2. MODELS USED IN THIS STUDY

2.1. Overview of the Models

The analysis facilities used in this exercise are referred to as integrated assessment models (IAMs) in that they combine, in an integrated framework, the socio-economic and physical processes and systems that define the human influence on, and interactions with, the global climate. They integrate computer models of socio-economic and technological determinants of the emissions of greenhouse gases (GHGs) and other substances influencing the Earth's radiation balance with models of the natural science of Earth system response, including those of the atmosphere, oceans, and terrestrial biosphere. Although they differ in their specific design objectives and details of their mathematical structures, each of these IAMs was developed for the purpose of gaining insight into economic and policy issues associated with global climate change.

To create scenarios of sufficient depth, scope, and detail, a number of model characteristics were deemed critical for development of these scenarios. The criteria set forth in Chapter 1 led to the selection of three IAMs:

- The Integrated Global Systems Model (the IGSM) of the Massachusetts Institute of Technology's Joint Program on the Science and Policy of Global Change. The IGSM (Sokolov et al. 2005) is an Earth system model that comprises a multi-sector, multi-region economic component and a science component, including a two-dimensional atmosphere, a three-dimensional ocean, and a detailed biogeochemical model of the terrestrial biosphere. Because this study focuses on new emissions scenarios, results from the economic model component of the IGSM, the Emissions Prediction and Policy Analysis (EPPA) model (Paltsev et al. 2005), are featured in the discussion below. EPPA is a recursive-dynamic computable general equilibrium (CGE) model of the world economy and greenhouse-relevant emissions, solved on a five-year time step. Previous applications of the IGSM and its EPPA component system can be found at http://web.mit.edu/globalchange.

- The Model for Evaluating the Regional and Global Effects of GHG reduction policies (MERGE) was developed jointly at Stanford University and the Electric Power Research Institute. MERGE (Manne and Richels 2005) is an intertemporal general equilibrium model of the global economy in which the world is divided into nine-geopolitical regions. It is solved on a ten-year time step. MERGE is a hybrid model combining a bottom-up representation of the energy supply sector, together with a top-down perspective on the remainder of the economy.[1] Savings and investment decisions are modeled as if each region maximizes the discounted utility of its consumption, subject to an intertemporal wealth constraint. Embedded within this structure is a reduced-form representation of the physical earth system. MERGE has been used to explore a range of climate-related issues, including multi-gas strategies, the value of low-carbon-emitting energy technologies, the choice of near-term hedging strategies under uncertainty, the impacts of learning-by-doing, and the potential importance of "when" and "where" flexibility. To support this analysis of stabilization scenarios, the multi-gas version has been revised by adjustments in technology and other assumptions. The MERGE code and publications describing its structure and applications can be found at http://www.stanford.edu/group/MERGE/.

- The MiniCAM is an integrated assessment model, (Brenkert et al. 2003) that combines a technologically detailed market equilibrium model of the global energy and agricultural systems with a suite of coupled gas-cycle, climate, and ice-melt models, integrated in the Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC). It is developed and maintained at the Joint Global Change Research Institute, a partnership between the Pacific Northwest National Laboratory and the University of Maryland. The model is solved on a 15-year time step. MiniCAM has been used extensively for energy, climate, and other environmental analyses conducted for organizations that include the U.S. Department of Energy (DOE), the U.S. Environmental Protection Agency (EPA), the Intergovernmental Panel on Climate Change (IPCC), and several major private sector energy companies. Its energy sector is based on a model developed by Edmonds and Reilly (1985). The model is designed to examine long-term, large-scale changes in global and regional energy systems, focusing on the impact of energy technologies. Documentation for MiniCAM can be found at http://www.globalchange.umd.edu/models/MiniCAM.pdf/.

These three are among the most detailed models of this type of IAM, and the roots of each extend back more than a decade.

Because these models were designed to address an overlapping set of climate-change issues, they are similar in many respects. All three have both social science-based components that capture the socio-economic and technology interactions underlying the emissions of GHGs. And each incorporates models of physical cycles for GHGs and other radiatively important substances and other aspects of the natural science of global climate. The differences among them lie in the detail and construction of these

[1] It differs from the pure "bottom-up" approach described in the box in that demands for energy are price-responsive.

components and in the ways they are modeled to interact. Each was designed with somewhat different aspects of the climate issue as a main focus. IGSM includes the most detailed representation of the chemistry, physics, and biology of the atmosphere, oceans, and terrestrial biosphere; thus, its EPPA component is designed to provide the emissions detail that these natural science components require. MERGE has its origins in an energy-sector model that was initially designed for energy technology assessment. It was subsequently modified to explore the influence of expectations (and uncertainty regarding expectations) about future developments related to climate policy on the economics of current investment and the cost-minimizing allocation of emissions mitigation over time. Its focus requires a forward-looking structure, which in turn requires simplification of the non-energy components of the economy. MiniCAM is a technology rich IAM. It features detailed representations of energy technologies, energy systems, and energy markets, their interactions with agriculture and land use technologies and markets, and interactions with the terrestrial carbon cycle. The MiniCAM modeling team also emphasized the role of demographic developments and transitions in shaping the nature and scale of economic systems.

Each of these IAMs thus has its unique strengths and areas of special insight. In this scenario study, the simultaneous application of different model structures is useful in revealing different aspects of the task of atmospheric stabilization. The differences among their results, presented in Chapters 3 and 4, are an indication of the limits of our knowledge about future GHG emissions and the challenges in stabilizing atmospheric conditions. Indeed, differences among the reference forecasts and in the implications of various stabilization targets are likely within the range that would be realized from an uncertainty analysis applied to any one of the three, as indicated by the analysis of the EPPA model by Webster et al. (2003).

Table 2.1 provides a cross-model overview of some of the key characteristics to be compared in the following sections of this chapter. Section 2.2 focuses on social science components, describing similarities and differences and highlighting the assumptions that have the greatest influences on the resulting scenarios. Section 2.3 does the same for the natural science sub-models of each IAM, which in this study make the connection between the emissions of GHGs and other radiatively important substances and the resulting atmospheric conditions.

Table 2.1. Characteristics of the Models

2.2. Socio-Economic and Technology Components

2.2.1. Equilibrium, Expectations, and Trade

As can be seen in Table 2.1, the models represent economic activity and associated emissions in a similar way; each divides the world economy into several regions, and further divides each region into economic sectors. In all three, the greatest degree of disaggregation is applied to the various components of energy supply and demand.

The models differ, however, in the representation of the equilibrium structure, the role of future expectations, and in the goods and services traded.

MERGE and the EPPA component of the IGSM are CGE models, which solve for a consistent set of supply-demand and price equilibria for each good and factor of production that is distinguished in the analysis. In the process, CGE models ensure a balance in each period of income and expenditure and of savings and investment for the economy, and they maintain a balance in international trade in goods and emissions permits. MiniCAM is a partial equilibrium model, focusing on solving for supply-demand and price equilibria within linked energy and agricultural markets. Other economic sectors that influence the demand for energy and agricultural products and the costs of factors of production in these sectors are represented through exogenous assumptions.

The models also differ in how expectations about the future affect current decisions. The EPPA component of the IGSM and MiniCAM are recursive-dynamic models, meaning they are solved one period at a time with economic agents modeled as responding to conditions in that period. This behavior is also referred to as "myopic" because these agents do not consider expected future market conditions in their decisions. The underlying behavioral assumption is that consumers and producers maximize their individual utilities or profits. In MiniCAM this process is captured implicitly through the use of demand and supply functions that evolve over time as a function of evolving economic activity and regional economic development; in IGSM explicit representative-agent utility and sector production functions ensure that consumer and producer decisions are consistent with welfare and profit maximization. In both of these models, the patterns of emissions mitigation over time are imposed by assumptions intended to capture the features of a strategy that, as explained in Section 2.4, would be cost-efficient. MERGE, on the other hand, is an intertemporal optimization model where all periods are solved simultaneously such that resources and mitigation effort are allocated optimally over time as well as among sectors. Intertemporal models of this type are often referred to as "forward-looking" or "perfect foresight" models because actors in the economy base current decisions not only on current conditions but on future ones which are assumed to be known with certainty. Simultaneous solution of all periods ensures that agents' expectations about the future are realized in the model solution. MERGE's forward-looking structure allows it to explicitly solve for cost-minimizing emissions pathways, in contrast to MiniCAM and IGSM which exogenously prescribe emissions mitigation policies over time.

Although all three models also represent international trade in goods and services and include exchange in emissions permits, they differ in the combinations of goods and services traded. In IGSM, all goods and services represented in the model are traded, with electricity trade limited to geographically contiguous regions to the extent that it occurs in the base data. MiniCAM models international trade in oil, coal, natural gas, agricultural goods, and emission permits. MERGE models trade in oil and natural gas, emissions permits, energy-intensive industrial goods, and a single non-energy good representing all other tradeable goods and services.

2.2.2. Population and Economic Growth

A projected increase in the overall scale of economic activity is among the most important drivers of GHG emissions. However, economic growth depends, in part, on growth in population, which in all three models is an exogenously determined input. Although economic activity is ostensibly a projected output of the models, its level is largely determined by assumptions about labor productivity and labor force growth, which are also model inputs. Policies to reduce emissions below those in the reference scenarios also affect economic activity, which may be measured as changes in GDP or in national consumption (see Chapter 4, which provides a discussion of the interpretation and limitations of GDP and other welfare measures).

In MiniCAM, labor productivity and growth in the labor force are the main drivers of GDP growth. GDP is calculated as the product of labor force and average labor productivity modified by an energy-service price elasticity. The labor force and labor productivity are both exogenous inputs to MiniCAM, but were developed for these scenarios from detailed demographic 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, and then summed and adjusted by a fixed unemployment rate. Trends were explicitly considered, such as 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 region to represent these evolving demographics.

In MERGE and the EPPA component of the IGSM the labor force and its productivity, while extremely important, are not the only factors determining GDP. Savings and investment and productivity growth in other factors (e.g., materials, land, labor, and energy) variously contribute as well. IGSM and MERGE use population directly as a measure of the labor force and apply assumptions about labor productivity change that are appropriate for that definition.

2.2.3. Energy Demand

In all three models, energy demands are represented regionally and driven by regional economic activity. As a region's economic activity increases, its corresponding demand for energy services rises. Energy demand is also affected by assumptions about changing technology, structure of the economy, and other varying economic conditions (see Section 2.2.5). Similarly, all the models represent the way demand will respond to changes in price. The formulation of price response is particularly important in the construction of stabilization scenarios because the imposition of a constraint on carbon emissions will require the use of more expensive energy sources with lower emissions and will, therefore, raise the price of all forms of energy.

All three IAMs calculate energy demand at the level of each model's aggregated sectors. None further disaggregates to engineering-process representations of specific energy-demand technologies (e.g., cars, air conditioners). However, the models differ in the way they disaggregate energy demand. In the IGSM each good- or service-producing sector demands energy. The production sector is an input-output structure where every industry (including the energy sector) supplies its outputs as inputs to intermediate production in other industries and for final consumption. Households have separate demands for automobile fuel and for all other energy services. Each final demand sector can use electricity, liquid fuels (petroleum products or biomass liquids), gas, and coal; fuel for automobiles is limited to liquids. MiniCAM represents demands for solid fuels, liquid fuels, electricity, and gaseous fuels across three demand sectors: buildings, transportation, and industry. MERGE has a single non-energy production sector for each region that is the sole source of demand for fuels and electricity.

2.2.4. Energy Resources

Because the future availability of energy resources, particularly of exhaustible fossil fuels, is a fundamental determinant of human influence on climate, the models provide explicit treatments of the underlying resource base. All three include empirically based estimates of in-ground resources of oil, coal, and natural gas that might ultimately be available, along with a model of the costs of extraction. The levels of detail in the different models are shown in Table 2.1. Each of the models includes both conventional and unconventional sources in its resource base and represents the process of exhaustion of resources by an increasing cost of exploitation. That is, lower-cost resources are utilized first so that the costs of extraction rise as the resources are depleted. The models differ, however, in the way they represent the increasing costs of extraction. MiniCAM divides the resource base for each fossil fuel into discrete grades with increasing costs of extraction, along with an exogenous technical change that lowers resource extraction costs over time. MERGE has similar differential grades for oil and gas, but assumes that the coal base is more than sufficient to meet potential demand and that exogenous technological improvements in extraction will be minimal. For these reasons, MERGE represents coal as having a constant cost over time irrespective of utilization. IGSM models resource grades with a continuous function and treats conventional oil, shale oil, natural gas, and coal with a common functional form. Fuel-producing sectors are subject to economy-wide technical progress (e.g., increased labor productivity growth), which partly offsets the rise in extraction costs. The models all incorporate tar sands and unconventional gas (e.g., tight gas, coal-seam gas) in the grade structure for oil and natural gas, and each also includes the potential development of shale oil.

The models seek to represent all resources that could be available as technology and economic conditions vary over time and across simulations. Thus, they reflect judgments that technology will advance to the point where currently unused resources can be economically exploited. Generally, then, they define a resource base that is more expansive than, for example, that of the U.S. Geological Survey, which estimates technological and economic feasibility only at current technology and prices. However, differences exist in the treatments of potentially available resources. MiniCAM includes a detailed representation of the nuclear power sector, including uranium resources, nuclear fuel fabrication, reactor technology options, and associated fuel-cycle cycles, including waste, storage, and fuel reprocessing. IGSM and MERGE assume that the uranium resources used for nuclear power generation are sufficient to meet likely use and, therefore, do not explicitly model their depletion.

The treatment of wind and solar resources also differs among the models. IGSM represents the penalty for intermittent supply by modeling wind and solar as imperfect substitutes for central station generation, where the elasticity of substitution implies a rising cost as these resources supply a larger share of electricity supply. Land is also an input, and the regional cost of wind/solar is based on estimates of regional resource availability and quality. MERGE represents these resources as having a fixed cost that improves over time, but it applies upper limits on the proportion of these resources, representing limits on the integration of these resources into the grid. MiniCAM represents wind and solar technologies as extracting power from a graded renewable resource base. Wind and solar technology choice also depends on incremental needs for energy storage and ancillary power associated with intermittency.

IGSM and MiniCAM model biomass production as competing for agricultural land. Increasing production leads to an increasing land rent, representing the scarcity of agricultural land, and, thus, to an increasing cost of biomass as production expands. MiniCAM also has a separate set of regional supply functions for biomass supplied from waste and residue sources. MERGE places an upper limit on the amount of biomass energy that might supply the electric and non-electric energy sectors, but otherwise assumes a fixed cost for biomass energy and allows biomass to compete unhindered in the market.

2.2.5. Technology and Technological Change

In most studies of energy and greenhouse gas emissions, “technology” is represented by some form of economic production function which specifies the quantities of inputs required to produce a unit of energy or some other good, or to supply a particular consumer demand using energy and other inputs. Models differ substantially, however, depending on their overall design objectives because data limitations and computational feasibility force tradeoffs between the inclusion of engineering detail and the representation of the interaction among the segments of a modern economy that determines supply, demand, and prices (see Box 2.1).

Though all three of the models applied here follow a “hybrid” approach to the representation of energy technology, involving substantial detail in some areas and more aggregate representations in others, some of the choices that flow from the distinct design of each can be seen in Table 2.1. They represent energy demand, as described in Section 2.2.3, with the application of an autonomous energy efficiency improvement (AEEI) factor to represent non-price-induced trends in energy use. However, AEEI parameter values are not directly comparable across the models because each has a unique representation of the processes that together explain the multiple forces that have contributed historically to changes in the energy intensity of economic activity. In IGSM and MERGE, the AEEI captures non-price changes (including structural change not accounted for in the models) that can be energy-using rather than energy-saving. MERGE represents the AEEI as a function of GDP growth in each region. MiniCAM captures shifts among fuels through differing income elasticities, which change over time, and separately represents AEEI efficiency gains.

--- BOX 2.1: TOP-DOWN, BOTTOM-UP, AND HYBRID MODELING ---

The models used in energy and environmental assessments are sometimes classified as top-down, as opposed to bottom-up, in structure, a distinction that refers to the way they represent technological options. A top-down model uses an aggregate representation of how producers and consumers can substitute non-energy inputs for energy inputs, or relatively energy-intensive goods for less energy-intensive goods. Often, these tradeoffs are represented by aggregate production functions or by utility functions that describe consumers' willingness and technical ability to substitute among goods. The bottom-up approach begins with explicit technological options, and fuel substitution or changes in efficiency occur as a result of a discrete change from one specific technology to another. The bottom-up approach has the advantage of being able to represent explicitly the combination of outputs, inputs, and emissions of types of capital equipment used to provide consumer services (e.g., a vehicle model or building design) or to perform a particular step in energy supply (e.g., a coal-fired powerplant or wind turbine). However, a limited number of technologies are typically included, which may not well represent the full set of possible options that exist in practice. Also, in a pure bottom-up approach, the demands for particular energy services are often characterized as fixed (unresponsive to price), and the prices of inputs such as capital, labor, energy and materials are exogenous. On the other hand, the top-down approach explicitly models demand responsiveness and input prices, which usually require the use of continuous functions to model at least some parts of the available technology set. The disadvantage of the latter approach is that production functions of this form will poorly represent switch points from one technology to another—as from one form of electric generation to another, or from gasoline to biomass blends as vehicle fuel. In practice, the vast majority of models in use today, including those applied in this study, are hybrids in that they include substantial technological detail in some sectors and more aggregate representations in others.

--- END BOX ---

Other areas shown in the table where there are significant differences among the models are in energy conversion—from fossil fuels or renewable sources to electricity, and from solid fossil fuels or biomass to liquid fuels or gas. In the IGSM, discrete energy technologies are represented as energy supply sectors contained within the input-output structure of the economy. Those sources of fuels and electricity that now dominate supply are represented as production functions with the same basic structure as the other sectors of the economy. Technologies that may play a large role in the future (e.g., power plants with carbon capture and storage or oil from shale) are introduced using this same structure, calibrated to current engineering estimates of required inputs. They are subject to economy-wide productivity improvements (e.g., labor, land, and energy productivity), whose effect on cost depends on the share of each factor in the technology production function. MERGE and MiniCAM characterize energy-supply technologies in terms of discrete technologies. In MERGE, technological improvements are captured by allowing for the introduction of more advanced technologies in future periods; in MiniCAM, the cost and performance of technologies are assumed to improve over time and new technologies become available in the future. Similar differences among the models hold for other conversion technologies, such as coal gasification or liquefaction or liquids from biomass.

The entry into the market of new sources and their levels of production by region are determined endogenously in all three models and depend on the relative costs of supply. It should be emphasized that the models do not explicitly represent the research and development (R&D) process and how it leads to technical change through, for example, public and private R&D, spillovers from innovation in other economic sectors, and learning-by-doing. A number of recent efforts have been made to incorporate such processes and their effects as an endogenous component of modeling exercises. However, generally these studies have not been applied to models of the complexity needed to meet the requirements of this scenario product.

Because of the differences in structure among these models, there is no simple technology-by-technology comparison of performance and cost across particular sources of supply or technical options. Not only do specifications differ somewhat in the base year, but costs and performance evolve over time in different ways, for example, because of changes in input prices in the IGSM model or exogenous assumptions about technological progress in MERGE or MiniCAM.

The influence of differing technology specifications and assumptions is evident in the results shown in Chapters 3 and 4, with several of these features being particularly notable. In the absence of any greenhouse gas policy, motor fuel is drawn ever more heavily from high-emitting sources—for example, oil from shale comes in under IGSM's resource and technology assumptions, but liquids from coal enter in MERGE and MiniCAM. When stabilization conditions are imposed, all models show carbon capture and storage taking a key role over the study period. Nuclear power contributes heavily in MERGE and in MiniCAM, whereas the potential role of this technology is overridden in the IGSM results by a scenario assumption of political restraints on expansion. Finally, although differences in emissions in the no-policy scenario contribute to variation in the projected difficulty of achieving stabilization, alternative assumptions about rates of technical change in supply technologies also play a prominent role.

2.2.6. Land Use and Land Use Change

The models used in this study were developed originally with a focus on energy and fossil carbon emissions. The integration of the terrestrial biosphere, including human activity, into the climate system is less highly developed. Each model represents the global carbon cycle, including exchanges with the atmosphere of natural vegetation and soils, the effects of human land-use and responses to carbon policy, and feedbacks to global climate. But none represents all of these possible responses and interactions, and the level of detail varies substantially among the models. For example, they differ in the handling of natural vegetation and soils and in their responses to CO_2 concentration and changed climate. Furthermore, land-use practices (e.g., low- or no-till agriculture, or biomass production) and changes in land use (e.g., afforestation, reforestation, or deforestation) that influence GHG emissions and the sequestration of carbon in terrestrial systems are handled at different levels of detail. Indeed, improved two-way linking of global economic and climate analysis with models of physical land use (land use responding to climate and economic pressures and to climate response changes in the terrestrial biosphere) is the subject of ongoing research in these modeling groups.

In IGSM, land is an input to agriculture, biomass production, and wind/solar energy production. Agriculture is a single sector that aggregates crops, livestock, and forestry. Biomass energy production is modeled as a separate sector, which competes with agriculture for land. Markets for agricultural goods and biomass energy are international, and demand for these products determines the price of land in each region and its allocation among uses. In other sectors, returns to capital include returns to land, but the land component is not explicitly identified. Anthropogenic emissions of GHGs (importantly including CH_4 and N_2O) are estimated within the IGSM model as functions of agricultural activity and assumed levels of tropical deforestation. The response of terrestrial vegetation and soils to climate change and CO_2 increase is captured in the Earth system component of the model, which provides a detailed treatment of biogeochemical and land-surface properties of terrestrial systems. However, the biogeography of natural ecosystems and human uses remains unchanged over the simulation period, with the area of cropland fixed to the pattern of the early 1990s. By this procedure, the emissions associated with deforestation are included in the year the clearing occurs, but the associated land use is not corrected to reflect the replacement activity. IGSM does not simulate carbon; price-induced changes in carbon sequestration (e.g., reforestation, tillage) and change among land-use types in EPPA is not fed to the terrestrial biosphere component of the IGSM.

The version of MERGE used here incorporates a neutral terrestrial biosphere across all scenarios. That is, it is assumed that the net CO_2 exchange with the atmosphere by natural ecosystems and managed systems—the latter including agriculture, deforestation, afforestation, reforestation and other land-use change—sums to zero.

MiniCAM includes a model that allocates the land area in a region among various components of human use and unmanaged land—with changes in allocation over time in relation to income, technology and prices—and estimates the resulting CO_2 emissions (or sinks) that result. Land conditions and associated emissions are parameterized for a set of regional sub-aggregates. The supply of primary agricultural production (four food crop types, pasture, wood, and commercial biomass) is simulated regionally with competition for a finite land resource based on the average profit rate for each good potentially produced in a region. In stabilization scenarios, the value of carbon stored in the land is added to this profit, based on the average carbon content of different land uses in each region. This allows carbon mitigation policies to explicitly extend into land and agricultural markets. The model is solved by clearing a global market for primary agricultural goods and regional markets for pasture. The biomass market is cleared with demand for biomass from the energy component of the model. Exogenous assumptions are made for the rate of intrinsic increase in agricultural productivity although net productivity can decrease in the case of expansion of agricultural lands into less productive areas (Sands and Leimbach 2003). Unmanaged land can be converted to agro-forestry, which in general results in net CO_2 emissions from tropical regions in the early decades. Emissions of non-CO_2 GHGs are tied to relevant drivers, for example, with CH_4 from ruminant animals related to beef production. MiniCAM thus treats the effects on carbon emissions of gross changes in land use (e.g., from forests to biomass production) using an average emission factor for such conversion. The pricing of carbon stocks in the model provides a counterbalance to increasing demand for biomass crops in stabilization scenarios.

2.2.7. Emissions of CO_2 and Non-CO_2 Greenhouse Gases

In all three models, the main source of CO_2 emissions is fossil fuel combustion, which is computed on the basis of the carbon content of each of the underlying resources: oil, natural gas, and coal. Special adjustments are made to account for emissions associated with the additional processing required to convert coal, tar sands, and shale sources into products equivalent to those from conventional oil. Other industrial CO_2 emissions also are included, primarily from cement production.

As required for this study, all three models also include representations of emissions and abatement of CH_4, N_2O, HFCs, PFCs, and SF_6 (plus other substances not considered in this study). The models use somewhat different approaches to represent abatement of the non-CO_2 GHGs. The IGSM includes the emissions and abatement possibilities directly in the production functions of the sectors that are responsible for emissions of the different gases. Abatement possibilities are represented by substitution elasticities (i.e., the degree to which one factor of production can be substituted for another) in a nested structure that encompasses gas emissions and other inputs, benchmarked to reflect bottom-up studies of abatement potential. This construction is parallel to the representation of fossil fuels in production functions, where abatement potential is similarly represented by the substitution elasticity between fossil fuels and other inputs, with the specific set of substitutions governed by the nest structure. Abatement opportunities vary by sector and region.

In MERGE, methane emissions from natural gas use are tied directly to the level of natural gas consumption, with the emissions rate decreasing over time to represent reduced leakage during the transportation process. Non-energy sources of CH_4, N_2O, HFCs, PFCs, and SF_6 are based largely on the guidelines provided by the Energy Modeling Forum (EMF) Study No. 21 on Multi-Gas Mitigation and Climate Change (Weyant and de la Chesnaye 2005). The EMF developed baseline projections from 2000 through 2020. For all gases but N_2O and CO_2, the baseline for beyond 2020 was derived by extrapolation of these estimates. Abatement cost functions for these two gases are also based on EMF 21, which provided estimates of the abatement potential for each gas in each of 11 cost categories in 2010. These abatement cost curves are directly incorporated in the model and extrapolated after 2010 following the baseline. There is also an allowance for technical advances in abatement over time.

MiniCAM calculates emissions of CH_4, N_2O, and seven categories of industrial sources for HFCFCs, HFCs, PFCs, and SF_6 (plus other substances not considered in this study). 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. For details, see Smith (2005) and Smith and Wigley (2006). 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 from the EMF-21 exercise are applied, including shifts in the curves for methane due to changes in natural gas prices. Any "below zero" reductions in MAC curves are assumed to apply in the reference scenario.

2.3. Earth Systems Component

The earth system components of the models serve to compute the response of the atmosphere, ocean, and terrestrial biosphere to emissions and increasing concentrations of GHGs and other substances. Representation of these processes, including the carbon cycle (see Box 2.2), is necessary to determine emissions paths consistent with stabilization because these systems determine how long each of these substances remains in the atmosphere and how it interacts in the modification of the Earth's radiation balance. Each of the models includes such physical-chemical-biological components, but differs from the other models in the level of detail incorporated. The most elaborated Earth system components are found in the IGSM (Sokolov et al. 2005), which falls in a class of models classified as Earth System Models of Intermediate Complexity, or EMICs (Claussen et al. 2002) These are models that fall between the full three-dimensional atmosphere-ocean general circulation models (AOGCMs) and energy balance models with a box model of the carbon cycle. The Earth system components of MERGE and MiniCAM fall in the class of energy balance/carbon cycle box models. Table 2.1 shows how each of the models treat different components of the Earth systems.

--- BOX 2.2: THE CARBON CYCLE ---

Although an approximate atmospheric "lifetime" is sometimes calculated for CO_2, the term is potentially misleading because it implies that CO_2 put into the atmosphere by human activity always declines over time by some stable process, such as that associated with radioactive materials. In fact, the calculated concentration of CO_2 is not related to any mechanism of destruction, or even to the length of time an individual molecule spends in the atmosphere, because CO_2 is constantly exchanged between the atmosphere and the surface layer of the ocean and with vegetation. Instead, it is more appropriate to think about how the quantity of carbon that the Earth contains is partitioned between stocks of in-ground fossil resources, the atmosphere (mainly as CO_2), surface vegetation and soils, and the surface and deep layers of the ocean. When stored CO_2 is released into the atmosphere, either from fossil or terrestrial sources, atmospheric concentrations increase, leading to disequilibrium with the ocean, and more carbon is taken up than is cycled back. For land processes, vegetation growth may be enhanced by increases in atmospheric CO_2, and this change could augment the stock of carbon in vegetation and soils. As a result of the ocean and terrestrial uptake, only about half of the carbon currently emitted remains in the atmosphere. But this large removal only occurs because current levels of emissions lead to substantial disequilibrium between atmosphere and ocean. Lower emissions would lead to less uptake, as atmospheric concentrations come into balance with the ocean and interact with the terrestrial system. Rising temperatures themselves will reduce uptake by the ocean, and will affect terrestrial vegetation uptake, processes that the models in this study variously represent.

An important policy implication of these carbon-cycle processes as they affect stabilization scenarios is that stabilization of emissions at anything like today's level will not lead to stabilization of atmospheric concentrations. CO_2 concentrations were increasing in the 1990s at just over 3 ppmv per year, an annual increase of 0.8 percent. Thus, even if societies were able to stabilize emissions at current levels, atmospheric concentrations of CO_2 would continue to rise. As long as emissions exceed the rate of uptake, even very stringent abatement will only slow the rate of increase.

--- END BOX ---

The IGSM has explicit spatial detail, resolving the atmosphere into multiple layers and by latitude, and includes a terrestrial vegetation model with multiple vegetation types that are also spatially resolved. A version of the IGSM with a full three-dimensional ocean model was used for this study, and it includes temperature dependent uptake of carbon. The IGSM models atmospheric chemistry, resolved separately for urban (i.e., heavily polluted) and background conditions. Processes that move carbon into or out of the ocean and vegetation are modeled explicitly. IGSM also models natural emissions of CH_4 and N_2O, which are weather/climate-dependent. The model includes a radiation code that computes the net effect of atmospheric concentrations of the GHGs studied in the scenarios considered below. Also included in the global forcing is the effect of changing ozone levels, which result from projected emissions of methane and non-GHGs, such as NO_x and volatile organic hydrocarbons.

MERGE's physical Earth system component is embedded in the intertemporal optimization framework, thus allowing solution of an optimal allocation of resources through time, accounting for damages related to climate change, or optimizing the allocation of resources with regard to other constraints such as concentrations, temperature, or radiative forcing. In this study, the second of these capabilities is applied, with a constraint on radiative forcing (see Chapter 4). In contrast, the IGSM and MiniCAM Earth system models are driven by emissions as simulated by the economic components. In that regard, they are simulations rather than optimization models.

The carbon cycle in MERGE relates emissions to concentrations using a convolution ocean carbon-cycle model and assuming a neutral biosphere (i.e., no net CO_2 exchange). It is a reduced-form carbon cycle model developed by Maier-Reimer and Hasselmann (1987). Carbon emissions are divided into five classes, each with different atmospheric lifetimes. The behavior of the model compares favorably with atmospheric concentrations provided in the IPCC's Third Assessment Report (2001) when the same

SRES scenarios of emissions are simulated in the model (Nakicenovic et al. 2000). MERGE models the radiative effects of GHGs using relationships consistent with summaries by the IPCC, and applies the median aerosol forcing from Wigley and Raper (2001). The aggregate effect is obtained by summing the radiative forcing effect of each gas.

MiniCAM uses the MAGICC model (Wigley and Raper 2001, 2002) as its biophysical component. MAGICC is an energy-balance climate model that simulates the energy inputs and outputs of key components of the climate system (sun, atmosphere, land surface, ocean) with parameterizations of dynamic processes such as ocean circulations. It operates by taking anthropogenic emissions from the other MiniCAM components, converting these to global average concentrations (for gaseous emissions), then determining anthropogenic radiative forcing relative to pre-industrial conditions, and finally computing global mean temperature changes. The carbon cycle is modeled with both terrestrial and ocean components: the terrestrial component includes CO_2 fertilization and temperature feedbacks; the ocean component is a modified version of the Maier-Reimer and Hasselmann (1987) model that also includes temperature effects on CO_2 uptake. Net land-use change emissions from the MiniCAM's land-use change component are fed into MAGICC so that the global carbon cycle is consistent with the amount of natural vegetation. Reactive gases and their interactions are modeled on a global-mean basis using equations derived from results of global atmospheric chemistry models (Wigley and Raper 2002).

In MiniCAM, global mean radiative forcing for CO_2, CH_4, and N_2O are determined from GHG concentrations using analytic approximations. Forcings for other GHGs are taken to be proportional to concentrations. Forcings for aerosols (for sulfur dioxide and for black and organic carbon) are taken to be proportional to emissions. Indirect forcing effects, such as the effect of CH_4 on stratospheric water vapor, are also included. Given radiative forcing, global mean temperature changes are determined by a multiple box model with an upwelling-diffusion ocean component. The climate sensitivity is specified as an exogenous parameter. MAGICC's ability to reproduce the global mean temperature change results of atmosphere-ocean general circulation models has been demonstrated (Cubasch et al. 2001, Raper and Gregory 2001).

We note here that while the models are all capable of computing climate change effects these effects not part of the Prospectus and climate change variables are not reported in this study. As noted in Chapter 1 such computations require making a suite of assumptions about interactions between atmosphere, radiative forcing and climate systems, most of which remain highly uncertain. This means that the three models employed in this exercise are not fully closed. With few exceptions, these three models do not include the consequences of such feedback effects as temperature on heating and cooling degree days, local climate change on agricultural productivity, a CO_2 fertilization effect on agricultural productivity (though a CO_2 fertilization effect is included in the terrestrial carbon cycle models employed by IGSM and MiniCAM), climate effects of water availability for applications ranging from crop growing to power plant cooling. We leave such improvements to future research.

2.4. References

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Table 2.1 Characteristics of the Integrated Assessment Models

Feature	**IGSM & EPPA economics component**	**MiniCAM**	**MERGE**
Regions	16	14	9
Time Horizon, Time Steps	2100, 5-year steps	2095, 15-year steps	2200, 10-year steps
Model Structure	General Equilibrium	Partial Equilibrium	General Equilibrium
Solution	Recursive Dynamic	Recursive Dynamic	Intertemporal Optimization
Final Energy Demand Sectors in Each Region	Households, private transportation, commercial transportation, service sector, agriculture, energy intensive industries, other industry	Buildings, transportation, industry (including agriculture)	A single non-energy production sector
Capital Turnover	Five vintages of capital with a depreciation rate	Vintages with constant deprecation rate for all electricity-sector capital; capital structure not explicitly modeled in other sectors	A "putty clay" approach wherein the input-output coefficients for each cohort are optimally adjusted to the future trajectory of prices at the time of investment
Goods in International Trade	All energy and non-energy goods, emissions permits	Oil, coal, natural gas, biomass, agricultural goods, emissions permits	Energy, energy intensive industry goods, emissions permits, representative tradeable good.
Emissions	CO_2, CH_4, N_2O, HFCs, PFCs, SF_6, CO, NOx, SOx, NMVOCs, BC, OC, NH_3	CO_2, CH_4, N_2O, CO, NOx, SO_2, NMVOCs, BC, OC, HFC245fa, HFC134a, HFC125, HFC143a, SF_6, C_2F_6, CF_4	CO_2, CH_4, N_2O, long-lived F-gases, short-lived F-gases, SOx
Land use	Agriculture (crops, livestock, forests), biomass land use, land use for wind/solar	Agriculture (crops, pasture, forests) & biomass land use and unmanaged land. The agriculture-land-use module directly determines land-use change emissions and terrestrial carbon stocks.	Reduced-form emissions from land-use. No explicit land use sector. Assume no net terrestrial emissions of CO_2
Population	Exogenous	Exogenous	Exogenous
GDP Growth	Exogenous productivity growth assumptions for labor, energy, land; exogenous labor force growth determined from population growth; endogenous capital growth through savings and investment	Exogenous productivity growth assumptions for labor; exogenous labor force growth based on population demographics	Exogenous productivity growth assumptions for labor, energy; exogenous labor force growth determined from population growth; endogenous capital growth through savings and investment
Energy Efficiency Change	Exogenous	Exogenous	Proportional the rate of GDP growth in each region

Energy Resources	Oil (including tar sands), shale oil, gas, coal, wind/solar, land (biomass), hydro, nuclear fuel	Conventional oil, unconventional oil (including tar sands and shale oil), gas, coal, wind, solar, biomass (waste/residues, & crops), hydro, nuclear fuel including a full representation of the nuclear fuel cycle.	Conventional oil, unconventional oil (coal-based synthetics, tar sands and shale oil), gas, coal, wind, solar, biomass, hydro, nuclear fuel
Electricity Technologies	Conventional fossil (coal, gas, oil); nuclear, hydro, natural gas combined cycle w/ & w/o capture, integrated coal gasification with capture, wind/solar, biomass	Conventional fossil (coal, gas, oil) w/ & w/o capture; IGCCs w/ & w/o capture; natural gas combined cycle (NGCC) w/ & w/o capture; Gen II, III, and IV reactors and associated fuel cycles, hydro, wind, solar, biomass (traditional & modern commercial)	Conventional fossil (coal, gas, oil); nuclear, hydro, natural gas combined cycle integrated coal gasification with capture, wind, solar, biomass, fuel cells
Conversion Technologies	Oil refining, coal gasification, bio-liquids	Oil refining, natural gas processing, natural gas to liquids conversion, coal, and biomass conversion, to synthetic liquids and gases. Hydrogen production using liquids, natural gas, coal, biomass, electrolysis including direct production from wind and solar, and nuclear thermal conversion.	Oil refining, coal gasification and liquefaction, bio-liquids, electrolysis
Atmosphere- Ocean	2-Dimensional Atmosphere w/ a 3 Dimensional Ocean General Circulation Model, resolved at 20 minute time steps, 4^{o} latitude, 4 surface types, 12 vertical layers in the atmosphere.	Global multi-box energy balance model with upwelling-diffusion ocean heat transport.	Parameterized ocean thermal lag.
Carbon Cycle	Biogeochemical models of terrestrial and ocean processes, depend on climate/atmospheric conditions with 35 terrestrial ecosystem types	Globally balanced carbon-cycle with separate ocean and terrestrial components, with terrestrial response to land-use changes	Convolution ocean carbon cycle model assuming a neutral biosphere
Natural Emissions	CH_4, N_2O,weather/climate dependent as part of biogeochemical process models	Fixed natural emissions over time	Fixed natural emissions over time
Atmospheric fate of GHGs, pollutants	Process models of atmospheric chemistry resolved for urban & background conditions	Reduced form models for reactive gases and their interactions	Single box models with fixed decay rates. No consideration of reactive gases
Radiation Code	Radiation code accounting for all significant GHGs and aerosols	Reduced form, top of the atmosphere forcing including indirect forcing effects	Reduced form, top of the atmosphere forcing