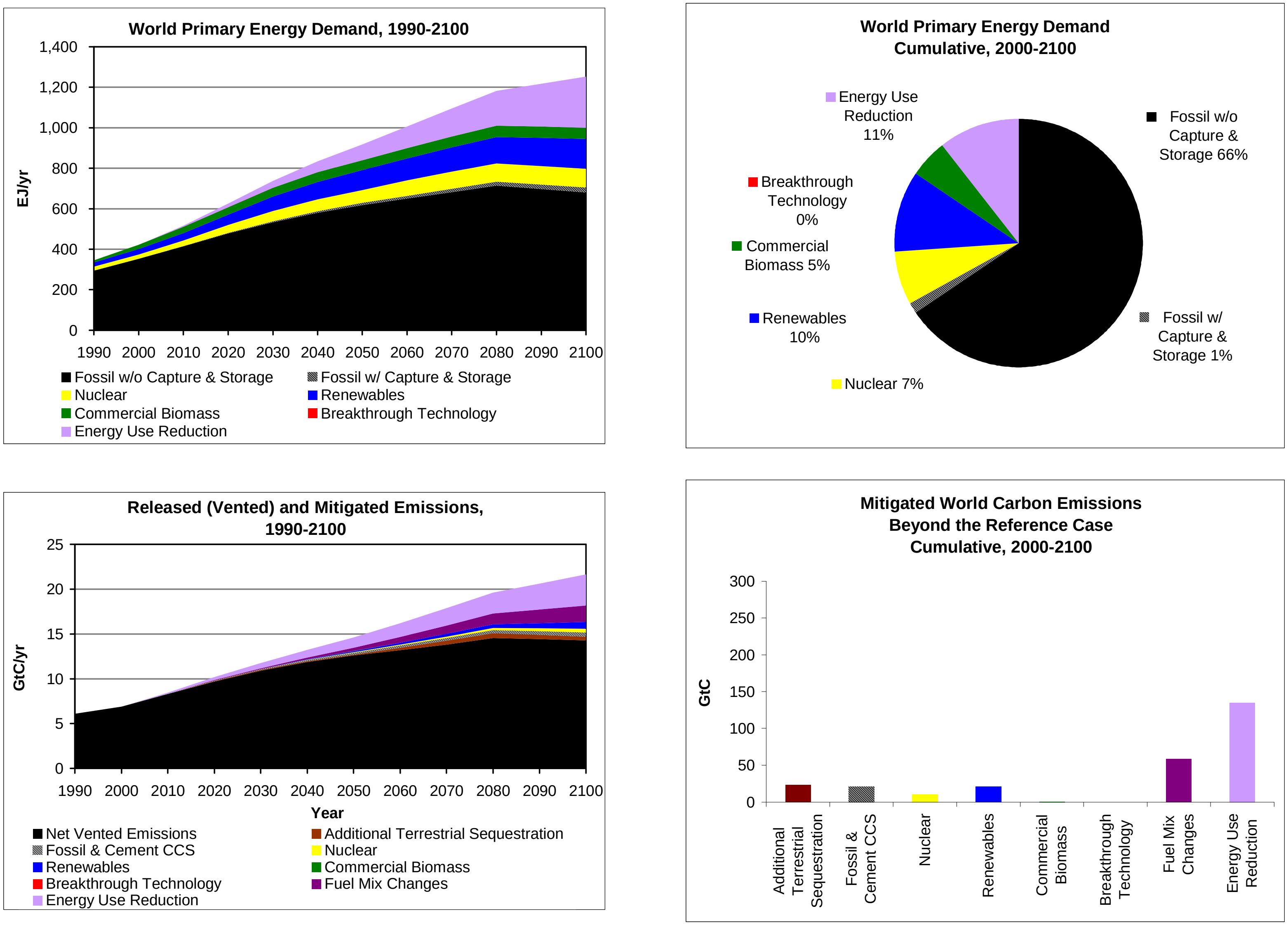


**Figure A.7.** Closing the Loop on Carbon, Level 4

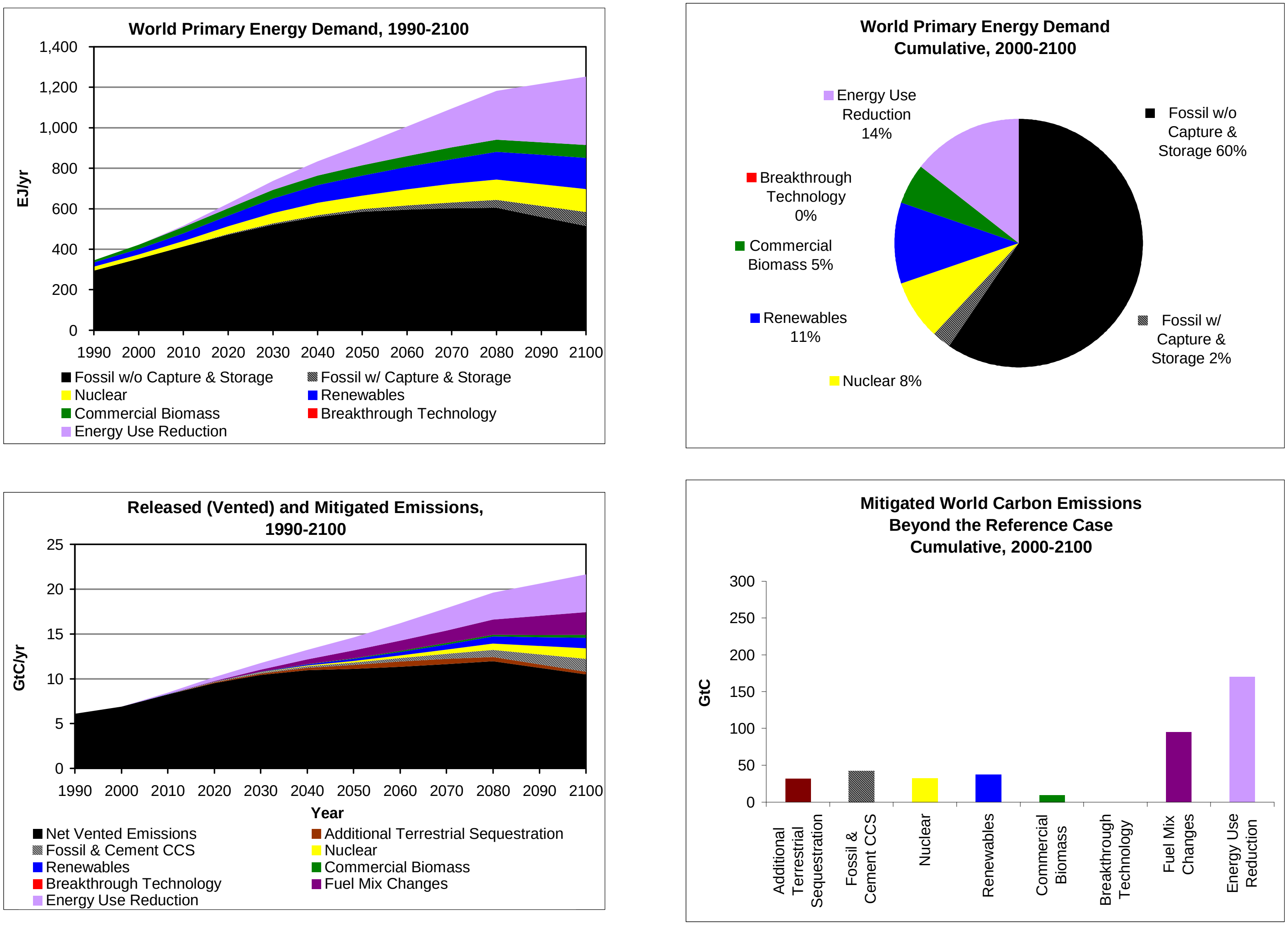


**Figure A.8**. Closing the Loop on Carbon, Level 3

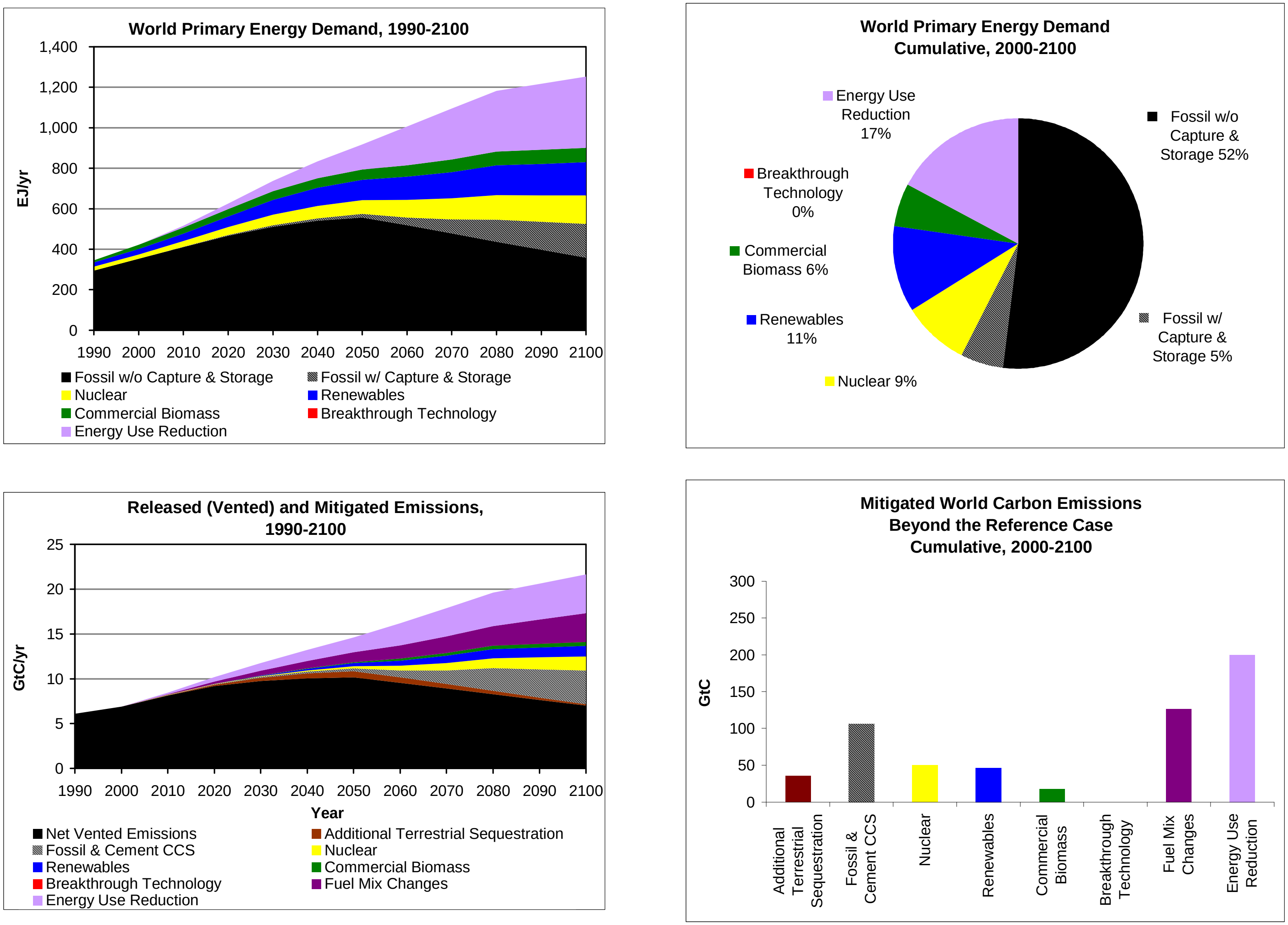


**Figure A.9**. Closing the Loop on Carbon, Level 2

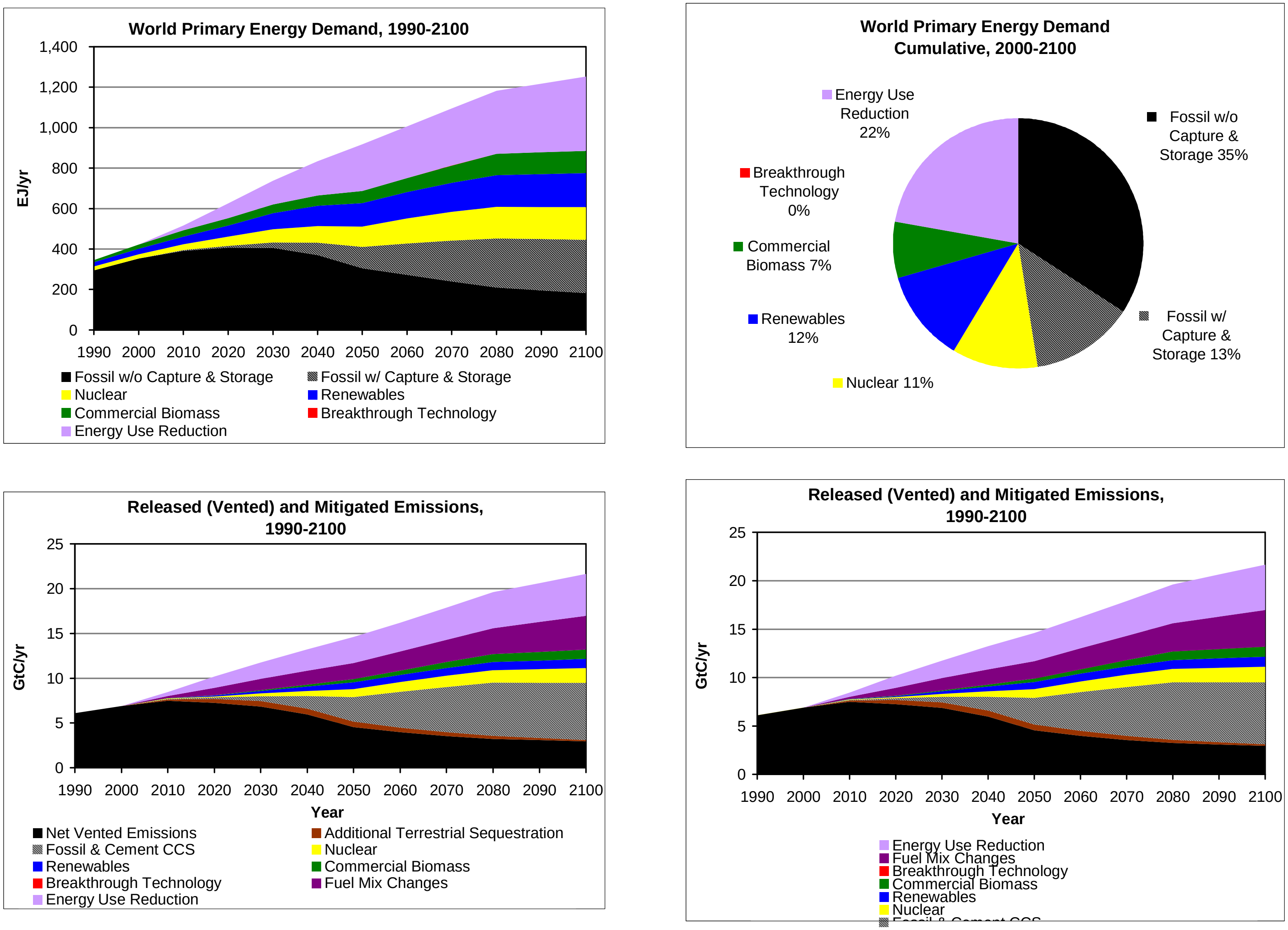
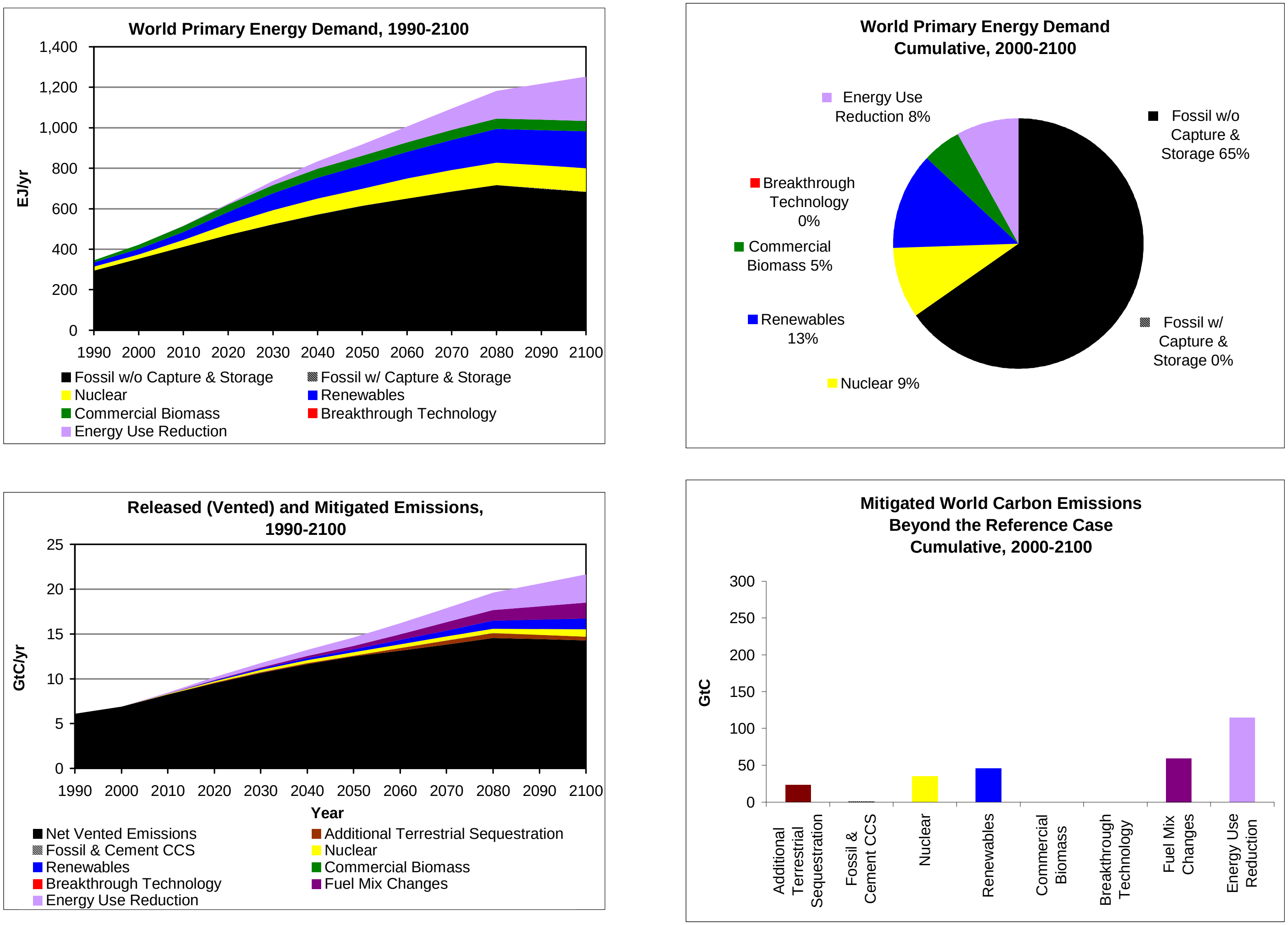


**Figure A.10**. Closing the Loop on Carbon, Level 1



World Primary Energy Demand, 1990-2100

World Primary Energy Demand Cumulative, 2000-2100

Released (Vented) and Mitigated Emissions, 1990-2100

Mitigated World Carbon Emissions Beyond the Reference Case Cumulative, 2000-2100

**Figure A.11**. New Energy Backbone, Level 4

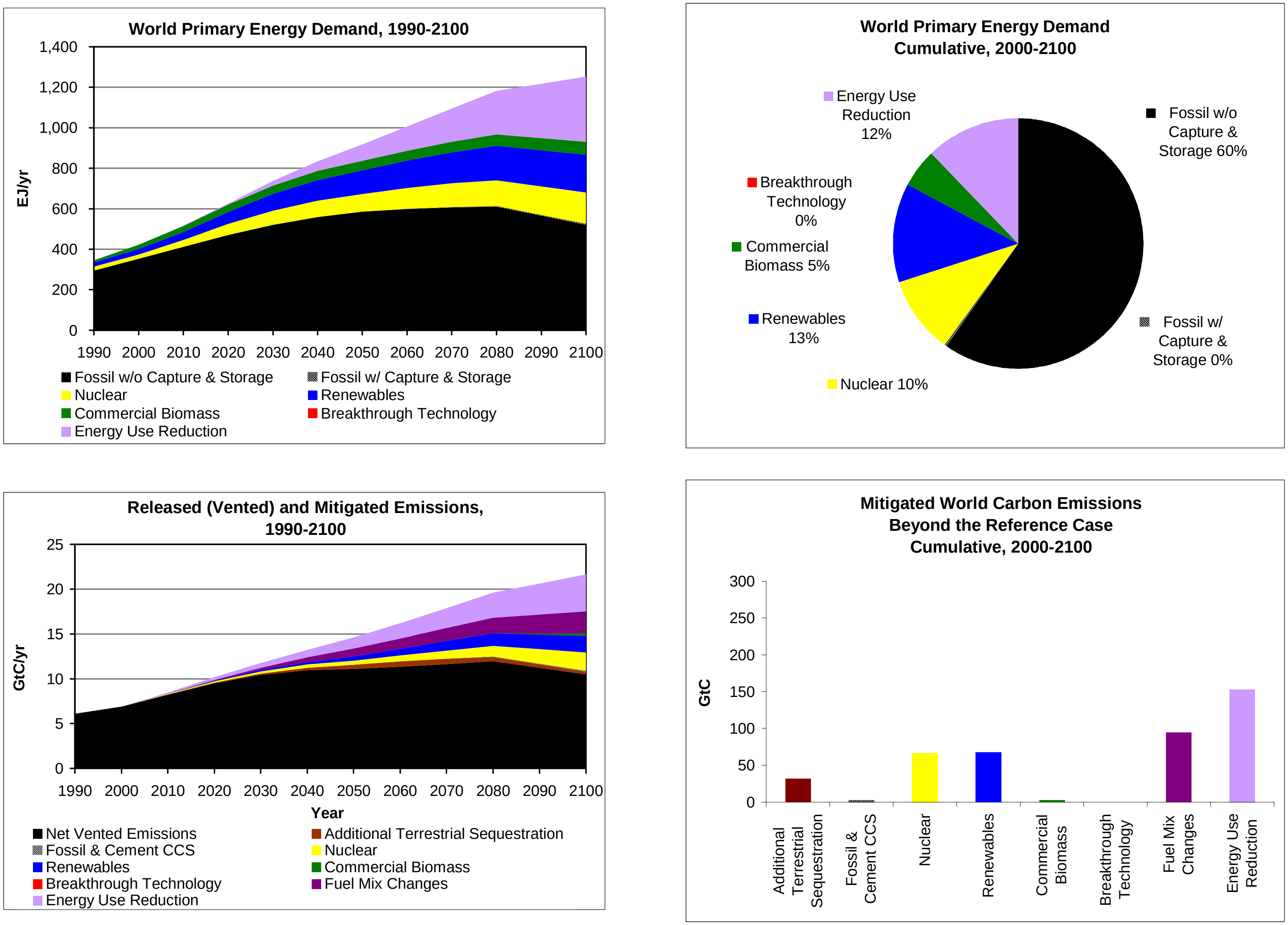


**Figure A.12**. New Energy Backbone, Level 3

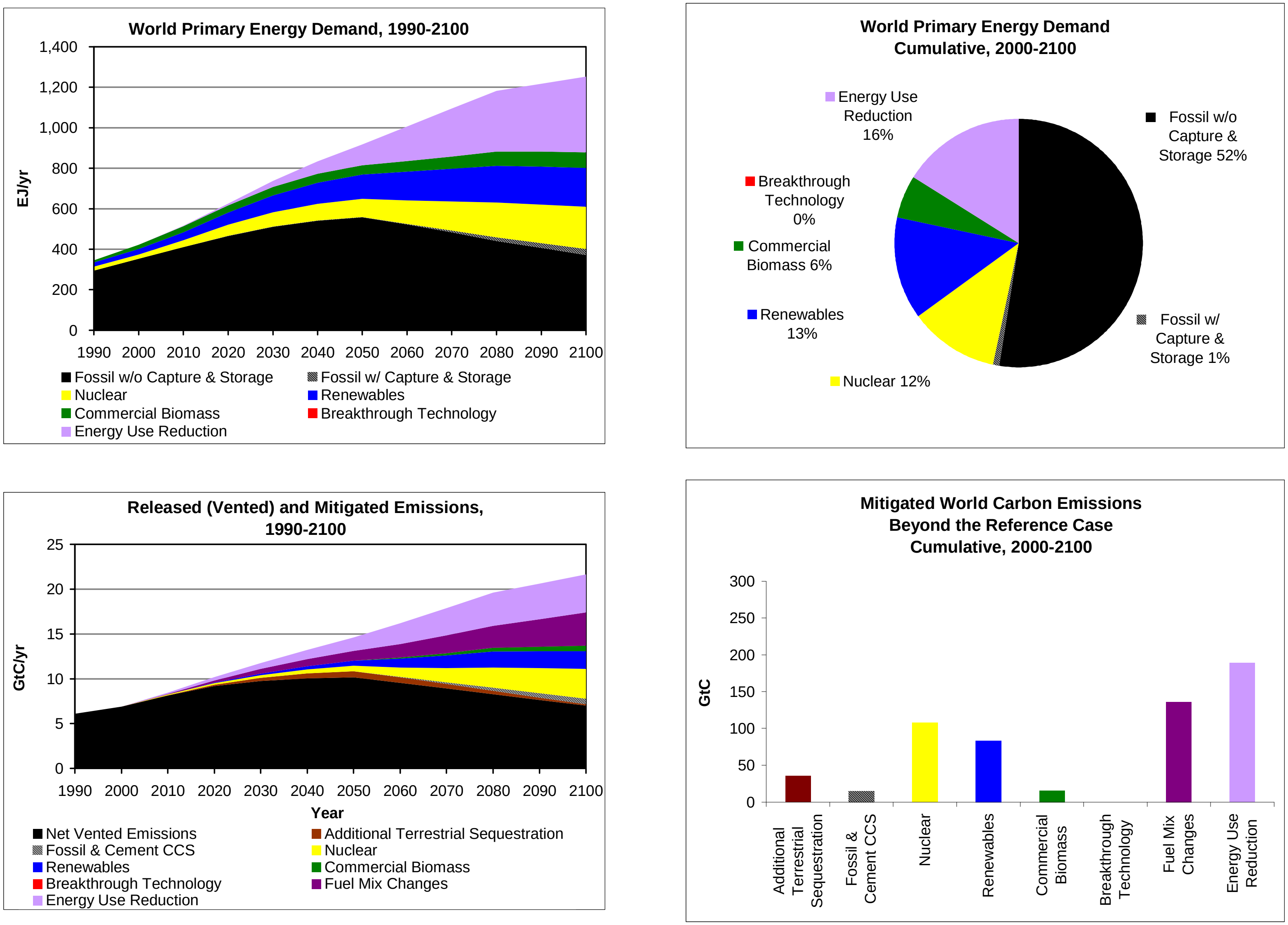


**Figure A.13**. New Energy Backbone, Level 2

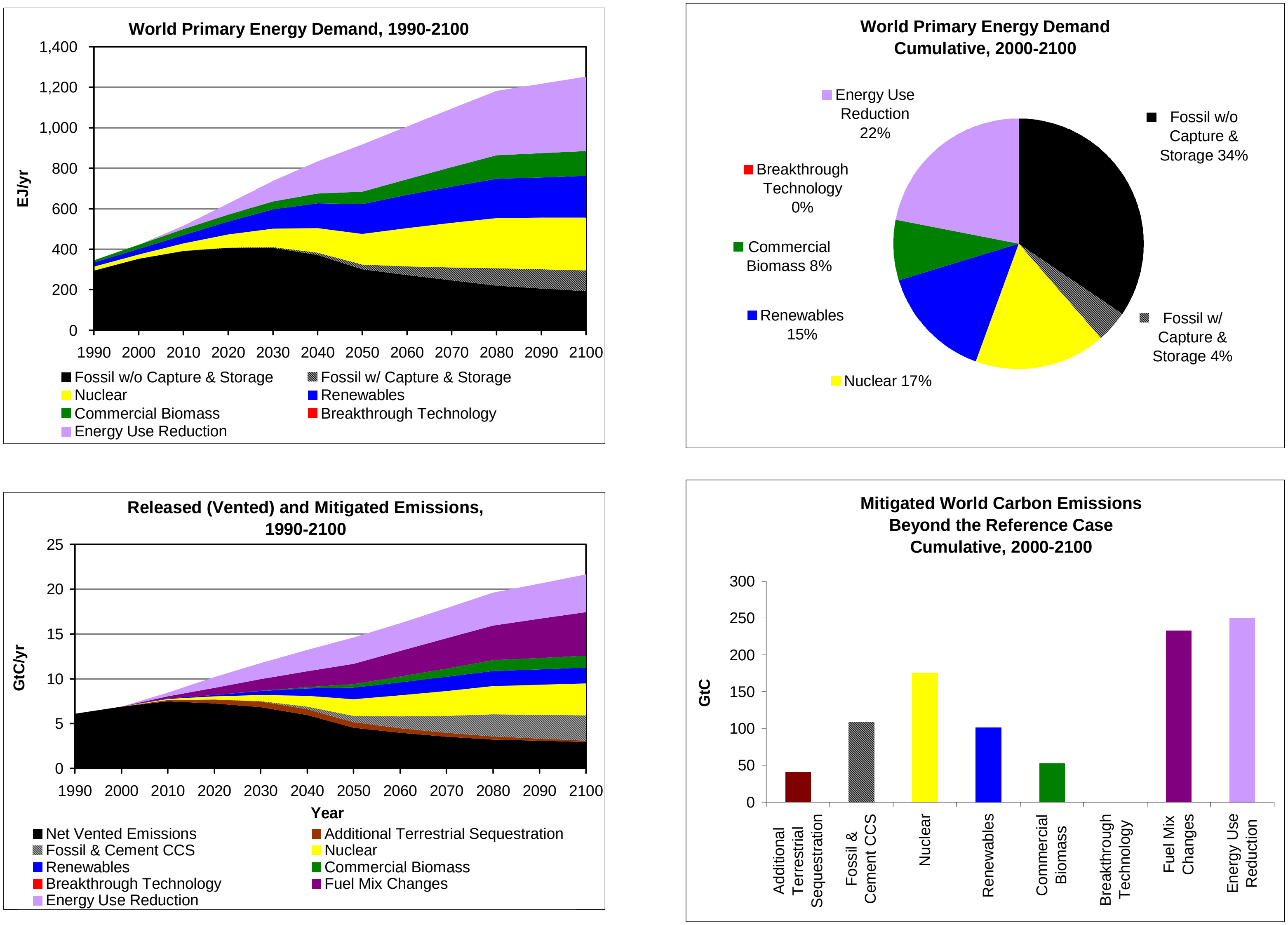


**Figure A.14**. New Energy Backbone, Level 1

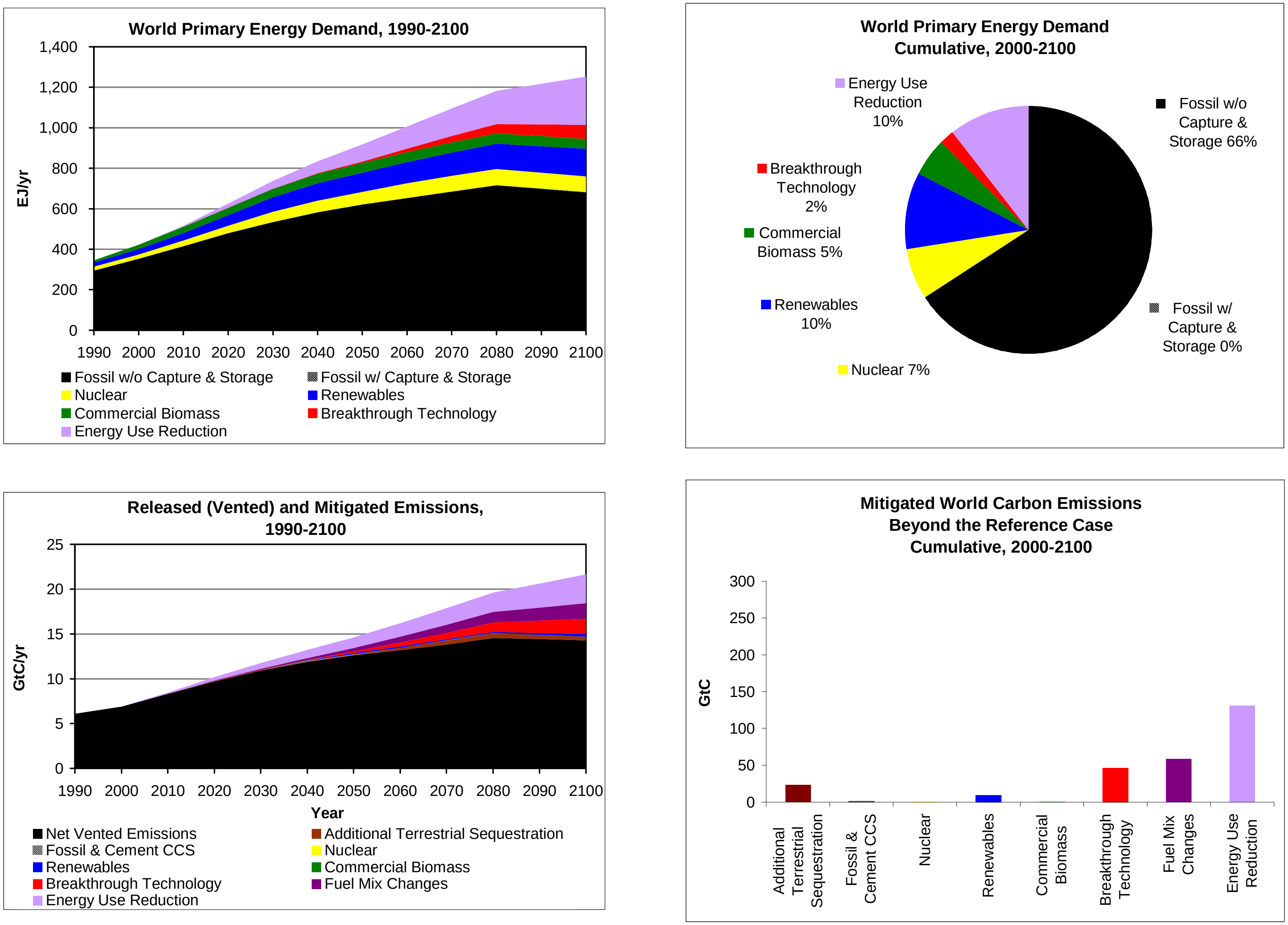


**Figure A.15**. Beyond the Standard Suite, Level 4

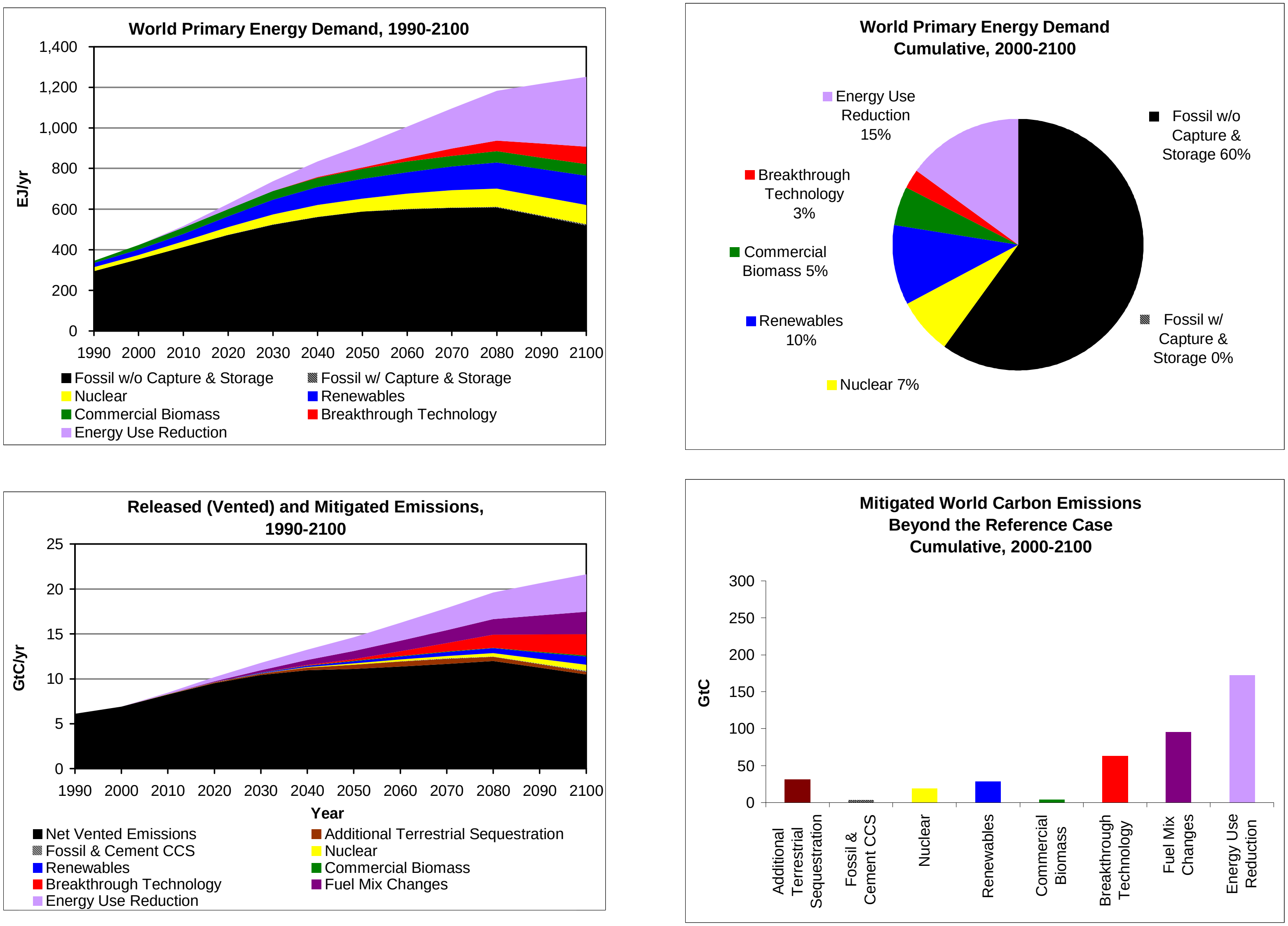


**Figure A.16**. Beyond the Standard Suite, Level 3

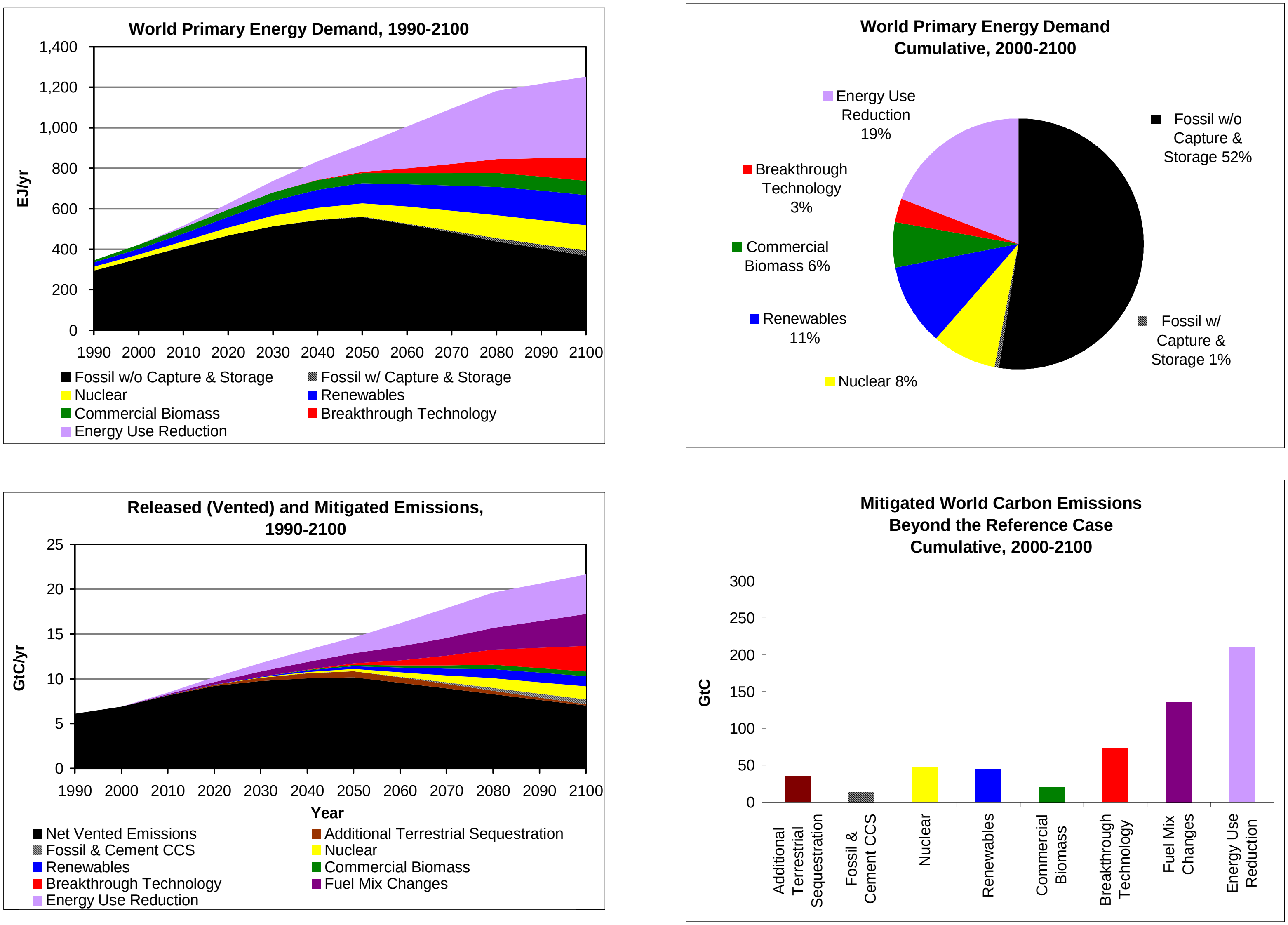


**Figure A.17**. Beyond the Standard Suite, Level 2

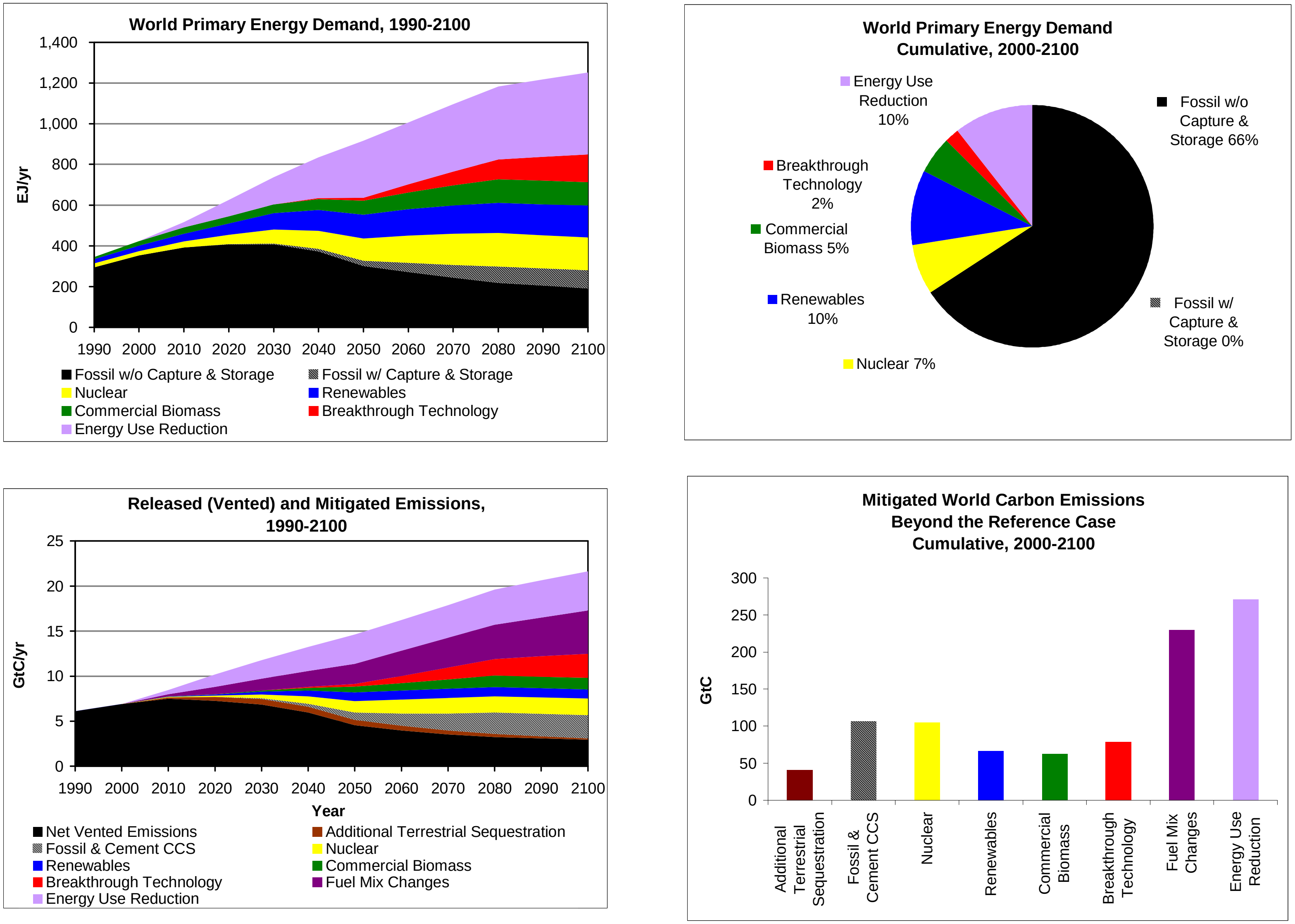


**Figure A.18.** Beyond the Standard Suite, Level 1

# Appendix B: Scenario Summary Data

# Appendix B:  Scenario Summary Data

## Annual Primary Energy (EJ/yr):  Reference Case

| | 1990 | 2000 | 2010 | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 | 2080 | 2090 | 2100 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fossil w/o Capture & Storage | 295 | 353 | 421 | 498 | 569 | 636 | 698 | 758 | 818 | 878 | 902 | 925 |
| Fossil w/ Capture & Storage | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Nuclear | 19 | 21 | 28 | 38 | 51 | 60 | 66 | 80 | 91 | 97 | 98 | 99 |
| Renewables | 21 | 26 | 37 | 53 | 73 | 89 | 101 | 111 | 124 | 138 | 146 | 155 |
| Commercial Biomass | 10 | 22 | 31 | 37 | 44 | 50 | 53 | 57 | 62 | 69 | 71 | 73 |
| Breakthrough Technology | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Energy Use Reduction | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Total | 345 | 422 | 517 | 626 | 738 | 834 | 917 | 1,007 | 1,095 | 1,182 | 1,217 | 1,252 |

## Annual Emissions & Emissions Reductions (GtC/yr):  Reference Case

| | 1990 | 2000 | 2010 | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 | 2080 | 2090 | 2100 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Net Vented Emissions | 6.1 | 6.9 | 8.5 | 10.3 | 11.8 | 13.3 | 14.7 | 16.3 | 17.9 | 19.7 | 20.7 | 21.7 |
| Additional Terrestrial Sequestration | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Fossil & Cement CCS | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Nuclear | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Renewables | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Commercial Biomass | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Breakthrough Technology | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Fuel Mix Changes | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Energy Use Reduction | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Total | 6.1 | 6.9 | 8.5 | 10.3 | 11.8 | 13.3 | 14.7 | 16.3 | 17.9 | 19.7 | 20.7 | 21.7 |

### Annual Primary Energy (EJ/yr): Baseline Level 4

| | 1990 | 2000 | 2010 | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 | 2080 | 2090 | 2100 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fossil w/o Capture & Storage | 295 | 353 | 417 | 487 | 548 | 599 | 640 | 662 | 676 | 680 | 633 | 585 |
| Fossil w/ Capture & Storage | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 2 |
| Nuclear | 19 | 21 | 28 | 39 | 53 | 63 | 71 | 88 | 104 | 117 | 130 | 141 |
| Renewables | 21 | 26 | 37 | 53 | 74 | 90 | 103 | 115 | 129 | 145 | 154 | 162 |
| Commercial Biomass | 10 | 22 | 31 | 37 | 45 | 50 | 55 | 61 | 72 | 88 | 114 | 140 |
| Breakthrough Technology | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Energy Use Reduction | 0 | 0 | 3 | 9 | 18 | 32 | 50 | 80 | 114 | 151 | 186 | 223 |
| Total | 345 | 422 | 517 | 626 | 738 | 834 | 917 | 1,007 | 1,095 | 1,182 | 1,217 | 1,252 |

### Annual Emissions & Emissions Reductions (GtC/yr): Baseline Level 4

| | 1990 | 2000 | 2010 | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 | 2080 | 2090 | 2100 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Net Vented Emissions | 6.1 | 6.9 | 8.4 | 9.9 | 11.0 | 11.9 | 12.6 | 13.0 | 13.4 | 13.8 | 13.1 | 12.3 |
| Additional Terrestrial Sequestration | 0.0 | 0.0 | 0.0 | 0.1 | 0.2 | 0.3 | 0.4 | 0.4 | 0.4 | 0.3 | 0.3 | 0.2 |
| Fossil & Cement CCS | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Nuclear | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.2 | 0.4 | 0.6 | 0.9 | 1.2 | 1.5 |
| Renewables | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.2 | 0.3 | 0.5 | 0.7 | 0.8 | 0.9 |
| Commercial Biomass | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 0.2 | 0.4 | 0.8 | 1.4 | 2.0 |
| Breakthrough Technology | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Fuel Mix Changes | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 0.3 | 0.5 | 0.8 | 1.2 | 1.4 | 1.7 | 2.0 |
| Energy Use Reduction | 0.0 | 0.0 | 0.1 | 0.2 | 0.3 | 0.5 | 0.6 | 1.0 | 1.3 | 1.8 | 2.2 | 2.7 |
| Total | 6.1 | 6.9 | 8.5 | 10.2 | 11.8 | 13.2 | 14.6 | 16.2 | 17.9 | 19.6 | 20.6 | 21.6 |

## Annual Primary Energy (EJ/yr): Baseline Level 3

| | 1990 | 2000 | 2010 | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 | 2080 | 2090 | 2100 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fossil w/o Capture & Storage | 295 | 353 | 414 | 477 | 531 | 570 | 595 | 598 | 590 | 572 | 501 | 430 |
| Fossil w/ Capture & Storage | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 2 | 4 | 6 |
| Nuclear | 19 | 21 | 28 | 40 | 55 | 66 | 75 | 96 | 117 | 136 | 156 | 173 |
| Renewables | 21 | 26 | 37 | 53 | 75 | 92 | 105 | 118 | 134 | 150 | 158 | 165 |
| Commercial Biomass | 10 | 22 | 31 | 37 | 45 | 51 | 56 | 65 | 83 | 110 | 163 | 216 |
| Breakthrough Technology | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Energy Use Reduction | 0 | 0 | 6 | 18 | 33 | 55 | 86 | 128 | 170 | 213 | 236 | 263 |
| Total | 345 | 422 | 517 | 626 | 738 | 834 | 917 | 1,007 | 1,095 | 1,182 | 1,217 | 1,252 |

## Annual Emissions & Emissions Reductions (GtC/yr): Baseline Level 3

| | 1990 | 2000 | 2010 | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 | 2080 | 2090 | 2100 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Net Vented Emissions | 6.1 | 6.9 | 8.3 | 9.6 | 10.4 | 11.0 | 11.2 | 11.3 | 11.4 | 11.2 | 10.0 | 8.7 |
| Additional Terrestrial Sequestration | 0.0 | 0.0 | 0.0 | 0.1 | 0.3 | 0.4 | 0.5 | 0.4 | 0.4 | 0.3 | 0.2 | 0.2 |
| Fossil & Cement CCS | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 |
| Nuclear | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.2 | 0.4 | 0.7 | 1.0 | 1.4 | 1.8 | 2.2 |
| Renewables | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.2 | 0.3 | 0.6 | 0.7 | 0.9 | 0.9 | 1.0 |
| Commercial Biomass | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.2 | 0.4 | 0.8 | 1.3 | 2.5 | 3.6 |
| Breakthrough Technology | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Fuel Mix Changes | 0.0 | 0.0 | 0.0 | 0.1 | 0.3 | 0.6 | 1.0 | 1.3 | 1.7 | 1.9 | 2.3 | 2.6 |
| Energy Use Reduction | 0.0 | 0.0 | 0.1 | 0.3 | 0.5 | 0.8 | 1.1 | 1.5 | 2.0 | 2.5 | 2.9 | 3.3 |
| Total | 6.1 | 6.9 | 8.5 | 10.2 | 11.8 | 13.2 | 14.6 | 16.2 | 17.9 | 19.6 | 20.6 | 21.6 |

## Annual Primary Energy (EJ/yr): Baseline Level 2

| | 1990 | 2000 | 2010 | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 | 2080 | 2090 | 2100 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fossil w/o Capture & Storage | 295 | 353 | 409 | 461 | 504 | 526 | 528 | 491 | 452 | 409 | 363 | 318 |
| Fossil w/ Capture & Storage | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 6 | 11 | 15 | 20 |
| Nuclear | 19 | 21 | 29 | 42 | 58 | 72 | 84 | 115 | 147 | 178 | 198 | 215 |
| Renewables | 21 | 26 | 38 | 54 | 76 | 95 | 109 | 126 | 143 | 158 | 162 | 165 |
| Commercial Biomass | 10 | 22 | 31 | 37 | 45 | 52 | 59 | 80 | 115 | 164 | 213 | 262 |
| Breakthrough Technology | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Energy Use Reduction | 0 | 0 | 11 | 32 | 55 | 89 | 137 | 192 | 234 | 262 | 266 | 273 |
| Total | 345 | 422 | 517 | 626 | 738 | 834 | 917 | 1,007 | 1,095 | 1,182 | 1,217 | 1,252 |

## Annual Emissions & Emissions Reductions (GtC/yr): Baseline Level 2

| | 1990 | 2000 | 2010 | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 | 2080 | 2090 | 2100 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Net Vented Emissions | 6.1 | 6.9 | 8.0 | 9.0 | 9.5 | 9.7 | 9.5 | 8.9 | 8.2 | 7.5 | 6.9 | 6.2 |
| Additional Terrestrial Sequestration | 0.0 | 0.0 | 0.1 | 0.3 | 0.4 | 0.5 | 0.5 | 0.4 | 0.3 | 0.2 | 0.2 | 0.1 |
| Fossil & Cement CCS | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 |
| Nuclear | 0.0 | 0.0 | 0.0 | 0.1 | 0.2 | 0.4 | 0.7 | 1.1 | 1.7 | 2.2 | 2.6 | 2.9 |
| Renewables | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.3 | 0.5 | 0.8 | 1.0 | 1.1 | 1.0 | 0.9 |
| Commercial Biomass | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.2 | 0.3 | 0.8 | 1.4 | 2.4 | 3.3 | 4.3 |
| Breakthrough Technology | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Fuel Mix Changes | 0.0 | 0.0 | 0.1 | 0.3 | 0.6 | 1.0 | 1.4 | 1.9 | 2.4 | 2.8 | 3.1 | 3.4 |
| Energy Use Reduction | 0.0 | 0.0 | 0.2 | 0.6 | 0.9 | 1.3 | 1.7 | 2.3 | 2.7 | 3.1 | 3.2 | 3.3 |
| Total | 6.1 | 6.9 | 8.5 | 10.2 | 11.8 | 13.2 | 14.6 | 16.2 | 17.9 | 19.6 | 20.6 | 21.6 |

## Annual Primary Energy (EJ/yr): Baseline Level 1

| | 1990 | 2000 | 2010 | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 | 2080 | 2090 | 2100 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fossil w/o Capture & Storage | 295 | 353 | 382 | 381 | 378 | 327 | 230 | 196 | 170 | 151 | 151 | 151 |
| Fossil w/ Capture & Storage | 0 | 0 | 0 | 0 | 2 | 9 | 21 | 40 | 60 | 81 | 87 | 92 |
| Nuclear | 19 | 21 | 34 | 55 | 87 | 122 | 156 | 201 | 239 | 271 | 276 | 281 |
| Renewables | 21 | 26 | 40 | 60 | 90 | 115 | 134 | 147 | 159 | 170 | 174 | 178 |
| Commercial Biomass | 10 | 22 | 31 | 36 | 44 | 79 | 143 | 184 | 223 | 261 | 283 | 305 |
| Breakthrough Technology | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Energy Use Reduction | 0 | 0 | 31 | 94 | 137 | 182 | 234 | 239 | 244 | 247 | 246 | 246 |
| Total | 345 | 422 | 517 | 626 | 738 | 834 | 917 | 1,007 | 1,095 | 1,182 | 1,217 | 1,252 |

## Annual Emissions & Emissions Reductions (GtC/yr): Baseline Level 1

| | 1990 | 2000 | 2010 | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 | 2080 | 2090 | 2100 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Net Vented Emissions | 6.1 | 6.9 | 7.4 | 6.9 | 6.5 | 5.3 | 3.2 | 2.6 | 2.1 | 1.9 | 1.9 | 1.8 |
| Additional Terrestrial Sequestration | 0.0 | 0.0 | 0.1 | 0.3 | 0.4 | 0.5 | 0.5 | 0.4 | 0.4 | 0.3 | 0.2 | 0.1 |
| Fossil & Cement CCS | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.4 | 1.1 | 1.6 | 2.1 | 2.6 | 2.7 | 2.8 |
| Nuclear | 0.0 | 0.0 | 0.1 | 0.3 | 0.7 | 1.3 | 1.9 | 2.3 | 2.7 | 3.1 | 3.1 | 3.2 |
| Renewables | 0.0 | 0.0 | 0.1 | 0.2 | 0.5 | 0.8 | 1.0 | 1.0 | 1.0 | 1.0 | 0.9 | 0.9 |
| Commercial Biomass | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 0.7 | 1.8 | 2.3 | 2.8 | 3.2 | 3.6 | 3.9 |
| Breakthrough Technology | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Fuel Mix Changes | 0.0 | 0.0 | 0.2 | 0.8 | 1.2 | 1.6 | 2.3 | 3.0 | 3.8 | 4.6 | 5.2 | 5.9 |
| Energy Use Reduction | 0.0 | 0.0 | 0.6 | 1.6 | 2.1 | 2.6 | 2.9 | 2.9 | 2.9 | 3.0 | 3.0 | 3.0 |
| Total | 6.1 | 6.9 | 8.5 | 10.2 | 11.8 | 13.2 | 14.6 | 16.2 | 17.9 | 19.6 | 20.6 | 21.6 |

## Annual Primary Energy (EJ/yr): Closing the Loop on Carbon, Level 4

| | 1990 | 2000 | 2010 | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 | 2080 | 2090 | 2100 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fossil w/o Capture & Storage | 295 | 354 | 414 | 478 | 533 | 580 | 618 | 650 | 682 | 714 | 697 | 680 |
| Fossil w/ Capture & Storage | 0 | 0 | 1 | 3 | 6 | 8 | 11 | 14 | 16 | 19 | 22 | 25 |
| Nuclear | 19 | 21 | 27 | 38 | 50 | 58 | 63 | 76 | 85 | 90 | 91 | 92 |
| Renewables | 21 | 26 | 37 | 52 | 72 | 87 | 99 | 108 | 119 | 131 | 140 | 147 |
| Commercial Biomass | 10 | 22 | 31 | 36 | 43 | 47 | 49 | 52 | 54 | 56 | 56 | 55 |
| Breakthrough Technology | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Energy Use Reduction | 0 | 0 | 6 | 18 | 34 | 54 | 77 | 107 | 138 | 172 | 212 | 252 |
| Total | 345 | 422 | 517 | 626 | 738 | 834 | 917 | 1,007 | 1,095 | 1,182 | 1,217 | 1,252 |

## Annual Emissions & Emissions Reductions (GtC/yr): Closing the Loop on Carbon, Level 4

| | 1990 | 2000 | 2010 | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 | 2080 | 2090 | 2100 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Net Vented Emissions | 6.1 | 6.9 | 8.3 | 9.7 | 10.9 | 11.9 | 12.6 | 13.2 | 13.8 | 14.5 | 14.4 | 14.3 |
| Additional Terrestrial Sequestration | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 0.1 | 0.1 | 0.3 | 0.4 | 0.5 | 0.5 | 0.4 |
| Fossil & Cement CCS | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 0.1 | 0.2 | 0.2 | 0.3 | 0.4 | 0.4 | 0.5 |
| Nuclear | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 0.2 | 0.2 | 0.3 | 0.4 |
| Renewables | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 0.2 | 0.3 | 0.4 | 0.6 | 0.8 |
| Commercial Biomass | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Breakthrough Technology | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Fuel Mix Changes | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 0.2 | 0.4 | 0.6 | 0.9 | 1.2 | 1.5 | 1.8 |
| Energy Use Reduction | 0.0 | 0.0 | 0.1 | 0.3 | 0.6 | 0.9 | 1.1 | 1.6 | 2.0 | 2.3 | 2.9 | 3.5 |
| Total | 6.1 | 6.9 | 8.5 | 10.2 | 11.8 | 13.2 | 14.6 | 16.2 | 17.9 | 19.6 | 20.6 | 21.6 |

## Annual Primary Energy (EJ/yr): Closing the Loop on Carbon, Level 3

| | 1990 | 2000 | 2010 | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 | 2080 | 2090 | 2100 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fossil w/o Capture & Storage | 295 | 354 | 412 | 472 | 521 | 559 | 585 | 596 | 602 | 605 | 560 | 515 |
| Fossil w/ Capture & Storage | 0 | 0 | 1 | 4 | 7 | 10 | 14 | 20 | 29 | 39 | 54 | 69 |
| Nuclear | 19 | 21 | 28 | 38 | 51 | 60 | 66 | 80 | 92 | 101 | 107 | 113 |
| Renewables | 21 | 26 | 37 | 52 | 72 | 88 | 100 | 110 | 122 | 136 | 145 | 154 |
| Commercial Biomass | 10 | 22 | 31 | 36 | 43 | 48 | 50 | 53 | 57 | 60 | 62 | 64 |
| Breakthrough Technology | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Energy Use Reduction | 0 | 0 | 8 | 24 | 44 | 70 | 103 | 147 | 193 | 241 | 289 | 337 |
| Total | 345 | 422 | 517 | 626 | 738 | 834 | 917 | 1,007 | 1,095 | 1,182 | 1,217 | 1,252 |

## Annual Emissions & Emissions Reductions (GtC/yr): Closing the Loop on Carbon, Level 3

| | 1990 | 2000 | 2010 | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 | 2080 | 2090 | 2100 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Net Vented Emissions | 6.1 | 6.9 | 8.2 | 9.5 | 10.4 | 11.0 | 11.1 | 11.4 | 11.7 | 12.0 | 11.2 | 10.5 |
| Additional Terrestrial Sequestration | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 0.3 | 0.5 | 0.6 | 0.6 | 0.5 | 0.4 | 0.3 |
| Fossil & Cement CCS | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 0.2 | 0.3 | 0.4 | 0.6 | 0.8 | 1.1 | 1.4 |
| Nuclear | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.2 | 0.3 | 0.5 | 0.7 | 0.9 | 1.2 |
| Renewables | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.2 | 0.4 | 0.6 | 0.8 | 1.0 | 1.2 |
| Commercial Biomass | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 0.2 | 0.2 | 0.2 | 0.3 |
| Breakthrough Technology | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Fuel Mix Changes | 0.0 | 0.0 | 0.0 | 0.1 | 0.3 | 0.5 | 0.9 | 1.1 | 1.4 | 1.7 | 2.1 | 2.5 |
| Energy Use Reduction | 0.0 | 0.0 | 0.1 | 0.4 | 0.7 | 1.1 | 1.4 | 2.0 | 2.5 | 3.0 | 3.6 | 4.2 |
| Total | 6.1 | 6.9 | 8.5 | 10.2 | 11.8 | 13.2 | 14.6 | 16.2 | 17.9 | 19.6 | 20.6 | 21.6 |

## Annual Primary Energy (EJ/yr): Closing the Loop on Carbon, Level 2

| | 1990 | 2000 | 2010 | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 | 2080 | 2090 | 2100 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fossil w/o Capture & Storage | 295 | 354 | 411 | 467 | 511 | 541 | 557 | 519 | 478 | 436 | 397 | 358 |
| Fossil w/ Capture & Storage | 0 | 0 | 1 | 4 | 7 | 12 | 18 | 38 | 69 | 110 | 139 | 168 |
| Nuclear | 19 | 21 | 28 | 38 | 51 | 61 | 68 | 87 | 104 | 121 | 131 | 140 |
| Renewables | 21 | 26 | 37 | 53 | 73 | 89 | 101 | 114 | 129 | 147 | 155 | 164 |
| Commercial Biomass | 10 | 22 | 31 | 36 | 43 | 48 | 51 | 56 | 62 | 69 | 70 | 71 |
| Breakthrough Technology | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Energy Use Reduction | 0 | 0 | 9 | 28 | 52 | 83 | 123 | 193 | 252 | 300 | 326 | 352 |
| Total | 345 | 422 | 517 | 626 | 738 | 834 | 917 | 1,007 | 1,095 | 1,182 | 1,217 | 1,252 |

## Annual Emissions & Emissions Reductions (GtC/yr): Closing the Loop on Carbon, Level 2

| | 1990 | 2000 | 2010 | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 | 2080 | 2090 | 2100 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Net Vented Emissions | 6.1 | 6.9 | 8.1 | 9.2 | 9.8 | 10.1 | 10.2 | 9.6 | 8.9 | 8.3 | 7.7 | 7.0 |
| Additional Terrestrial Sequestration | 0.0 | 0.0 | 0.0 | 0.1 | 0.4 | 0.5 | 0.7 | 0.6 | 0.5 | 0.4 | 0.3 | 0.2 |
| Fossil & Cement CCS | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 0.2 | 0.3 | 0.8 | 1.5 | 2.6 | 3.2 | 3.7 |
| Nuclear | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.3 | 0.5 | 0.8 | 1.1 | 1.3 | 1.6 |
| Renewables | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.2 | 0.3 | 0.6 | 0.8 | 1.0 | 1.1 | 1.2 |
| Commercial Biomass | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 0.2 | 0.3 | 0.4 | 0.4 | 0.4 |
| Breakthrough Technology | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Fuel Mix Changes | 0.0 | 0.0 | 0.1 | 0.2 | 0.5 | 0.8 | 1.1 | 1.5 | 1.9 | 2.2 | 2.7 | 3.2 |
| Energy Use Reduction | 0.0 | 0.0 | 0.2 | 0.5 | 0.9 | 1.2 | 1.7 | 2.5 | 3.2 | 3.7 | 4.0 | 4.3 |
| Total | 6.1 | 6.9 | 8.5 | 10.2 | 11.8 | 13.2 | 14.6 | 16.2 | 17.9 | 19.6 | 20.6 | 21.6 |

## Annual Primary Energy (EJ/yr): Closing the Loop on Carbon, Level 1

| | 1990 | 2000 | 2010 | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 | 2080 | 2090 | 2100 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fossil w/o Capture & Storage | 295 | 354 | 391 | 407 | 405 | 371 | 305 | 272 | 240 | 210 | 195 | 181 |
| Fossil w/ Capture & Storage | 0 | 0 | 3 | 9 | 28 | 60 | 105 | 155 | 202 | 243 | 254 | 264 |
| Nuclear | 19 | 21 | 30 | 44 | 65 | 83 | 100 | 124 | 142 | 156 | 159 | 162 |
| Renewables | 21 | 26 | 38 | 55 | 80 | 100 | 117 | 130 | 143 | 156 | 162 | 168 |
| Commercial Biomass | 10 | 22 | 31 | 37 | 43 | 51 | 59 | 70 | 86 | 106 | 108 | 109 |
| Breakthrough Technology | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Energy Use Reduction | 0 | 0 | 24 | 73 | 117 | 170 | 231 | 255 | 282 | 312 | 340 | 368 |
| Total | 345 | 422 | 517 | 626 | 738 | 834 | 917 | 1,007 | 1,095 | 1,182 | 1,217 | 1,252 |

## Annual Emissions & Emissions Reductions (GtC/yr): Closing the Loop on Carbon, Level 1

| | 1990 | 2000 | 2010 | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 | 2080 | 2090 | 2100 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Net Vented Emissions | 6.1 | 6.9 | 7.5 | 7.2 | 6.9 | 6.0 | 4.6 | 4.0 | 3.5 | 3.2 | 3.1 | 2.9 |
| Additional Terrestrial Sequestration | 0.0 | 0.0 | 0.1 | 0.4 | 0.6 | 0.7 | 0.6 | 0.5 | 0.4 | 0.4 | 0.3 | 0.1 |
| Fossil & Cement CCS | 0.0 | 0.0 | 0.1 | 0.2 | 0.5 | 1.4 | 2.8 | 4.0 | 5.0 | 5.9 | 6.2 | 6.4 |
| Nuclear | 0.0 | 0.0 | 0.0 | 0.1 | 0.3 | 0.6 | 0.9 | 1.1 | 1.3 | 1.4 | 1.5 | 1.6 |
| Renewables | 0.0 | 0.0 | 0.0 | 0.1 | 0.3 | 0.5 | 0.7 | 0.8 | 0.9 | 0.9 | 1.0 | 1.0 |
| Commercial Biomass | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.2 | 0.3 | 0.5 | 0.7 | 0.9 | 1.0 | 1.0 |
| Breakthrough Technology | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Fuel Mix Changes | 0.0 | 0.0 | 0.2 | 0.8 | 1.3 | 1.6 | 1.8 | 2.2 | 2.5 | 2.9 | 3.3 | 3.8 |
| Energy Use Reduction | 0.0 | 0.0 | 0.4 | 1.3 | 1.8 | 2.4 | 2.9 | 3.2 | 3.6 | 4.0 | 4.3 | 4.7 |
| Total | 6.1 | 6.9 | 8.5 | 10.2 | 11.8 | 13.2 | 14.6 | 16.2 | 17.9 | 19.6 | 20.6 | 21.6 |

## Annual Primary Energy (EJ/yr): New Energy Backbone, Level 4

| | 1990 | 2000 | 2010 | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 | 2080 | 2090 | 2100 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fossil w/o Capture & Storage | 295 | 354 | 412 | 470 | 523 | 571 | 614 | 650 | 684 | 717 | 699 | 682 |
| Fossil w/ Capture & Storage | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 2 |
| Nuclear | 19 | 21 | 33 | 55 | 69 | 79 | 84 | 98 | 106 | 110 | 113 | 117 |
| Renewables | 21 | 26 | 40 | 60 | 83 | 102 | 116 | 132 | 148 | 166 | 174 | 182 |
| Commercial Biomass | 10 | 22 | 30 | 35 | 41 | 45 | 46 | 48 | 49 | 51 | 51 | 51 |
| Breakthrough Technology | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Energy Use Reduction | 0 | 0 | 1 | 6 | 20 | 37 | 56 | 78 | 105 | 137 | 178 | 219 |
| Total | 345 | 422 | 517 | 626 | 738 | 834 | 917 | 1,007 | 1,095 | 1,182 | 1,217 | 1,252 |

## Annual Emissions & Emissions Reductions (GtC/yr):New Energy Backbone, Level 4

| | 1990 | 2000 | 2010 | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 | 2080 | 2090 | 2100 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Net Vented Emissions | 6.1 | 6.9 | 8.2 | 9.5 | 10.7 | 11.6 | 12.5 | 13.1 | 13.8 | 14.5 | 14.4 | 14.3 |
| Additional Terrestrial Sequestration | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 0.1 | 0.1 | 0.3 | 0.4 | 0.5 | 0.5 | 0.4 |
| Fossil & Cement CCS | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Nuclear | 0.0 | 0.0 | 0.0 | 0.2 | 0.2 | 0.3 | 0.4 | 0.4 | 0.5 | 0.5 | 0.6 | 0.8 |
| Renewables | 0.0 | 0.0 | 0.0 | 0.1 | 0.2 | 0.3 | 0.3 | 0.5 | 0.7 | 0.9 | 1.1 | 1.2 |
| Commercial Biomass | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Breakthrough Technology | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Fuel Mix Changes | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 0.2 | 0.4 | 0.6 | 0.9 | 1.2 | 1.5 | 1.8 |
| Energy Use Reduction | 0.0 | 0.0 | 0.1 | 0.3 | 0.5 | 0.7 | 0.9 | 1.2 | 1.6 | 1.9 | 2.5 | 3.1 |
| Total | 6.1 | 6.9 | 8.5 | 10.2 | 11.8 | 13.2 | 14.6 | 16.2 | 17.9 | 19.6 | 20.6 | 21.6 |

### Annual Primary Energy (EJ/yr): New Energy Backbone, Level 3

| | 1990 | 2000 | 2010 | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 | 2080 | 2090 | 2100 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fossil w/o Capture & Storage | 295 | 354 | 412 | 470 | 520 | 559 | 585 | 598 | 606 | 610 | 565 | 520 |
| Fossil w/ Capture & Storage | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 2 | 3 | 5 | 7 |
| Nuclear | 19 | 21 | 33 | 55 | 69 | 80 | 87 | 103 | 117 | 128 | 141 | 153 |
| Renewables | 21 | 26 | 40 | 60 | 84 | 103 | 118 | 135 | 152 | 170 | 179 | 187 |
| Commercial Biomass | 10 | 22 | 30 | 35 | 41 | 45 | 46 | 49 | 52 | 55 | 60 | 64 |
| Breakthrough Technology | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Energy Use Reduction | 0 | 0 | 1 | 6 | 23 | 48 | 80 | 120 | 165 | 216 | 269 | 322 |
| Total | 345 | 422 | 517 | 626 | 738 | 834 | 917 | 1,007 | 1,095 | 1,182 | 1,217 | 1,252 |

### Annual Emissions & Emissions Reductions (GtC/yr): New Energy Backbone, Level 3

| | 1990 | 2000 | 2010 | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 | 2080 | 2090 | 2100 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Net Vented Emissions | 6.1 | 6.9 | 8.2 | 9.5 | 10.4 | 11.0 | 11.1 | 11.4 | 11.7 | 12.0 | 11.2 | 10.5 |
| Additional Terrestrial Sequestration | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 0.3 | 0.5 | 0.6 | 0.6 | 0.5 | 0.4 | 0.3 |
| Fossil & Cement CCS | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 |
| Nuclear | 0.0 | 0.0 | 0.0 | 0.2 | 0.3 | 0.4 | 0.5 | 0.7 | 0.9 | 1.2 | 1.6 | 2.0 |
| Renewables | 0.0 | 0.0 | 0.0 | 0.1 | 0.2 | 0.3 | 0.5 | 0.7 | 1.1 | 1.4 | 1.6 | 1.9 |
| Commercial Biomass | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.2 |
| Breakthrough Technology | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Fuel Mix Changes | 0.0 | 0.0 | 0.0 | 0.1 | 0.2 | 0.5 | 0.9 | 1.2 | 1.4 | 1.8 | 2.1 | 2.5 |
| Energy Use Reduction | 0.0 | 0.0 | 0.1 | 0.3 | 0.5 | 0.8 | 1.2 | 1.7 | 2.2 | 2.8 | 3.5 | 4.1 |
| Total | 6.1 | 6.9 | 8.5 | 10.2 | 11.8 | 13.2 | 14.6 | 16.2 | 17.9 | 19.6 | 20.6 | 21.6 |

## Annual Primary Energy (EJ/yr): New Energy Backbone, Level 2

| | 1990 | 2000 | 2010 | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 | 2080 | 2090 | 2100 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fossil w/o Capture & Storage | 295 | 354 | 410 | 466 | 511 | 542 | 558 | 523 | 484 | 441 | 406 | 372 |
| Fossil w/ Capture & Storage | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 4 | 9 | 17 | 24 | 30 |
| Nuclear | 19 | 21 | 34 | 55 | 70 | 82 | 90 | 116 | 143 | 172 | 191 | 207 |
| Renewables | 21 | 26 | 40 | 60 | 84 | 104 | 119 | 141 | 162 | 182 | 188 | 192 |
| Commercial Biomass | 10 | 22 | 30 | 35 | 41 | 45 | 47 | 52 | 59 | 70 | 73 | 77 |
| Breakthrough Technology | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Energy Use Reduction | 0 | 0 | 2 | 10 | 31 | 61 | 102 | 172 | 237 | 300 | 335 | 374 |
| Total | 345 | 422 | 517 | 626 | 738 | 834 | 917 | 1,007 | 1,095 | 1,182 | 1,217 | 1,252 |

## Annual Emissions & Emissions Reductions (GtC/yr): New Energy Backbone, Level 2

| | 1990 | 2000 | 2010 | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 | 2080 | 2090 | 2100 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Net Vented Emissions | 6.1 | 6.9 | 8.1 | 9.2 | 9.8 | 10.1 | 10.2 | 9.6 | 8.9 | 8.3 | 7.7 | 7.0 |
| Additional Terrestrial Sequestration | 0.0 | 0.0 | 0.0 | 0.1 | 0.4 | 0.5 | 0.7 | 0.6 | 0.5 | 0.4 | 0.3 | 0.2 |
| Fossil & Cement CCS | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.2 | 0.4 | 0.5 | 0.6 |
| Nuclear | 0.0 | 0.0 | 0.1 | 0.2 | 0.3 | 0.4 | 0.6 | 1.0 | 1.6 | 2.2 | 2.8 | 3.3 |
| Renewables | 0.0 | 0.0 | 0.0 | 0.1 | 0.2 | 0.4 | 0.6 | 1.0 | 1.4 | 1.8 | 1.9 | 2.0 |
| Commercial Biomass | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.2 | 0.4 | 0.5 | 0.6 |
| Breakthrough Technology | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Fuel Mix Changes | 0.0 | 0.0 | 0.1 | 0.2 | 0.5 | 0.8 | 1.1 | 1.5 | 2.0 | 2.5 | 3.1 | 3.7 |
| Energy Use Reduction | 0.0 | 0.0 | 0.1 | 0.4 | 0.7 | 1.0 | 1.5 | 2.3 | 3.1 | 3.7 | 4.0 | 4.2 |
| Total | 6.1 | 6.9 | 8.5 | 10.2 | 11.8 | 13.2 | 14.6 | 16.2 | 17.9 | 19.6 | 20.6 | 21.6 |

## Annual Primary Energy (EJ/yr): New Energy Backbone, Level 1

| | 1990 | 2000 | 2010 | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 | 2080 | 2090 | 2100 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fossil w/o Capture & Storage | 295 | 354 | 391 | 407 | 407 | 371 | 300 | 272 | 245 | 220 | 207 | 193 |
| Fossil w/ Capture & Storage | 0 | 0 | 0 | 1 | 3 | 11 | 24 | 44 | 64 | 86 | 94 | 103 |
| Nuclear | 19 | 21 | 37 | 65 | 92 | 122 | 152 | 189 | 221 | 247 | 255 | 262 |
| Renewables | 21 | 26 | 41 | 63 | 94 | 123 | 146 | 164 | 179 | 194 | 199 | 205 |
| Commercial Biomass | 10 | 22 | 30 | 35 | 40 | 49 | 61 | 77 | 96 | 117 | 120 | 122 |
| Breakthrough Technology | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Energy Use Reduction | 0 | 0 | 17 | 55 | 101 | 159 | 234 | 260 | 289 | 318 | 343 | 368 |
| Total | 345 | 422 | 517 | 626 | 738 | 834 | 917 | 1,007 | 1,095 | 1,182 | 1,217 | 1,252 |

## Annual Emissions & Emissions Reductions (GtC/yr): New Energy Backbone, Level 1

| | 1990 | 2000 | 2010 | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 | 2080 | 2090 | 2100 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Net Vented Emissions | 6.1 | 6.9 | 7.5 | 7.2 | 6.9 | 6.0 | 4.6 | 4.0 | 3.5 | 3.2 | 3.1 | 2.9 |
| Additional Terrestrial Sequestration | 0.0 | 0.0 | 0.1 | 0.4 | 0.6 | 0.7 | 0.6 | 0.5 | 0.4 | 0.4 | 0.3 | 0.1 |
| Fossil & Cement CCS | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.3 | 0.7 | 1.3 | 1.9 | 2.5 | 2.7 | 2.8 |
| Nuclear | 0.0 | 0.0 | 0.1 | 0.3 | 0.7 | 1.2 | 1.9 | 2.3 | 2.8 | 3.1 | 3.4 | 3.6 |
| Renewables | 0.0 | 0.0 | 0.1 | 0.2 | 0.4 | 0.8 | 1.3 | 1.5 | 1.6 | 1.7 | 1.7 | 1.8 |
| Commercial Biomass | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.4 | 0.6 | 0.9 | 1.2 | 1.3 | 1.3 |
| Breakthrough Technology | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Fuel Mix Changes | 0.0 | 0.0 | 0.2 | 0.8 | 1.3 | 1.8 | 2.3 | 2.8 | 3.4 | 3.9 | 4.4 | 4.9 |
| Energy Use Reduction | 0.0 | 0.0 | 0.4 | 1.2 | 1.8 | 2.4 | 2.9 | 3.1 | 3.4 | 3.7 | 3.9 | 4.2 |
| Total | 6.1 | 6.9 | 8.5 | 10.2 | 11.8 | 13.2 | 14.6 | 16.2 | 17.9 | 19.6 | 20.6 | 21.6 |

## Annual Primary Energy (EJ/yr): Beyond the Standard Suite, Level 4

| | 1990 | 2000 | 2010 | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 | 2080 | 2090 | 2100 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fossil w/o Capture & Storage | 295 | 354 | 415 | 479 | 535 | 582 | 621 | 653 | 684 | 716 | 698 | 681 |
| Fossil w/ Capture & Storage | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 |
| Nuclear | 19 | 21 | 27 | 38 | 50 | 57 | 61 | 72 | 78 | 80 | 78 | 76 |
| Renewables | 21 | 26 | 37 | 52 | 72 | 86 | 96 | 104 | 114 | 124 | 131 | 137 |
| Commercial Biomass | 10 | 22 | 31 | 36 | 43 | 47 | 48 | 50 | 51 | 52 | 50 | 48 |
| Breakthrough Technology | 0 | 0 | 0 | 0 | 0 | 2 | 6 | 18 | 31 | 46 | 58 | 70 |
| Energy Use Reduction | 0 | 0 | 7 | 21 | 39 | 59 | 84 | 109 | 136 | 164 | 201 | 238 |
| Total | 345 | 422 | 517 | 626 | 738 | 834 | 917 | 1,007 | 1,095 | 1,182 | 1,217 | 1,252 |

## Annual Emissions & Emissions Reductions (GtC/yr): Beyond the Standard Suite, Level 4

| | 1990 | 2000 | 2010 | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 | 2080 | 2090 | 2100 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Net Vented Emissions | 6.1 | 6.9 | 8.3 | 9.7 | 10.9 | 11.9 | 12.6 | 13.2 | 13.8 | 14.5 | 14.4 | 14.3 |
| Additional Terrestrial Sequestration | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 0.1 | 0.1 | 0.3 | 0.4 | 0.5 | 0.5 | 0.4 |
| Fossil & Cement CCS | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Nuclear | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Renewables | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.2 | 0.3 |
| Commercial Biomass | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Breakthrough Technology | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.2 | 0.4 | 0.7 | 1.1 | 1.4 | 1.7 |
| Fuel Mix Changes | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 0.2 | 0.4 | 0.7 | 0.9 | 1.2 | 1.5 | 1.7 |
| Energy Use Reduction | 0.0 | 0.0 | 0.1 | 0.4 | 0.6 | 0.9 | 1.2 | 1.5 | 1.9 | 2.2 | 2.7 | 3.2 |
| Total | 6.1 | 6.9 | 8.5 | 10.2 | 11.8 | 13.2 | 14.6 | 16.2 | 17.9 | 19.6 | 20.6 | 21.6 |

## Annual Primary Energy (EJ/yr): Beyond the Standard Suite, Level 3

| | 1990 | 2000 | 2010 | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 | 2080 | 2090 | 2100 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fossil w/o Capture & Storage | 295 | 354 | 413 | 473 | 523 | 561 | 588 | 599 | 606 | 608 | 564 | 519 |
| Fossil w/ Capture & Storage | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 2 | 2 | 3 | 4 | 6 |
| Nuclear | 19 | 21 | 28 | 38 | 51 | 59 | 63 | 76 | 85 | 90 | 93 | 96 |
| Renewables | 21 | 26 | 37 | 52 | 72 | 87 | 97 | 106 | 117 | 128 | 136 | 144 |
| Commercial Biomass | 10 | 22 | 31 | 36 | 43 | 47 | 49 | 51 | 54 | 55 | 56 | 57 |
| Breakthrough Technology | 0 | 0 | 0 | 0 | 0 | 2 | 7 | 20 | 35 | 52 | 69 | 85 |
| Energy Use Reduction | 0 | 0 | 8 | 26 | 49 | 77 | 112 | 153 | 197 | 245 | 295 | 345 |
| Total | 345 | 422 | 517 | 626 | 738 | 834 | 917 | 1,007 | 1,095 | 1,182 | 1,217 | 1,252 |

## Annual Emissions & Emissions Reductions (GtC/yr): Beyond the Standard Suite, Level 3

| | 1990 | 2000 | 2010 | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 | 2080 | 2090 | 2100 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Net Vented Emissions | 6.1 | 6.9 | 8.2 | 9.5 | 10.4 | 11.0 | 11.1 | 11.4 | 11.7 | 12.0 | 11.2 | 10.5 |
| Additional Terrestrial Sequestration | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 0.3 | 0.5 | 0.6 | 0.6 | 0.5 | 0.4 | 0.3 |
| Fossil & Cement CCS | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 0.1 |
| Nuclear | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.7 |
| Renewables | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.2 | 0.3 | 0.4 | 0.6 | 0.7 | 0.9 |
| Commercial Biomass | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 0.1 | 0.0 | 0.1 | 0.1 |
| Breakthrough Technology | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.2 | 0.5 | 0.9 | 1.5 | 1.9 | 2.4 |
| Fuel Mix Changes | 0.0 | 0.0 | 0.0 | 0.1 | 0.3 | 0.6 | 0.9 | 1.2 | 1.4 | 1.7 | 2.1 | 2.5 |
| Energy Use Reduction | 0.0 | 0.0 | 0.2 | 0.5 | 0.8 | 1.1 | 1.5 | 2.0 | 2.5 | 3.0 | 3.6 | 4.2 |
| Total | 6.1 | 6.9 | 8.5 | 10.2 | 11.8 | 13.2 | 14.6 | 16.2 | 17.9 | 19.6 | 20.6 | 21.6 |

## Annual Primary Energy (EJ/yr): Beyond the Standard Suite, Level 2

| | 1990 | 2000 | 2010 | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 | 2080 | 2090 | 2100 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fossil w/o Capture & Storage | 295 | 354 | 411 | 468 | 513 | 544 | 560 | 523 | 483 | 438 | 403 | 368 |
| Fossil w/ Capture & Storage | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 4 | 9 | 16 | 21 | 25 |
| Nuclear | 19 | 21 | 28 | 38 | 51 | 60 | 66 | 83 | 99 | 114 | 120 | 125 |
| Renewables | 21 | 26 | 37 | 53 | 73 | 88 | 98 | 110 | 124 | 139 | 145 | 148 |
| Commercial Biomass | 10 | 22 | 31 | 36 | 43 | 47 | 50 | 55 | 61 | 70 | 70 | 70 |
| Breakthrough Technology | 0 | 0 | 0 | 0 | 0 | 3 | 7 | 23 | 44 | 69 | 91 | 112 |
| Energy Use Reduction | 0 | 0 | 10 | 31 | 57 | 91 | 135 | 208 | 275 | 337 | 368 | 403 |
| Total | 345 | 422 | 517 | 626 | 738 | 834 | 917 | 1,007 | 1,095 | 1,182 | 1,217 | 1,252 |

## Annual Emissions & Emissions Reductions (GtC/yr): Beyond the Standard Suite, Level 2

| | 1990 | 2000 | 2010 | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 | 2080 | 2090 | 2100 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Net Vented Emissions | 6.1 | 6.9 | 8.1 | 9.2 | 9.8 | 10.1 | 10.2 | 9.6 | 8.9 | 8.3 | 7.7 | 7.0 |
| Additional Terrestrial Sequestration | 0.0 | 0.0 | 0.0 | 0.1 | 0.4 | 0.5 | 0.7 | 0.6 | 0.5 | 0.4 | 0.3 | 0.2 |
| Fossil & Cement CCS | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 |
| Nuclear | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.2 | 0.5 | 0.8 | 1.1 | 1.3 | 1.5 |
| Renewables | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.2 | 0.3 | 0.5 | 0.8 | 1.0 | 1.1 | 1.1 |
| Commercial Biomass | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 0.2 | 0.4 | 0.5 | 0.5 | 0.5 |
| Breakthrough Technology | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.2 | 0.6 | 1.1 | 1.7 | 2.3 | 2.9 |
| Fuel Mix Changes | 0.0 | 0.0 | 0.1 | 0.3 | 0.6 | 0.9 | 1.1 | 1.6 | 2.0 | 2.4 | 3.0 | 3.6 |
| Energy Use Reduction | 0.0 | 0.0 | 0.2 | 0.6 | 0.9 | 1.3 | 1.8 | 2.6 | 3.3 | 4.0 | 4.2 | 4.4 |
| Total | 6.1 | 6.9 | 8.5 | 10.2 | 11.8 | 13.2 | 14.6 | 16.2 | 17.9 | 19.6 | 20.6 | 21.6 |

### Annual Primary Energy (EJ/yr): Beyond the Standard Suite, Level 1

| | 1990 | 2000 | 2010 | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 | 2080 | 2090 | 2100 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fossil w/o Capture & Storage | 295 | 354 | 391 | 408 | 408 | 372 | 301 | 271 | 244 | 218 | 204 | 190 |
| Fossil w/ Capture & Storage | 0 | 0 | 0 | 1 | 4 | 13 | 27 | 45 | 63 | 80 | 85 | 89 |
| Nuclear | 19 | 21 | 30 | 45 | 68 | 89 | 108 | 134 | 153 | 164 | 163 | 161 |
| Renewables | 21 | 26 | 38 | 56 | 81 | 102 | 117 | 129 | 139 | 149 | 153 | 156 |
| Commercial Biomass | 10 | 22 | 31 | 36 | 43 | 54 | 68 | 83 | 99 | 116 | 116 | 115 |
| Breakthrough Technology | 0 | 0 | 0 | 0 | 0 | 5 | 14 | 40 | 67 | 97 | 117 | 137 |
| Energy Use Reduction | 0 | 0 | 26 | 80 | 134 | 200 | 282 | 304 | 330 | 358 | 380 | 402 |
| Total | 345 | 422 | 517 | 626 | 738 | 834 | 917 | 1,007 | 1,095 | 1,182 | 1,217 | 1,252 |

### Annual Emissions & Emissions Reductions (GtC/yr): Beyond the Standard Suite, Level 1

| | 1990 | 2000 | 2010 | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 | 2080 | 2090 | 2100 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Net Vented Emissions | 6.1 | 6.9 | 7.5 | 7.2 | 6.9 | 6.0 | 4.6 | 4.0 | 3.5 | 3.2 | 3.1 | 2.9 |
| Additional Terrestrial Sequestration | 0.0 | 0.0 | 0.1 | 0.4 | 0.6 | 0.7 | 0.6 | 0.5 | 0.4 | 0.4 | 0.3 | 0.1 |
| Fossil & Cement CCS | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.3 | 0.8 | 1.4 | 1.9 | 2.4 | 2.5 | 2.6 |
| Nuclear | 0.0 | 0.0 | 0.0 | 0.1 | 0.4 | 0.8 | 1.3 | 1.5 | 1.7 | 1.8 | 1.8 | 1.8 |
| Renewables | 0.0 | 0.0 | 0.0 | 0.1 | 0.3 | 0.6 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Commercial Biomass | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.3 | 0.6 | 0.8 | 1.1 | 1.3 | 1.3 | 1.3 |
| Breakthrough Technology | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.3 | 0.8 | 1.3 | 1.8 | 2.3 | 2.7 |
| Fuel Mix Changes | 0.0 | 0.0 | 0.2 | 0.8 | 1.3 | 1.8 | 2.2 | 2.8 | 3.3 | 3.8 | 4.3 | 4.8 |
| Energy Use Reduction | 0.0 | 0.0 | 0.5 | 1.4 | 2.0 | 2.7 | 3.3 | 3.4 | 3.6 | 3.9 | 4.1 | 4.4 |
| Total | 6.1 | 6.9 | 8.5 | 10.2 | 11.8 | 13.2 | 14.6 | 16.2 | 17.9 | 19.6 | 20.6 | 21.6 |