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Second Generation Model 2004: An Overview

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Second Generation Model 2004: An Overview

I. Introduction

The Second Generation Model (SGM) is a computable general equilibrium model designed specifically to analyze issues related to energy, economy, and greenhouse gas emissions. It has fourteen global regions, multiple greenhouse gas emissions, vintaged capital stocks, explicit connections between technology and the economy, explicit treatment of energy and land stocks and is disaggregated to reflect the relative importance of sectors in determining greenhouse gas emissions. Model development began in 1991. The first model design paper was published in 1993 (Edmonds, et al., 1993). The SGM was developed to complement the “first generation model,” referred to as the MiniCAM. The MiniCAM was also explicitly designed to address long-term, strategic issues related to energy, economy, and greenhouse gas emissions (Edmonds and Reilly, 1983)² and continues to be used for that purpose. In contrast the SGM was designed to address transitional energy-economy-technology-greenhouse-gas-emissions issues.

This paper documents the present version of the SGM: SGM 2004. The SGM 2004 consists of a theoretical structure, computational implementation, and statistical expression. This paper documents the theoretical structure and some of the most important data shaping model behavior. It does not attempt to document the software employed to solve the statistical expression of the theoretical relationships nor does it provide a complete documentation of all of the data employed in SGM 2004. The SGM was developed at the Pacific Northwest National Laboratory (PNNL) and is maintained by the PNNL Joint Global Change Research Institute (JGCRI)³.

The SGM theoretical structure reflects the specific issue the model is designed to address. Thus SGM emphasizes both economic principles, which lead to the selection of a neoclassical computable general equilibrium (CGE) framework, and specific economic sectors, especially the energy sector. Both play important roles in shaping the SGM structure.

SGM 2004 is a direct descendent of the model described in Edmonds et al. 1993. Needless to say, SGM 2004 has evolved substantially over the last decade. The SGM was designed from the start to address the climate problem with particular focus on greenhouse gas emissions and their relationship to the economy. To understand the structure of the SGM and why particular aspects of economic activity were chosen and others given lesser emphasis, one needs to understand the relationship between emissions of greenhouse related gases and climate change. Physical science relationships play a major role in shaping which aspects of the economy are emphasized and which are deemphasized in the SGM.

In Section II we discuss the relationship between climate change and the design of the SGM. The SGM has been designed with capabilities that may not yet be implemented. That is, it is designed to be capable of being extended without any substantial change to model structure.⁴ Section II

² The MiniCAM evolved to include agriculture, land-use, terrestrial and ocean carbon cycle, radiative forcing, sea level rise, and climate change. See Appendix D for a brief comparison of the MiniCAM and the SGM.

³ The JGCRI is a collaboration between the PNNL and the University of Maryland at College Park. The JGCRI is located on the campus of the University of Maryland in College Park, MD.

⁴ From the start SGM design has sought to create a flexible modeling structure with capabilities that may only be implemented in later expressions of the model. The transformation of the SGM from a Fortran-based code to a C++ based code takes this approach a major step further by creating a completely data-

therefore focuses on structure and capability. Section III focuses on the mathematical formulation of the model. Section IV addresses the data that populate SGM 2004, and Section V discusses the model as it is currently implemented.

II. The Climate Problem and SGM Design

The overriding design philosophy of the SGM is build the model to address a specific problem. The climate issue has a variety of important characteristics that make it different from traditional pollution problems. The following characteristics are critical:

- Climate change is global. Unlike local and regional environmental issues, radiative forcing is driven by the concentration of greenhouse gases in the atmosphere, which in turn is determined by the present and prior emissions of all sources everywhere in the world. This is particularly true for the atmospherically well-mixed gases such as carbon dioxide (CO₂), nitrous oxide (N₂O), methane (CH₄), chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF₆). It is also true for extremely short-lived gases such as sulfur aerosols and black carbon. While these gases do not mix completely, they are emitted in sufficient quantity to affect the energy balance of the planet. Beyond radiatively active gases, other gases such as carbon monoxide (CO) and volatile organic compounds (VOCs) affect the energy balance of the planet indirectly by affecting the concentration of other greenhouse gases such as CH₄ and ozone (O₃). The SGM was designed to produce estimates of global emissions of all anthropogenic greenhouse related gases.
- Emissions occur across heterogeneous global regions. Greenhouse gases are emitted under a wide range of local circumstances. Two of the world's largest emitters of CO₂ are the United States and China⁵. These two regions have dramatically different economies. Emissions of greenhouse gases are distributed unevenly around the world. Ten nations and the European Union account for more than 75 percent of global emissions of fossil fuel CO₂. The SGM was disaggregated by region to enable it to explicitly consider major greenhouse gas emitting regions⁶.

SGM model development was pursued using regional research partners. Major SGM regions were developed through an explicit collaboration with a partner institution

driven model. Thus, the addition of sectors or inputs or markets to the model within the original modeling framework becomes merely a matter of data inputs and entails no additional code. This is analogous to a building with rooms that have not yet been occupied.

⁵ The United States for example, is modeled as a market economy. China on the other hand has a substantial history of investments that occurred under a period of central planning. The vintage structure of the SGM helps address this difference. India, another major fossil fuel carbon emitter, is a mixed economy requiring special treatment of investment decisions.

⁶ The SGM regions are: United States, Western Europe, China, Former Soviet Union, Japan, India, Canada, Korea, Mexico, Australia & New Zealand, Brazil, Eastern Europe, Mideast and Rest of the World. These regions correspond to the major fossil fuel carbon emitters. In 1999 fossil fuel carbon emissions were as follows: United States (25%), European Union (14%), China (13%), Russian Federation (6%), Japan (5%), India (5%), Canada (2%), Korea (2%), Mexico (2%), Ukraine (2%), and Australia (2%). The inclusion of the Eastern Europe region enables the SGM to match the structure of major international agreements such as the United Nations Framework Convention on Climate Change UNFCCC (United Nations, 1992) and the Kyoto Protocol (United Nations, 1997).

resident in the region⁷. This ensured that regional elements in the SGM explicitly considered important regional characteristics, and insured an enhanced understanding of regional data. Because data availability is heterogeneous the SGM was designed so that each region could be disaggregated to different levels of sectoral detail. While a set of commodity aggregates that trade internationally were fixed, those aggregates could reflect differing degrees of underlying sectoral disaggregation in each region. Investment behavior was also allowed to differ from region to region. Investment behavior in India was not assumed to be the same as in the United States.

- Climate change is a long-term issue that must be addressed at multiple time scales. Radiative forcing is determined by the concentrations of greenhouse gases in the atmosphere, not emissions rates. The importance of this distinction varies from atmospheric constituent to atmospheric constituent. For black carbon, the distinction is unimportant. For short-lived gases there is a relationship between steady-state emissions rates and steady-state atmospheric concentrations. For the long-lived gases and CO₂ the distinction is critical. The concentration of CO₂ is determined by cumulative emissions, at least on time scales of 1000 years or less.⁸ The SGM was thus designed to go fifty years or more into the future.

Technology development and deployment occurs on decadal scales. It can take fifty years for a technology to increase its market share from one percent to 50 percent (Häfele, 1981; DeCanio and Laitner, 1997). The SGM was designed to encompass the time scale of technology transitions.

But policy occurs on a much shorter time scale. The Kyoto Protocol (United Nations 1997)⁹ proposes limitations that would enter into effect over the period 2008 to 2012, a five-year time frame, but a decade after its negotiation. The McCain-Lieberman Bill (S139, 2003) focused on the period 2010 to 2016. The SGM was designed to assess policy proposals that are framed on time scales that are ten to fifteen years into the future.

Policy intervention proposals can also take many forms ranging from fiscal instruments to cap-and-trade to regulatory regimes to combinations of regimes. See for example S139 (2003). The SGM model structure was designed to be capable of examining the

⁷ Model development partnerships were as follows: Canada, University of Victoria; Western Europe Centre International de Recherche sur l'Environnement et le Développement; Japan, National Institute for Environmental Studies; Australia and New Zealand, the Australian Bureau of Agricultural and Resource Economics; Korea, Korean Energy Economics Institute; Former Soviet Union, Center for Energy Efficiency; China, China Energy Research Institute; India, The Indian Institute for Management; Mexico, Universidad Nacional Autónoma de México, Colegio de Postgraduados and Mexicano Instituto del Petróleo.

⁸ This is the consequence of the fact that fossil fuel carbon was removed from the atmosphere millions of years before the present and stored in geologic formations. Reintroducing carbon from the geologic reservoir into the fast cycling ocean-atmosphere-terrestrial system adds to the stock cycling in those three pools. While it can take 1000 years or more for these three reservoirs to reestablish equilibrium, some of the carbon is expected to remain in the atmosphere pool effectively permanently. On average approximately 20 percent of carbon released into the atmosphere would be expected to remain more than 1000 years (Kheshgi, Smith and Edmonds, 2004).

⁹ The Kyoto Protocol remains a proposal as of this writing (August 2004) and has not entered into force. The United States is not a party to the Protocol and has announced an independent approach to emissions mitigation (Bush, 2002).

implications of explicit policy intervention ranging from fiscal policies to regulatory intervention.

Long time scales carry other implications for model design as well. For example, analysis of CO₂ concentration stabilization scenarios reveals that for concentrations ranging from 350 ppm to 750 ppm¹⁰ that annual global emissions must peak and decline during the 21st century (Wigley et al., 1996; IPCC, 2001). This requires substantial departures from present technology deployment, potentially very substantial policy intervention, and dramatically different relative price regimes. Thus, the behavior of the economic system at points substantially removed from present and historical equilibria is an important SGM model design consideration.

The SGM tracks historical capital stock by vintage. The decision to produce from existing capital stocks differs from the decision to acquire and operate new investments. *Ex post* options are inherently more limited than *ex ante* decisions. Once in place, the ability of a sector to substitute between inputs is fundamentally more limited than before the choice of a specific technology and capital investment. But, once in place, existing plant and equipment need only cover operating costs to continue to operate. Sunk costs are ignored. Policies that lead to premature retirement of capital stock are reflected literally in the SGM. That is, productive capacity in the form of existing plant and equipment is removed from the model. The SGM was designed to clear investment markets, track capital stocks, and insure consistency across the economy within a CGE framework.

- Greenhouse Emitting Human Activities Are Pervasive. Unlike simpler environmental problems, emissions of greenhouse related gases are associated with human activities across the entire economy. Energy alone is associated with virtually every aspect of human society and an understanding of fossil fuel CO₂ emissions requires an understanding of the global energy system from production to transformation to transport to end use. Land-use change is the next largest source of net CO₂ emissions to the atmosphere after fossil fuel use. Other greenhouse gases are associated with a variety of human activities, e.g. methane is emitted by ruminant livestock, wetland rice cultivation, landfills, coal mining, deforestation, and natural gas transmission and distribution. These human activities are interconnected. For example, one response to emissions mitigation could be to expand production of commercial biomass energy¹¹. An increase in the production of commercial biomass requires land. Expanding land-use in turn can lead to expansion of land use into presently unmanaged ecosystems. This in turn can lead to carbon fluxes from soils and existing carbon stocks. Such interactions can be significant. Similarly, under some policy regimes, reductions in carbon emissions can also reduce aerosol emissions leading to near-term warming. The SGM was therefore designed as a CGE model to enable system interactions to be addressed explicitly and completely and to be consistent with economic principles.

¹⁰ Preindustrial (1750) concentrations were approximately 280 ppm. If emissions ceased instantaneously, the atmospheric concentrations would relax to approximately 300 ppm over the course of the next 1000 years, but would not return to preindustrial concentrations without a substantial program to remove CO₂ from the atmosphere.

¹¹ Commercial biomass energy is attractive because it is produced and consumed in the short carbon cycle. That is, the carbon released in its oxidation was removed from the atmosphere during the growth of the plant. Growing and consuming commercial biomass fuels produces no direct net carbon release to the atmosphere over the growth-consumption period. Of course, there can be indirect net carbon emissions.

- Technology is a central feature shaping anthropogenic greenhouse emissions. Given that technology is “the broad set of processes covering know-how, experience and equipment, used by humans to produce services and transform resources” (Edmonds and Moreira, 2004), technology is a central issue in understanding climate change. Technology unifies the elements of the system. Technology shapes many elements of SGM design.

Model formulations—First, the SGM is a neoclassical CGE model and therefore can use technology represented either as production functions (the primal relationship between inputs and outputs) or as a dual cost or profit function (the dual relationship between prices of inputs and outputs).

Emissions coefficients—Emissions can be associated with either inputs or outputs. Emissions are usefully reported in physical units. The SGM was designed to track emissions at their point of release. For some greenhouse related gases, e.g. CO₂¹² emissions are associated directly with fuel use. Thus, in the SGM CO₂ emissions are directly related to the fuel input¹³. In other instances emissions are closely related to the output, e.g. CO₂ from cement manufacture. For other emissions, e.g. NO_x and fine particulates emissions are non-stoichiometric¹⁴. The SGM was designed to address the breadth of emissions associated with different technologies and different greenhouse related gases.

Hierarchical structure—Data are always the limiting constraint for modelers. There are virtually no limits to the detail that modelers want. Yet data in the real world are limited. Furthermore, data that are available in one place may not be available in another. To address this reality the SGM defined a data driven structure including markets, sectors, subsectors and technologies. Trade occurs in markets. Markets clear supplies and demands for a specific product. The SGM is designed to clear a user-defined number of markets. The number of markets in SGM 2004 was chosen to best address questions of greenhouse related emissions and mitigation¹⁵. Products are frequently associated with the aggregate output of a sector¹⁶. The selection of sectors in turn is determined by

¹² The traditional treatment of CO₂ emissions is to measure the emission by its carbon weight. This is unlike the traditional pollution measurement which would have counted the weight of the CO₂ molecule rather than the carbon atom only. The reason for this convention is that regardless of the oxidation process, all of the emission components are converted to CO₂ in a relatively short period of time. For example the e-folding time for carbon monoxide removal from the atmosphere (transformation to CO₂) is denominated in months. Thus, the measurement of fossil fuel CO₂ emissions depends only on the carbon-to-energy ratio of the fuel and fuel use.

¹³ Average values of carbon emissions per unit of energy are: Natural gas, 13.7 TgC/EJ; Petroleum, 20.2 TgC/EJ; and Coal, 25.5 TgC/EJ. (TgC: teragrams of carbon = 10¹² C, EJ: exajoules = 10¹⁸ Joules)

¹⁴ That is, emissions rates depend on the conditions under which the reaction takes place.

¹⁵ SGM markets are crude oil production, natural gas production, coal production, hydrogen production, electricity production, oil refining, natural gas distribution, paper and pulp, chemicals, primary metals, food processing, other industry and construction, the everything else (approximates services) sector, passenger transport, freight transport, grains and oil crops, animal products, forestry, biomass production, other agriculture plus a market for labor and loanable investment funds. In mitigation cases markets for greenhouse gas emissions allowances can be formed.

¹⁶ A product can be supplied by more than one sector in the SGM. For example, the SGM 2004 has an electricity market. Electricity is the aggregate output of the electricity sector. However, it is also possible for a manufacturing sector, such as petroleum refining, to employ a technology that produces combined heat and power, and excess power could show up as a supply of electricity from the petroleum refining sector.

importance in addressing the climate problem¹⁷. In addition, the SGM defines subsectors and technologies as components whose output is aggregated to define sectoral production. Production from technologies aggregate to total subsector production and subsector production aggregates to sectoral production. For example, the electricity generation sector as currently implemented has two sectors (base load and peak) and seven subsectors within base load labeled for the primary fuel input: oil, gas, coal, biomass, nuclear, hydro, and other renewables. The coal subsector can be disaggregated into electricity produced from various coal technologies such as for example, pulverized coal, integrated combined cycle coal gasification, and each of these can occur with or without a CO₂ scrubber. Since trade occurs at the level of markets, regions can have dramatically different degrees of technology detail at the subsector and technology levels, and still be compatible with the overall SGM system integration.

- Energy focus—Since CO₂ is the most important greenhouse gas and energy the overwhelming determinant of anthropogenic CO₂ emissions, model design gives special prominence to treatment of the energy production, transformation and use. CO₂ as well as other greenhouse related emissions are directly associated with physical energy flows. Both energy stocks and flows are important to the problem. Stock concepts include resources and reserves, while flows include production and consumption rates. Resources of energy include the total potentially available amounts that could be delivered from known and inferred sources using both presently available and potentially available technologies. Once a resource is identified by place and can be produced profitably with known technology it is defined as a reserve (a subset of the larger resource pool). Production occurs out of reserves both in reality and in the SGM¹⁸. The most important energy transformation is electric power generation. It is a major source of fossil fuel CO₂ emissions and potentially one of the most important sectors in any emissions mitigation policy response. Technology substitution shapes this sector's response to any policy intervention. Electric power generation has a very wide array of technology options, motivating in part the hierarchical structure of the SGM. Similarly, transportation plays a special role in greenhouse related emissions. The transportation sector is a major source of emissions, but unlike power generation it is dominated by a single fuel, and is highly insensitive to a carbon value¹⁹. Transportation emissions are largely determined by technology availability. Furthermore, substitution of energy for other inputs is limited in many processes. This in turn has influenced the choice of functional forms in the SGM. SGM design emphasizes a detailed treatment of the energy sector.
- New investments, expectations and vintaged capital stocks—The SGM five-year time step and the importance of technology motivated an explicit treatment of capital. Whereas it is tempting to treat capital as a malleable factor input to all production

¹⁷ Sectors for SGM 2004 are described in the next section. They include: crude oil production, natural gas production, coal production, hydrogen production, electricity production, oil refining, natural gas distribution, paper and pulp, chemicals, primary metals, food processing, other industry and construction, the service or everything else sector, passenger transport, freight transport, grains and oil crops, animal products, forestry, biomass production, and other agriculture.

¹⁸ Obviously depletable resources (e.g. petroleum, natural gas, and coal) are treated differently from renewable resources (e.g. wind and solar). For the former the use of the resource is consumptive, while for the latter it is not.

¹⁹ The provision of transportation services, e.g. passenger-miles, is dominated by non-fuel costs. There are few economically competitive options for fuel switching in the sector.

functions, the importance of technology in shaping energy transitions argues for a more sophisticated treatment. The SGM was designed to distinguish between existing capital and associated technologies and new investment options; it uses a vintaged approach to capital stocks.

Production occurs out of existing capital stocks and technologies. Technologies are described with a production function that prescribes the relationship between inputs to the production process and outputs. For existing vintages of the technology, capital is limited to the amount initially deployed. This also limits production from each existing vintage. Existing vintages continue to be operated up to the point at which they can no longer cover their operating costs. New plant and equipment is added to the economy each period. Technology options are described by *ex ante* production functions that describe the envelope of potential *ex post* production functions that can be deployed. The *ex post* production function differs from the *ex ante* production function in that the substitution between inputs to the production process is more limited once a specific production function has been selected from within the *ex ante* envelope of possibilities.

The selection of new investments depends on expected profitability. Expected profitability in turn depends on both the suite of *ex ante* production relationships available and expectations about future input prices, output prices, fiscal measures and regulations. The SGM is a recursive model and therefore expectations need not be realized. Price expectations in the SGM are variable, though the model defaults to myopic foresight²⁰. Other options include expectations built upon past experiences and perfect foresight. Combinations of the preceding are also possible. For example it is possible to combine myopic foresight for prices with perfect foresight for other potential policy interventions²¹. Assumptions about the formation of price expectations play an important role in the SGM.

III. SGM Model Description

The previous section described the motivation for the SGM model structure. In this section we describe the model itself, beginning with an overview and concluding with a description of the model's equation structure.

Overview of Model Structure

The SGM is a computable general equilibrium model that has been designed to address issues associated with the emission of greenhouse gases to the atmosphere²². Figure 3.1 provides a schematic of the key sectors of the economy that are interconnected in the SGM computable general equilibrium framework. On the left hand side of Figure 1 are two sectors that create final

²⁰ Decision makers assume prices will remain at then current levels indefinitely into the future.

²¹ The implications for ill formed expectations can also be explored. Decision makers can be given false information, e.g. act as if there will never be a policy intervention, and model output and behavior can be compared to the full-information alternative. As yet the model has not been operated in full perfect-foresight mode, though there is no reason this could not be done.

²² The SGM was designed to be a component of a larger integrated assessment of climate change modeling system. The role of the SGM was to provide a description of the human activities that generated anthropogenic emissions and ultimately experienced the consequences of climate change. To date the SGM has only been used to assess issues associated with the emission of greenhouse gases to the atmosphere.

demands for new net goods and services production in the economy, the household and government sectors. On the right hand side of Figure 3.1 are the sectors of the economy that produce new final goods and services, the energy production and transformation, agricultural, transportation, and industrial and services sectors²³. In addition to the production and consumption of goods and services, Figure 3.1 indicates that the release of greenhouse related emissions to the atmosphere are tracked by the point of release. Gases include both CO₂ and non-CO₂ emissions.

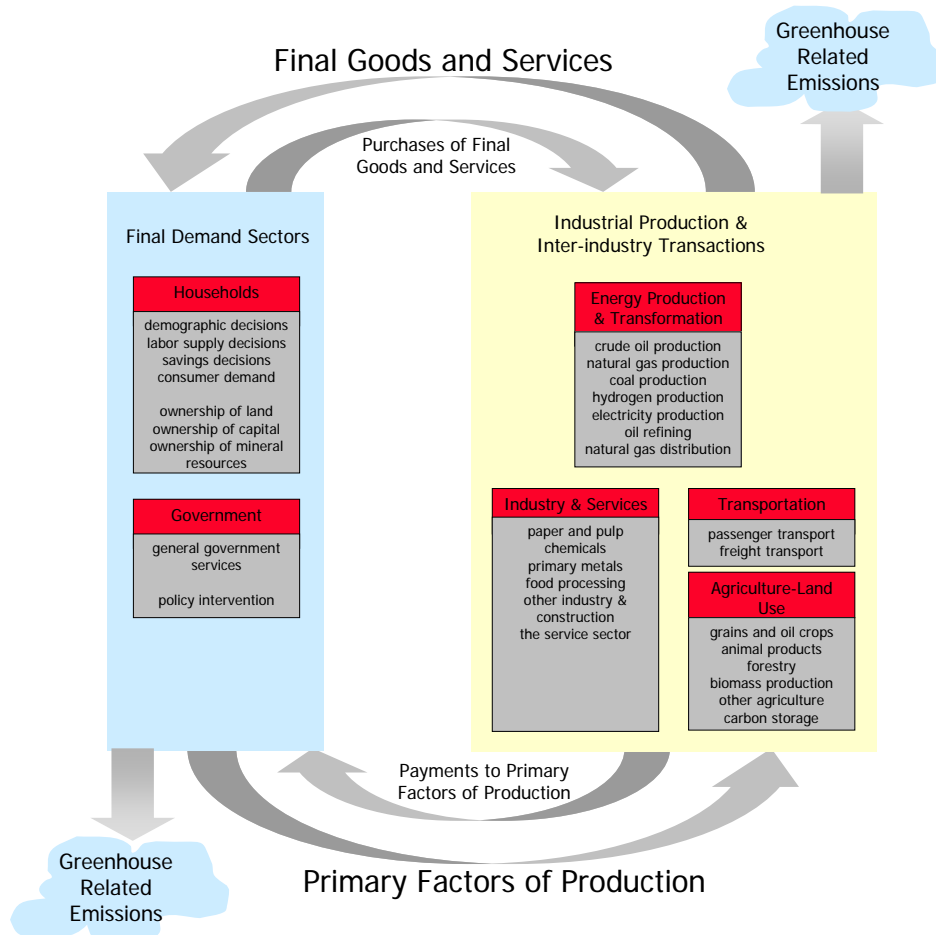


Figure 3.1: SGM 2004 Major Components.

The household sector makes decisions about four issues in the SGM: demographics, labor supply, savings out of income, and the distribution of consumption among alternative goods and services. The government sector consumes some final goods and services, and makes decisions about policy including fiscal policies, subsidies, regulations, and income distribution.

There are 21 producing sectors in SGM 2004. For ease of discourse we have grouped these 21 producing sectors into four larger aggregates (energy production and transformation, industry, transportation and agriculture), but as will become clearer as our discussion proceeds each of the 21 sectors is on a par with every other sector from the perspective of the model. The groupings,

²³ Those who have either taught or taken Economics 101 will recognize Figure 3.1 as simply the classic “circular flow” diagram used to describe an economy.

however, indicate relative emphasis within the SGM. Figure 3.2 gives an estimate of 2004 global CO₂ emissions and its distribution among sectors.

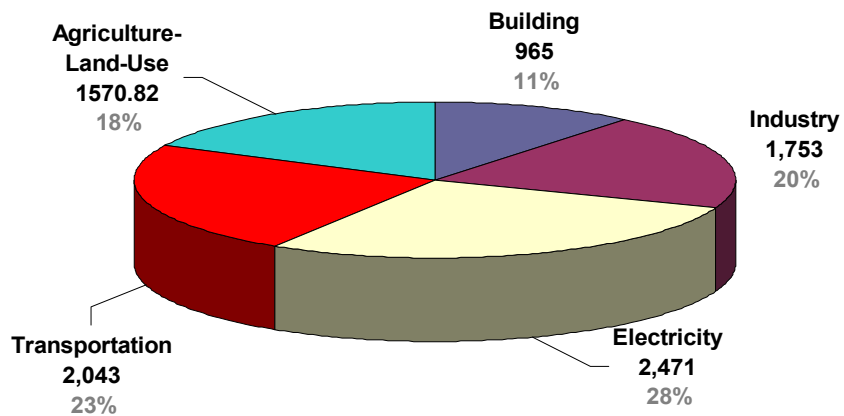


Figure 3.2: Estimated 2004 Global Anthropogenic CO₂ Emissions by Sector

Figure 3.2 reveals that each of the SGM sectoral groups represents a significant fraction of estimated global anthropogenic CO₂ emissions. The bulk of emissions (82 percent) are associated with fossil fuel use. The disaggregation of emissions by sector gives the largest single share to power generation, followed by transportation and industry, with a smaller share associated with buildings (the service and household sectors in the SGM). Since power generation is a derived demand, the share associated with the buildings sector would be closer to those of industry and transportation if electrical emissions were associated directly with the consuming sector.

About one fifth of anthropogenic CO₂ emissions are associated with agriculture and land-use change, principally deforestation and principally in the tropics. Emissions mitigation, however, is not limited to reducing net deforestation and loss from soils. The sector can be a major source of energy (growing commercial biomass as an energy feedstock) and has the potential to store significant quantities of carbon in soils and above ground plantations.

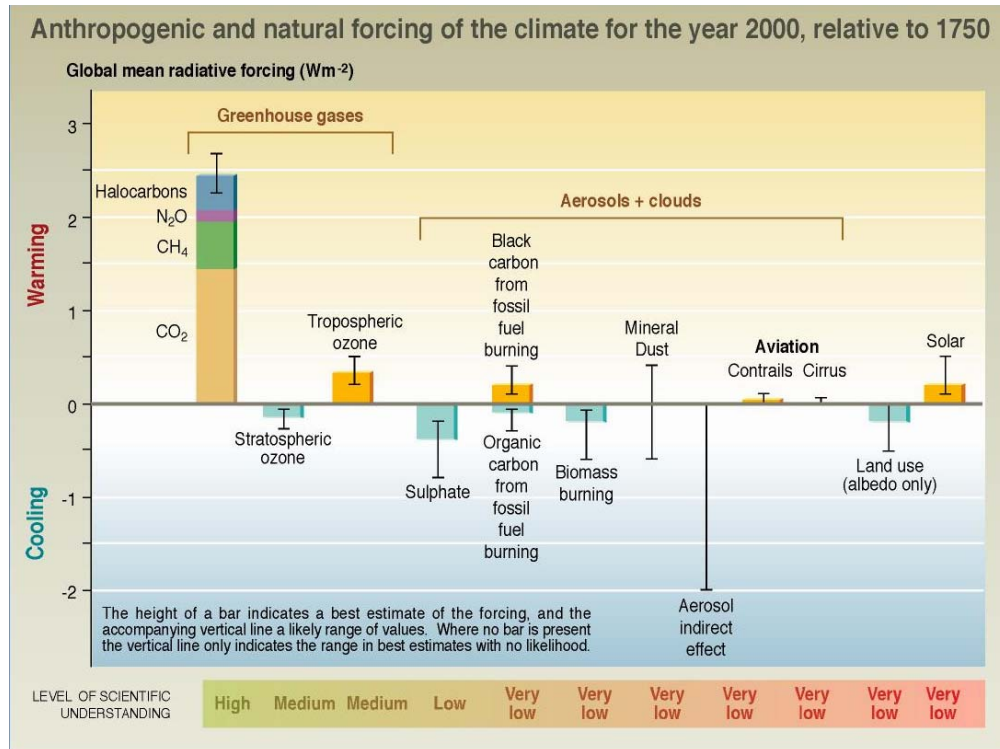


Figure 3.3: Anthropogenic and Natural Forcing of the Climate for the Year 2000, Relative to 1750

(Source: IPCC, Third Assessment Report, 2000.)

What is not shown in Figure 3.1 is the relative importance of different greenhouse gases. As discussed in Section II, the contribution of non-CO₂ greenhouse gases can be significant. Figure 3.3 shows the estimated contribution of all atmospheric constituents that directly affect the Earth's radiative energy balance. (The contribution of gases such as CO, which affect the radiative balance of the planet indirectly through atmospheric chemical reactivity, are not estimated). What is clear from Figure 3.3 is that while CO₂ is the largest single contributor to climate forcing in the industrial era, the non-CO₂ greenhouse gases are associated with a large contribution. Thus, the non-CO₂ greenhouse gases cannot be ignored in addressing climate change.

If one considers only the gases of the United States emissions mitigation policy²⁴ then the non-CO₂ greenhouse gases account for approximately 17 percent of United States emissions. Yet their potential importance in addressing climate change is belied by that aggregate statistic. Emissions of the non-CO₂ greenhouse gases, and particularly methane, have declined at a more rapid rate per unit of GDP than CO₂ (EIA, 2000). More importantly, the presence of each molecule of a non-CO₂ greenhouse gas in the atmosphere is generally associated with a larger change in radiative forcing than a molecule of CO₂. Mitigation of non-CO₂ greenhouse gases can therefore have a benefit in terms of climate change that is relatively large. Furthermore, mitigation of the emissions of short-lived gases, such as methane, can rapidly change the global concentration of these gases and can therefore influence radiative forcing and global mean surface temperature more rapidly than an equal change (in terms of tons mitigated) in the emissions of CO₂.

²⁴ See <http://www.whitehouse.gov/news/releases/2002/02/addendum.pdf> for details.

The SGM is a computable general equilibrium model. This modeling choice provides at least two critically important advantages. First, because a CGE model covers all economic activity, it is a fully internally consistent representation of all economic activities. Given the breadth of activities that are encompassed by the climate problem, it is a natural framework in which to work. Second, a CGE model applies economic principles to the climate problem. Because addressing the climate problem, and particularly the emissions mitigation component, is a problem of allocating scarce resources to competing ends, it is fundamentally an economics problem.

In some ways a CGE model does the same things that any market oriented model does. It gathers supplies and demands from all decision makers in the economy and adjusts prices until markets clear. What is different about a CGE model is that it adjusts all prices until all supplies and demands in all markets are balanced simultaneously²⁵. Effects in one part of the economy are reflected throughout the rest of the economy in a way that is both internally consistent and consistent with economic theory. Thus, quantities that are inputs to simpler, partial equilibrium models, such as for example, Gross Domestic Product (GDP), are outputs of a CGE model.

The Production Function in the SGM

Production in the SGM (the right side of Figure 1) is represented by a set of production functions. Each of the production activities has a relationship between the set of inputs and its output²⁶. That is, we can describe an output, Y, as being produced by using any other produced output, and/or any primary factor of production, capital, labor, land, or mineral resources, or

$$Y = F (X_1, X_2, \dots, X_N)$$

where X_i are the inputs from all 21 of the model's sectors of the economy (crude oil production, natural gas production, coal production, hydrogen production, electricity production, oil refining, natural gas distribution, paper and pulp, chemicals, primary metals, food processing, other industry and construction, the service sector, passenger transport, freight transport, grains and oil crops, animal products, forestry, biomass production, and other agriculture, plus the primary factors of production, capital, labor, land, and mineral resources). The relationship between inputs and outputs is described by the function, F.

Of course, F will be different for each sector. For some the relationship may be simple. For example, in some instances it is a familiar mathematical form such as the Constant Elasticity of Substitution (CES) production function²⁷. For others, it is a more sophisticated, hierarchical

²⁵ In point of fact, if there are N markets to clear, only N-1 prices need be adjusted as one price must serve as numeraire. This is known as Walras' Law.

²⁶ In principle, the structure is sufficiently flexible that it can accommodate multiple outputs as well as multiple inputs.

²⁷ There are many production function relationships that are potentially available. These range from the CES to the Translog (Christenson, Jorgenson, and Lau, 1971) to the Generalized Leontief (Diewert, 1971) to the Generalized Cobb-Douglas, the Generalized CES (Edmonds and Reister, 1982) and there are many more (Perroni and Rutherford, 1998). Production functions have a variety of properties. An attractive feature of production functions such as the Translog is that it is malleable. That is it can match any arbitrary neoclassical production functions to a second order at a point. This virtue is particularly valuable in the analysis of historical patterns of behavior. For models that are looking forward into the future, regularity of behavior becomes increasingly important, particularly under circumstances where changes in relative prices can be large. This is clearly the case for a model like the SGM which looks forward 50

relationship. Regardless, the principle is the same; at any point in time there is a well defined relationship between inputs and outputs. In all instances F accounts for the existing deployment of plant and equipment installed in prior time periods.

Given the relationship, F, and a set of assumptions about the nature of markets, for example, cost minimization as the objective of producers, input and output markets are competitive,²⁸ then the demands for inputs can be derived. From the perspective of production then, this provides an approach to derive both the demand by all sectors for all inputs in the production process, and the supply of all goods to the market, for any set of prices at any point in time. Of course, the demand for all produced goods plus the supply of primary factors of production from final consumers and the government (the left hand side of Figure 3.1) are required to close the system.

Form of the Production Functions in the SGM

In a numerical model such as the SGM the production function takes on an explicit form. The SGM employs the Constant Elasticity of Substitution (CES) production function extensively.

The CES production function (Uzawa, 1962) can be written,

$$q(\mathbf{x}) = \alpha_0 \left[\sum_{i=1}^N (\alpha_i x_i)^\rho \right]^{1/\rho} \quad (3)$$

where gross output q is a function of inputs \mathbf{x} and technical coefficients $\alpha_0, \alpha_i, i=1, \dots, N$. N is the number of inputs to production. Many subscripts have been suppressed for clarity; each sector, subsector, and vintage combination has its own set of technical coefficients. ρ is a parameter that controls the elasticity of substitution σ according to

$$\sigma = 1/(1 - \rho) \quad (4)$$

One attractive feature of the CES is the fact that it can reflect a wide range of substitutability between factors of production. At one extreme the amount of each input required per unit of output can be unchangeable. This is sometime referred to as a Leontief production function. But, it can also exhibit flexibility in substitution between inputs. The degree of flexibility is determined by the elasticity of substitution parameter, ρ .²⁹

years into the future and which can contemplate relative prices that can vary an order or magnitude or more from historical values.

²⁸ That is, individual producers behave as if they can sell as much or as little as they want at the market price, and can purchase as much or as little as they want of any input at the market price. Existing capital is the exception to that assumption. A production function using existing capital is limited to the amount of capital that was installed at the time the production technology was brought on line.

²⁹ This CES production function is written in a slightly different form from that in Edmonds et al. (1993). This functional form makes it easier to describe technical change in the SGM, and more clearly shows the relationship between CES production and fixed-coefficient (Leontief) production. Edmonds and Reister (1982) and Perroni and Rutherford (1995) have shown that nested versions of the CES production can exhibit high degrees of flexibility while maintaining attractive global properties. The elasticity of substitution in CES production functions has a practical lower bound of 0.05 in economic models such as SGM. Elasticities less than 0.05 result in numeric overflows or underflows in double-precision Fortran. Fixed-coefficient production functions in SGM have an elasticity of substitution of exactly zero. Therefore, there is a range of substitution elasticities between zero and 0.05 that SGM cannot simulate.

As discussed earlier, if we add assumptions about the ability of agents to buy and sell as much as they wish at market prices, plus the objective of minimizing the cost of production, then the demand for each input to the production process can be derived as a function of its price and the price of all other inputs. This is expressed mathematically in equation (7), which describes the demand for factors of production per unit output (input-output coefficients) as a function of prices,

$$a_{ij}(\mathbf{p}) = \alpha_{0j}^{-r} \alpha_{ij}^{-r} \left[\frac{p_j}{p_i} \right]^{1-r} \quad (7)$$

where a_{ij} is the amount of input i required per unit of output j . Note that these CES input-output coefficients always depend on prices. Also note that the above equation uses subscripts for inputs and outputs, except for the exponent r . This exponent actually does vary by producing sector, but subscripts on r have been suppressed.³⁰

Table 3.1: Sectors, Subsectors and Technologies in SGM 2004

Market:	ELECTRIC POWER	
Sector:	BASELOAD POWER	PEAKING POWER
Subsector:	Gas Natural Gas Combined Cycle Natural Gas Combined Cycle with Carbon Capture and Storage (CCS) Coal Coal Gasification Combined Cycle Coal Gasification Combined Cycle with CCS Pulverized Coal Pulverized Coal with CCS Nuclear Light Water Nuclear Reactor Hydro Other Renewable Geothermal Solar (generic) Wind (on-shore) Wind (off-shore) Municipal Solid Waste Biomass Biomass crop solids	Oil Gas

³⁰ The corresponding CES cost function is

$$g(\mathbf{p}) = \frac{1}{\alpha_0} \left[\sum_{i=1}^N \left(\frac{p_i}{\alpha_i} \right)^r \right]^{1/r} \quad (5)$$

where $r = \rho / (\rho - 1)$ and p_i is an element of the price vector \mathbf{p} . (6)

Technologies are shown indented beneath each subsector.
 As indicated above, the relationship between inputs and outputs can be relatively sophisticated.
 Consider electric power generation in the SGM 2004 as shown in Table 3.1 above.

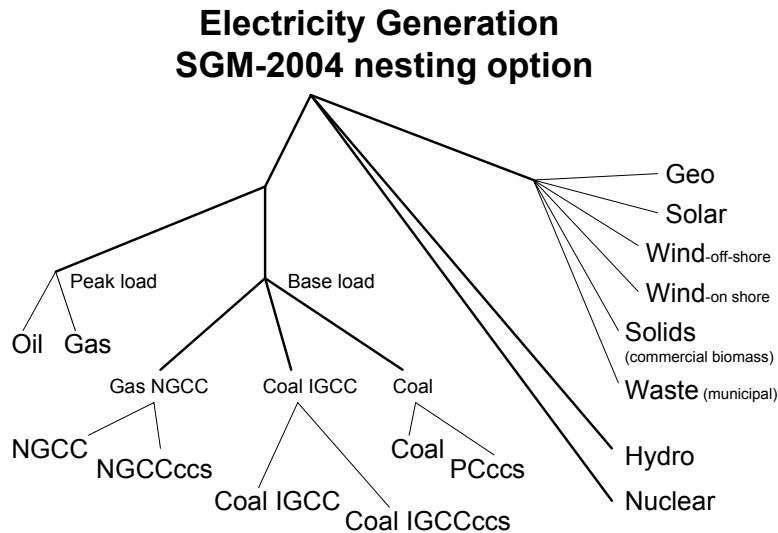


Figure 3.4 SGM 2004 Nesting of Power Generation Technologies

For each of the technologies listed above, there is an individual production relationship between inputs and the production of electricity. The total production of electricity is the sum of electricity production from all of the baseload technologies plus all of the peaking power technologies³¹. Total demand for production from each of the other sectors, plus the demand for labor and other primary factors of production is the sum of the demands from all of the baseload power technologies plus all of the peaking power technologies.

Historical Capital and Vintaged Production

Technology is never static; it evolves with time. The history of technology development can be seen in the distribution of previously deployed physical plant and equipment. Some technologies have been available for a century or more, e.g. electricity generation from coal. Other technologies have become available only more recently, e.g. combined cycle natural gas turbines. Other technologies remain to be deployed in commerce, e.g. coal gasification combined cycle with carbon capture and geologic storage. Yet even such long-lived technologies as electric power from coal generation have changed and evolved. The pulverized coal plants installed in the 1980s in the United States are fundamentally different from the plants deployed in the 1950s.

The SGM begins each period with a legacy of historical technologies and their associated plant and equipment (which constrains total production from historical plant and equipment). The SGM keeps track of capacity associated with each of the technologies. For example, in the electric power generation sector this includes tracking capacity for each of the technologies listed

³¹ It is worth noting that for electricity, physical production is additive. One base-load Watt-hour produced using coal is perfectly substitutable with a base-load Watt-hour produced using natural gas. This may not be true for other sectors, such as for example the Service sector.

in Table 3.1, in five-year intervals. For many of these technologies in the base year, 1990, no installed capacity exists. For example, there is no coal gasification combined cycle with carbon capture and geologic storage. For other technologies, there is substantial capacity in every vintage stretching back into history, e.g. pulverized coal.

The SGM has defined lifetimes for plant and equipment. Some old capacity is retired each period³². The SGM solves every five years, and infers retirements over the entire five-year time step since the previous solution year. Prior to reaching retirement age, capacity is operated as long as the owners can cover their operating costs. That is, once installed, returns to capital do not affect the decision to operate. Owners of the plant and equipment may receive precisely the returns they expected, or they may earn much more, or they may receive less than expected when the plant and equipment initially went into operation. Regardless, the plant and equipment is operated as long as operating costs are covered^{33, 34}.

The Demand for New Plant and Equipment

In addition to existing capacity, the SGM also invests in new plant and equipment in each five-year time step³⁵. This decision includes a consideration of all of the technology options potentially available—their input requirements (including capital investment) and their production, as well as expectations about the prices for inputs and outputs over the lifetime of the plant and equipment³⁶. Because there are many potential options in which to invest, the SGM

³² The lifetime of capital in SGM, while conceptually variable, is typically 20 years, or four model time steps. Existing vintages can be shut down before planned retirement if revenue is not sufficient to cover variable costs.

³³ This explains why for example existing nuclear power plants are some of the most profitable units in the United States' electric utility system, while there has not been a new unit brought on line in decades.

³⁴ At profit rates below a user specified value, the operating level of an existing capital stock will be scaled back in order to maintain a continuous supply function, a necessary condition for the solution algorithm to work.

³⁵ Production of outputs and input requirements are denominated in terms of annual rates. As a consequence, investments for years between any two five-year time steps are inferred by interpolation.

³⁶ The technology or production function choice set before the fact can be quite large. Because any potentially available technology can potentially be utilized, the degree of substitutability between inputs to the production process before a specific investment is made can be greater than after the fact. The relationship between inputs and outputs potentially available before an investment is made is referred to as the *ex ante* set of production possibilities, while the specific technology selected is said to contain the *ex post* set of production possibilities.

The CES production function is employed to represent both the *ex ante* and *ex post* relationship between inputs and outputs. An *ex post* production function is one that has been deployed in the economy. Production in the SGM only occurs after a particular production function is chosen, that is an *ex post* production function.

New plant and equipment enter the economy at the time of investment. Investments are made from the array of potentially available options. For any technology the suite of all potentially available technology options forms the *ex ante* production function. The *ex ante* production function is the envelope of all potentially available *ex post* production functions. Needless to say the elasticity of substitution of the *ex ante* production function always exceeds that of the *ex post* production function.

A wide range of price response is available by selecting various combinations of elasticities for the *ex ante* and *ex post* production functions. The four types of price response are putty-putty, putty-semiputty, putty-clay, and clay-clay.

At one extreme is the putty-putty relationship between the *ex post* and *ex ante* production functions. A putty-putty technology uses the same elasticity of substitution for both new and old capital. New capital and old capital respond in the same way to changes in price. This can occur when there is only one production function from which to choose.

assigns levels of investment based on expected profitability. That is, the demand for new capital is determined by the expected contribution of that investment to the net worth of the sector³⁷. The expected profit rate is the discounted profit stream divided by the amount of capital invested. Introducing a value for carbon increases the price paid for fossil fuels, which are inputs to production. If other prices don't change, then the profit rate goes down for all production processes that use fossil fuels. A carbon value, therefore, moves investment away from sectors or subsectors that use fossil fuels as inputs. Of course, the SGM only invests in sectors in which expected profits are positive.

The default assumption for expectations is that current prices are anticipated to remain fixed, but that future policy interventions are known with perfect foresight. This pair of assumptions is arbitrary. There is no well defined method for determining price and policy expectations, though there are competing representations. In fact, there is no reason to presume that one set of model derived parameters can accurately predict expectations for future prices or policies. The prediction of price and policy expectation remains as much an art as a science. But, other options can be employed. For example, experiments have been run in which price expectations are formed using prior period price trajectories as a guide to forming expectations of future prices. Similarly, experiments have been run in which model decision makers were assumed to be surprised by policy interventions. This flexibility allows experimentation with uncertainty associated with expectation formation.

When multiple *ex post* technologies are available, then a putty-semiputty relationship can emerge. A putty-semiputty technology provides a lower elasticity of substitution in old capital than in new. In this case, the choices of new capital provide greater flexibility in input substitution than does a particular type of capital once it has been constructed.

A putty-clay technology assumes that old capital is fixed-coefficient and the input-output coefficients do not respond to price. The input-output coefficients reflect relative prices that were in effect when the capital was new. Therefore, new capital is responsive to prices, but input-output coefficients are locked into place as the capital is converted from new to old. The elasticity of substitution between inputs in a fixed-coefficient (or Leontief) technology is zero.

Some technologies are considered to be fixed-coefficient whether new or old, and are completely unresponsive to prices. This technology is referred to as clay-clay or simply clay. This assumption is sometimes used in the energy transformation sectors, especially oil refining, where the ratio of energy input to energy output is fixed in advance by physical processes and cannot respond to changes in price.

³⁷ The primary algorithm presently used to determine investment demand scales previous period investment as shown:

$$x_{ij} = sclinv * base_kap * \frac{working_age_population_t}{working_age_population_{t-1}} * E(\pi)^\varepsilon \quad (22)$$

where *sclinv* is a scalar multiplier, *base_kap* is investment in the previous period,

$E(\pi)$ is expected profits per dollar of investment (normalized to one in the base period) and ε is an accelerator (typically set at one).

A second options begins by computing output expected from new capital as the difference between expected future output for the sector and output from the existing capital stock:

$$\tilde{q}_{j,new} = \tilde{q}_j - \tilde{q}_{j,old} \quad (23)$$

where \tilde{q}_j is total expected output and $\tilde{q}_{j,old}$ is output from old capital. The demand for new capital is thus computed as

$$x_{ij} = a_{ij}(\mathbf{p}) \tilde{q}_{j,new} E(\pi)^\varepsilon \quad (24)$$

where $a_{ij}(\mathbf{p})$ is a capital-output coefficient given by equation (7) and $E(\pi)^\varepsilon$ is as in (22).

Future price expectations are just that in the SGM, expectations. Investors can make mistakes. Market clearing prices in future periods may or may not fulfill prior expectations. Though full perfect foresight could in principle be enforced within the context of the SGM, this experiment has never been run. Implementing this assumption requires that the basic model be wrapped in software to enforce the consistency. While there is no obvious obstruction to implementing a perfect foresight version of the SGM, run times are typically significantly longer than for a recursive model and sponsors of the model have never encouraged development along these lines. Model development along other lines has held higher priority.

Whenever a production sector is split into subsectors, a method for allocating sector-level investment across subsectors is required. The electricity sector operates somewhat differently from the other producing sectors in that there are several generating technologies, or subsectors, each with its own production function. Each electric generating technology is represented by a production function with a very low elasticity of substitution. Price response in the electricity sector is governed mainly by a logit sharing process that controls investment rates in generating technologies as the relative expected profit per kWh changes. One advantage of this electricity generation structure is that it preserves energy balances: for any particular generating technology, heat rates remain in a limited range with limited response to changes in fuel prices; output of the sector is the sum of output by technology.

Investment is allocated to production activities in two stages, first to production sectors and then to subsectors within a sector. With the exception of the “everything else” sector, each separate sector in the SGM represents production of a distinct product. Subsectors represent different ways of making that product. Presently, electricity generation is the only sector with more than one subsector.

The allocation of investment to new plant and equipment is not a “winner-take-all” decision. Rather, the greater the expected profitability, the greater the share of investment allocated to the investment. Once new capacity is added to the economy, its capital stock and production function are fixed and remain in that state until retired.

The production of primary energy presents special issues that must be taken into account. The SGM distinguishes between resources and reserves of depletable energy resources: oil, natural gas, and coal. Energy reserves represent quantities of the resource that are known to exist and which can be profitably produced at current prices. The production of oil, natural gas, and coal all occur out of energy reserves. Reserves are generally adequate to provide continuous supply for only a limited time. They are constantly being drawn down by production and supplemented by additions from resources. In principle, resources include all occurrences that could ever be found and potentially produced with any possible technology. Thus, reserves are known with a high degree of certainty while resources are known with much lower certainty. Resources can be disaggregated into grades which partition by total cost of production. SGM 2004 has the potential to disaggregate resources into any number of grades, depending on the data.

At the beginning of any five-year time step, the SGM has a set of technology vintages for producing energy from reserves. Like any produced good in the SGM, the production rate from each vintage is limited by the historical capital stock. In addition, cumulative production is limited by the reserves that are associated with that particular vintage. The SGM augments that production capability from resources. Like other produced goods, the SGM has a set of available technologies, described in the form of available production functions, which can be applied to resources to produce new output. As the SGM brings a larger portion of the resource into the

reserve category, marginal cost rises. This in turn limits additions to reserves in any individual period. Inter-time-step additions to capacity are inferred by extrapolation.

Technological Change in SGM

Technology can change from one period to the next. Technological change is exogenously specified in the SGM. That is, the relationship between inputs and outputs can be changed. There is a multiplicity of potential modes of change available in the SGM. These range from the simplest, on-off types of change, to the enhancement or degradation of individual inputs to the production process. The “on-off” mode of change is simple. In this mode technology options can either be made available—new options coming on line—or can be taken off line. For example, coal gasification combined cycle with CO₂ capture and geologic storage may be unavailable prior to a specific date when it is “turned on”. Similarly, a technology could be “turned off”—made unavailable, for example as a consequence of a policy intervention such as a technology performance standard.

More common is technological change that incrementally enhances the contribution of inputs to the production process for new investments. For example the process for producing electricity using coal could require one-half percent less of each input every year for 10 years with no change after that. This of course, would only apply to new vintages of the technology installed. Alternatively, labor productivity may rise systematically from period to period. Improvements in labor productivity for new vintages of capital are the primary determinants of economic growth per capita in SGM.

Energy efficiency and labor productivity are the two most important productivity parameters in the SGM. Labor productivity parameters are the primary determinant of economic growth in SGM and are used to influence the time path of GDP in a reference case. These two sets of parameters, energy efficiency and labor productivity, assist in constructing reference or business-as-usual scenarios. The labor productivity parameters are used to determine a time path for GDP and the energy efficiency parameters are used to determine consumption of energy by fuel and therefore emissions.³⁸

³⁸ If the efficiency of all inputs to a given production process is changing at the same rate, then technical change is said to be neutral. If the rate of change in efficiency varies across inputs, then technical change is said to be non-neutral or biased. Neutral technical change in the SGM is represented by a multiplicative parameter in each production function. This parameter increases the input efficiency of all inputs by the same rate. The SGM can also represent non-neutral technical change. For example, we could have a technology for which labor productivity is improving at a faster rate than energy efficiency. In this case the amount of labor needed per unit of output is falling faster than the amount of energy needed per unit of output.

If the production process is fixed-coefficient, then these technical change parameters can be used to precisely control input efficiency. However, most production processes are not fixed-coefficient, at least in the long run as old capital is replaced by new capital. Most production processes respond to changes in prices of inputs by substituting away from those inputs that are relatively expensive. In this case, input efficiency is affected by both the exogenous technical change parameters described in this section and by changes in relative prices. Changes in input efficiency are a combination of exogenous technical change and price-induced technical change. Exogenous technical change is represented by a shifting isoquant; price-induced technical change is represented by shifts along an isoquant.

All of the α parameters in the CES production function, as well as the corresponding parameters in fixed-coefficient production, can be specified to have a growth rate γ during each of the SGM’s five-year time steps (NSTEP=5). This is similar to Autonomous Energy Efficiency Improvement (AEEI) used in some other energy models; but in the SGM, exogenous rates of technical change can be specified for all

Households

The left hand side of Figure 3.1 represents the final demands of the economy. The SGM treats the household and government sectors in a simplified manner. All of the revenues from taxes go to the government sector. All of the wages from labor, all of the returns to capital, all of the rents on land, and all of the returns to mineral resources are income for the household sector.

The household sector makes decisions about demographics, labor supply, savings, and the portfolio of final consumption. SGM 2004 treats demographics, labor supply, and savings simply. The demographic structure of the population is built up through assumptions about age- and gender-specific fertility rates and survival rates³⁹. This in turn implies a work-aged population. The application of age- and gender-specific labor-force participation rates, which can vary with time, yields a labor force for a model scenario. The supply of labor is assumed to be positively related to the wage rate⁴⁰.

inputs to production, not just energy. For example, the labor productivity parameter is used primarily for calibrating the SGM to a GDP growth path. The energy productivity parameters are then used to adjust energy consumption. Technical change growth rates can either grow smoothly over time or vary between time steps.

In this case all of the α_i parameters within a production function are assumed to change at the same rate under neutral technical change. This is equivalent to varying only α_0 , as is shown in the following equation.

$$\alpha_{0_j}(T) = \bar{\alpha}_{0_j} \prod_{S=1}^T (1 + \gamma_{0_j}(S))^{NSTEP} \quad (19)$$

T is an integer that represents the model time period, where T=0 during the base year of 1990. Since the model runs in five-year time steps, T=1 represents 1995. If t is the number of years since 1990, then

$$t = T \times NSTEP$$

Because neutral technical change over long periods of time can result in violation of physical laws concerning rates of conversion of energy from one form to another, it is used only sparingly in the SGM.

Instead of adjusting α_0 to represent technical change, each of the α_i parameters are adjusted with their own technical change parameters γ_i . Note that an increasing α_i represents improved technical efficiency.

$$\alpha_{ij}(T) = \bar{\alpha}_{ij} \prod_{S=1}^T (1 + \gamma_{ij}(S))^{NSTEP} \quad (20)$$

This is the preferred way to represent technical change in the SGM, as it allows for precise control over physical conversion of energy from one form to another and thus ensures physical consistency, critical in a model that seeks to understand physical climate process.

³⁹ The SGM keeps track of population within each region by gender and five-year age cohort. Population data may be read in directly, using projections from the World Bank, United Nations, or US Census Bureau for the model base year and all future SGM time steps. This is the usual way of specifying population in the SGM. Alternatively, base-year population may evolve in the SGM by applying assumptions with regard to survival rates, fertility rates, and migration rates. For any time period, total population is given by

$$POP_{tot} = \sum_{age=1}^{NAGE} POP_{age,males} + POP_{age,females} \quad (33)$$

where $POP_{age,males}$ is the number of males in age group age ; $POP_{age,females}$ is the number of females in age group age ; and $NAGE$ is the number of age groups defined.

⁴⁰ Labor supply in the SGM is derived using the following equation.

$$X_{labor} = \alpha_{labor} POP_{WorkingAge} (1 - \exp(\beta_{labor} P_{labor})) \quad (34)$$

The supply of land is constrained by the total surface area and positively related to the rental rate on land⁴¹. In addition to the supply of land, there is also a demand for land by the household sector.

The household sector is an important source of savings. The other major sources of savings are retained corporate earnings and net government savings (or dissavings). Savings is proportional to income and positively related to the rate of interest⁴².

The demand for final goods and services by the household sector is determined by prices and aggregate consumption⁴³ in conjunction with price and income elasticities⁴⁴.

Closing the System

Each regional representation of the SGM needs to describe how its markets include trade with the rest of the world. There are three options for each market: tradable, non-tradable, or traded at a fixed quantity. When an individual region is solved independently of the rest of the world, a fixed world price is assumed for certain tradable goods; regions may import or export as much of that good as desired at that fixed world price, subject to an overall balance of payments constraint. For all non-tradable goods, the quantity of trade is fixed in advance.

One produced good is selected as the numeraire. This is the “everything else”⁴⁵ good and it is tradable. The price of the numeraire good is set to 1 during each time period. Except for the

where α_{labor} is the maximum potential share of working age population employed in any given year; $POP_{WorkingAge}$ is the total working age population (ages 15 to 64); β_{labor} is a labor supply responsiveness coefficient; and P_{labor} is the average annual wage rate.

⁴¹ Households supply land, on the basis of a land rental rate, according to the following equation.

$$X_{land} = \alpha_{land} LAND(1 - \exp(\beta_{land} P_{land})) \quad (35)$$

where α_{land} is the maximum potential share of land supplied to the market; $LAND$ is the total land area that could be managed for agricultural or other purposes; β_{land} is a land supply responsiveness coefficient; and P_{land} is the average annual rental rate on a unit of land.

⁴² SGM represents savings as a function of present income and the interest rate,

$$S_{hh} = \alpha_{hhsave} Y(1 - \delta_{hhsave} \exp(\beta_{hhsave} r)) \quad (36)$$

where α_{hhsave} is the maximum potential savings rate; Y is disposable personal income; δ_{hhsave} is a scale parameter; β_{hhsave} determines the sensitivity of households to the interest rate; and r is the interest rate.

⁴³ The total value of consumption can then be calculated by

$$Y_c = Y - S_{hh} - X_{land, hh} P_{land} - X_{labor, hh} P_{labor} \quad (40)$$

⁴⁴ These demand functions are consistent with the existence of a utility function for the household sector and the assumption of utility maximization, though this places important constraints on parameter values. The functional relationships are given by

$$Xd_{i, hh} = \alpha_{i, hh} P_i^{\beta_{i, hh}} Y_c^{\gamma_{i, hh}} \left(\frac{1}{\lambda} \right) \quad (41)$$

where $Xd_{i, hh}$ is demand for good i by the household sector; $\alpha_{i, hh}$ is the household demand intensity factor for good i ; $\beta_{i, hh}$ is the price elasticity of demand by households for good i ; $\gamma_{i, hh}$ is the income elasticity of demand by households for good i ; and

$$\lambda = \sum_{i=1}^{NS} \alpha_{i, hh} P_i^{\beta_{i, hh} + 1} Y_c^{\gamma_{i, hh} - 1} \quad (42)$$

Middle East, all regions are price takers with respect to oil and natural gas. Land and labor are always non-tradable. All other sectors are either non-tradable or have the quantity of trade set in advance.

An exogenous balance-of-payments constraint is specified in advance for each region. Most regions are assumed to move linearly from a historical trade balance in the base year to balanced trade sometime in the future.

With specification of a trading status for each market, the model has all of the information that it needs to find a solution. The model is said to have solved when it has a set of prices for all goods and services that allows all sellers of a good, service, or primary factor of production to sell as much as they want at that set of prices and all buyers to be able to buy as much as they want at that set of prices. Furthermore, all economic agents, producers, households, and government have exactly the income necessary to match their demands and supplies. Obviously, the solution algorithm uses non-linear methods to obtain the necessary solution prices. Nevertheless, the system is sufficiently well behaved that finding a solution is not a problem⁴⁶.

Global Model with Trade in Emissions Permits

The global version of the SGM is used when there is at least one market that must clear globally. For example, carbon emissions permits may be traded among regions. The model searches for a global permit price that clears the market for permits.

Many of the SGM regions, including India and China, operate in local currency. Therefore, an exchange rate must be selected to convert the world market permit price, in U.S. dollars, into local currency. The SGM uses base-year (1990) market exchange rates for this conversion.

The global model can be run with oil prices set exogenously. Given the difficulty of modeling OPEC pricing behavior, most model exercises use a projected time path of oil prices provided by others. In this case, all regions except the Middle East treat this price parametrically. The Middle East then supplies whatever oil is needed to meet global demand.

Greenhouse Gas Emissions

As noted earlier there are multiple gases that are relevant to climate change. Non-CO₂ greenhouse related gases are critical to understanding climate change and are accorded commensurate importance in the SGM. The SGM can be run to mitigate just CO₂ or CO₂ plus the Kyoto “basket” of greenhouse gases—CH₄, N₂O, HFC’s, PFC’s and SF₆. The SGM solves the problem of the determining equivalencies between the different gases by using 100 year global warming potentials⁴⁷.

⁴⁵ In regions which have been updated to include energy intensive sectors, transport and buildings, “everything else” approximates the services sector. In less elaborate sectoral breakdowns it includes everything not explicitly modeled.

⁴⁶ In fact, failure of the system to solve is usually associated with a data input error.

⁴⁷ The global warming potential (GWP) is the instantaneous radiative forcing that results from the addition of one kilogram (kg) of a gas to the atmosphere, relative to that of one kg of carbon dioxide. They are defined for a variety of integration time horizons. The IPCC provides values for 20 years, 100 years, and 500 years. By selecting an integration time horizon, e.g. 100 years, GWP values can be used as a proxy to compare the relative climate impacts of one kg of a set of greenhouse gases.

Given the wide variety emissions and technologies for controlling them, there are a variety of mitigation options in the SGM. These options include 1) for CO₂ detailed modeling of the CO₂ emissions response to a carbon price, 2) for non-CO₂ emissions the use of exogenous curves relating percent reduction in emissions to the carbon price and 3) for soil and forest based sequestration, the use of exogenous results showing the amount sequestered as a function of the carbon price.

Investment and operating decisions respond to policy instruments. A carbon value can be associated with the carbon content of fuels and in this case would affect the price paid by consumers of the fuel. This in turn would affect investment decisions and the purchase of inputs to production processes. Carbon values can either be exogenously given or endogenously determined, as for example in cap-and-trade regimes. The presence of vintaged capital and low elasticity of substitution for existing capital stocks means that the full response to a carbon price takes time to materialize (see figure 4.4). The carbon price necessary to achieve a given target is a function not only of the target, but also of both the baseline trajectory and the portfolio of technologies available for investment. The technology portfolio has, in addition to its impact on the carbon price, a significant impact on the balance between lowering emissions and lowering energy use that is necessary to achieve the target.

For the non-CO₂ emissions, as shown in Table 3.2, there are six gases and more than a dozen sources, making the process modeling used for CO₂ impractical. Rather, the approach is to determine emissions as a function of a base period emissions factor and an activity level and then reduce these emissions as a function of the carbon price using exogenous process-based estimates of the relationship between the carbon price and the percent reduction in emissions. These external estimates, called marginal abatement cost curves (MACCs) are specific to each source and emission.

Table 3.2: Emission Sources, Drivers and Control Options

Activity	Emission	Driver	Mitigation option
Oil Combustion	CO ₂	Total Combustion	Endogenous
Gas Combustion	CO ₂	Total Combustion	Endogenous
Coal Combustion	CO ₂	Total Combustion	Endogenous
Coal Production	CH ₄	Coal	MAC
Enteric	CH ₄	Ag Production	MAC
NatGasSys	CH ₄	Gas Trans & Dist	MAC
OilSys	CH ₄	Oil Production	MAC
Manure	CH ₄	Ag Production	MAC
OthAgMeth	CH ₄	Ag Production	MAC
ManureN	N ₂ O	Ag Production	MAC
SoilN	N ₂ O	Ag Production	MAC
Landfills	CH ₄	Everything Else	MAC
OthNonAgMeth	CH ₄	Everything Else	MAC
Wastewater	CH ₄	Everything Else	MAC
HFC23	HFC-23	Everything Else	MAC
ODSSub	HFC's	Everything Else	MAC
IndProcsN	N ₂ O	Everything Else	MAC
MobileN	N ₂ O	Everything Else	MAC
StationaryN	N ₂ O	Everything Else	MAC
Aluminum	PFC's	Everything Else	MAC
Semiconductor	PFC's	Everything Else	MAC
Mg	SF ₆	Everything Else	MAC
ElecDist	SF ₆	Electricity	MAC
Soil and Forest		NA	Sequestration
Sequestration	CO ₂		function

(DeAngelo *et al* 2004, Delhotal *et al* 2004, Schaefer *et al* 2004, Scheele and Kruger, 2004)

The base period emissions factor is determined from the ratio of base period emissions to the base period activity level (denoted as the driver in Table 3.2). In addition to the cost curves and base period emissions, there are model inputs which can be used to match the time path of emissions to an external source. For the most recent analysis of the full set of greenhouse gases, Stanford Energy Modeling Forum (EMF-21), we used the Environmental Protection Agency's estimates of the emissions trajectories as well as their estimates of the reduction in emissions as the carbon price increases.

The third major emissions mitigation strategy is soil and forest carbon sequestration. Here through changes in management practices for crops and forest, carbon stores on the land can be increased. While we are working on making these sequestration options an endogenous part of the model, this effort is not yet complete, so in the meantime we use an exogenous estimate from Bruce McCarl⁴⁸ of the amount of sequestration which will occur as a function of the carbon price.

⁴⁸ McCarl, personal communication of FASOM results.

IV. The SGM in Use: Data and Parameters

While the theoretical structure of the SGM can accommodate any number of regions and sectors, the model as implemented has fourteen regions and varying numbers of sectors (10 to 24). Regions for which an operating SGM model version exists are given in Table 4.1. Each regional SGM is instantiated using the same generic procedures. The model is first calibrated so that it reproduces a base year, presently 1990.

Model Calibration and Initialization

Model calibration and initialization requires three different types of data:

1. Economic and Demographic Data
2. Energy Balances, and
3. Technology Descriptions.

Economic data include input-output tables and supplemental information from the national income accounts as well as energy balance tables obtained either from the International Energy Agency (IEA) or from government agencies within a region.

Table 4.1. Regions in the SGM

Annex I	Non-Annex I
United States	China
Canada	India
Western Europe	Brazil
Japan	Mexico
Australia and New Zealand	South Korea
Former Soviet Union	Middle East
Eastern Europe	Rest of World

Most input data require some form of processing before being used in the SGM. When constructing a new SGM region, or updating an existing region to a new base year, the majority of time is spent obtaining and processing the necessary data. Usually, available data will not exactly match SGM requirements and modeler's judgment is often needed to reconcile differences. This is especially true for multi-country regions.

Table 4.2. Data Transformation in SGM

Original Data	Derived Data for SGM
1990 Economic Input-Output Table 1990 Energy Balance Table	Hybrid Input-Output Table
Annual Investment Data by Sector	Capital Stocks by Sector
Data on Fossil Fuel Resources	Resource Grades
Electricity Supply: generation, installed capacity, energy consumption, capital costs, operating costs	Input-output representation of electricity generation by fuel
National Income Accounts	Tax rates, Savings rates

Input-Output Tables

The most important data set to be collected is a base-year input-output table of the economy. This forms the basic economic framework that all of the other data conform to.

Traditional economic input-output tables provide an economic framework for constructing a CGE model. However, input-output tables use currency units that might not convert consistently to physical units such as energy. We supplement the economic data from an input-output table with an energy balance table, which is essentially an energy input-output table. The resulting hybrid input-output table has energy units (joules) for energy carriers and currency units for all other goods. Such a table allows exact base-year model calibration to base-year energy balances and ensures that energy balance is maintained throughout all model time periods. This also facilitates base-year calibration of carbon emissions, as most carbon emissions are the result of energy combustion. The concept of a hybrid energy input-output table is described in Miller and Blair (1985).

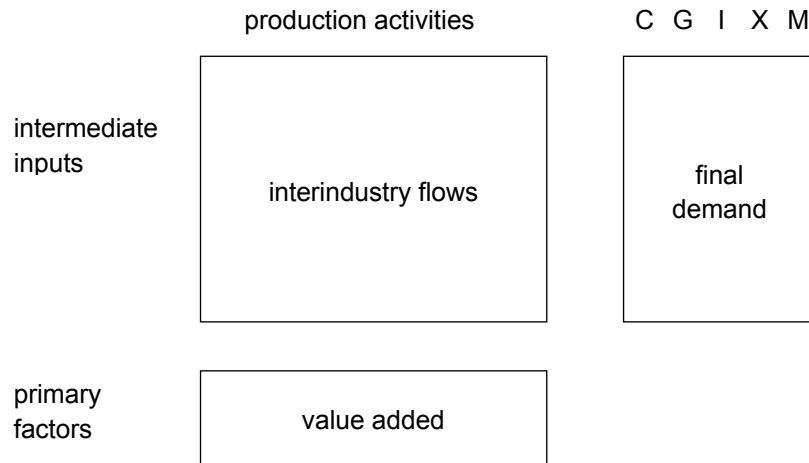
Economic Input-Output Tables

We have obtained input-output tables for the United States, Canada, Japan, China, India, Mexico, and South Korea. However, these are generally produced at five-year intervals and may not be available for the SGM base year of 1990. For example, input-output tables for the United States are available for 1987 and 1992. A 1990 input-output table for the United States was constructed through interpolation and the use of other economic data.

Multi-country regions present a particular challenge because input-output tables are not available for all countries in the region, and each country has its own currency. It may be necessary to build an input-output table based on data from the national income accounts and from patterns in other input-output tables. For single-country regions, the units are local currency, such as Korean *won* or Indian *rupees*. United States dollars are used as a common currency for multi-country regions.

An economic input-output table has three major sections: interindustry flows, value added, and final demand. An input-output table is organized with inputs as rows and activities as columns as shown in Figure 4.3. Inputs include intermediate inputs (those derived from a production process) and primary factors of production. The primary factors of production are labor, capital, and sometimes land. Activities that use inputs are industries, consumption by consumers, consumption by government, investment, and net exports (exports minus imports).

Figure 4.1. Typical Input-Output Table



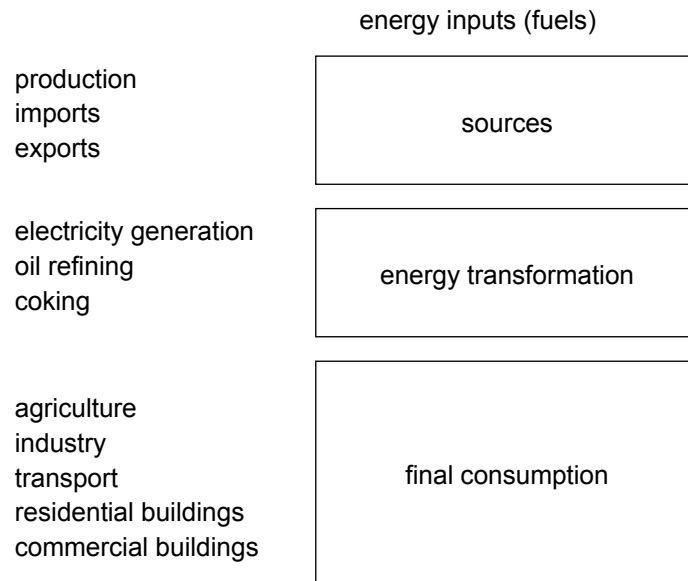
An economic input-output table is a snapshot of an economy, in value terms, for one particular year. Input-output tables contain varying amounts of sectoral detail, depending on the country, with anywhere from 30 to over 500 producing sectors. The tables are aggregated to the level of detail that best matches the structure of SGM. Usually, an input-output table contains the same number of producing sectors as there are intermediate inputs. This does not have to be the case, however, because some industries may produce more than one product and some inputs might not be produced domestically and must be imported.

Oil and natural gas present a special problem because they are often treated as a joint product from a single industry. Almost all input-output tables consider oil and natural gas production to be a single industry producing a single composite product. This is one area in which energy balance tables provide essential information to maintain a clear distinction between oil and natural gas production and consumption.

Energy Balance Input-Output Tables

Since the SGM is an energy model as well as an economic model, attention is paid to maintaining energy balances as the model operates through time. An energy balance table is used for base-year calibration of energy production and consumption. An energy balance table is essentially an energy input-output table in physical units. The original units might be tons of coal equivalent (China), tons of oil equivalent (IEA statistics), or calories (Japan). In the SGM, we convert all energy units to joules, expressed as either petajoules (PJ) or exajoules (EJ). The format of a typical energy balance table is shown in Figure 4.2. Note that the role of rows and columns is transposed relative to an economic input-output table: the columns contain energy inputs while the rows contain energy consumption activities.

Figure 4.2. Typical Energy Balance Table



The IIEA compiles annual energy balance tables for both OECD and non-OECD countries. IEA energy balances provide a consistent energy balance table format across countries. Energy balance tables may be summed across countries to form an energy balance table for a multi-country region. However, the IEA energy balance tables are not as detailed as may be obtained through local governments. The SGM uses IEA energy balances for all of the multi-country SGM regions, but uses local energy data for all of the single-country regions (United States, Canada, Japan, China, India, Mexico, South Korea, and Brazil).

The following steps are used to create a hybrid input-output table from an economic input-output table and energy balance table.

1. Put the economic input-output table in a format suitable for SGM. This involves aggregation across producing sectors and possible conversion to a 1990 base year.
2. Obtain 1990 energy balance table and convert units to joules.
3. Aggregate energy balance table across fuels to match SGM format.
4. Rearrange activities (rows) within the energy balance table to match those of the economic input-output table.
5. Transpose the energy balance table so that rows correspond to fuel inputs and columns correspond to energy-consuming activities.
6. Create a hybrid input-output table where the energy rows (inputs) come from the transposed energy balance table and all other rows come from the economic input output-table. This table is no longer in value terms but is now considered to be in quantity terms with units of joules for the energy rows and units of 1990 dollars (or other local currency) for all other rows.

7. Find a set of prices for all intermediate inputs that will “rebalance” the hybrid input-output table in value terms. By rebalancing, we mean that the value of output in each producing sector is equal to the total value of inputs. A linear equation may be derived for each producing sector, resulting in a system of equations that can be solved to obtain a price for each intermediate input. These linear equations are sometimes referred to as “zero-profit conditions”. It is important to note that these prices are derived from the calibration process and are not historical prices. This reflects our modeling philosophy that assumed technology characteristics, represented by the input-output and energy balance data, should determine relative prices in the model, and not the other way around. Finally, create a new hybrid input-output table in value terms by multiplying all quantities by their respective prices.

8. We have the option of redefining units for the non-energy inputs in the hybrid input-output table. We usually redefine these units so that prices equal 1.0 in the base year, but energy prices can remain in terms of dollars (or other local currency) per gigajoule.

The final hybrid input-output table provides us with a representation of the economy that is completely consistent with base-year energy balances. Energy production and consumption for each fuel will exactly match the quantities in the base-year energy balance table.

Investment Data and Capital Stocks

The SGM operates in five-year time steps and keeps track of capital stocks in five-year vintages. At the end of each SGM time period, the model converts investment for each producing sector into a capital stock, with the capital stock defined to be five year’s worth of investment. Each type of capital stock has a data-input specified lifetime, typically four time periods or 20 years. At the end of the capital stock lifetime, the capital is retired and no longer used. Capital stocks are operated across their lifetime with no decrease in technical efficiency.

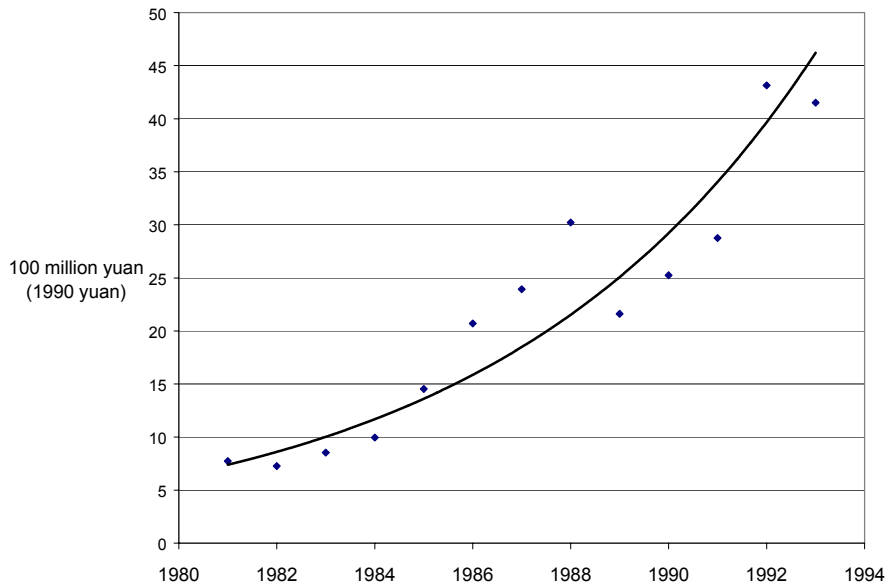
Calibration of the SGM requires that we determine the quantities of capital needed for all producing sectors by vintage. For example, using a 1990 base year and a capital lifetime of 20 years, we would need four capital stocks which equal investment during the time periods 1971-1975, 1976-1980, 1981-1985, and 1986-1990. The following steps are used to create capital stocks for a region.

1. Obtain historical time series of investment data for each producing sector.
2. Fit an exponential curve to the investment data for each producing sector. This provides a way to smooth out the effects of recessions or other temporary deviations from a long-term trend. This also provides a way to extrapolate data backwards in time if the historical time series of investment is not long enough to create all of the needed capital stocks.
3. Convert investment data to real 1990 currency (e.g., 1990 U.S. dollars) using a time series of GDP deflators.
4. Sum investment by sector across each five-year time period to create capital stocks with units of 1990 currency.

Figure 4.3 provides an example of annual investment data available for papermaking and paper products sector in China. An exponential line is fit to the historical data for China to smooth out the effects of a recession around 1990. The exponential fit also allows us to extrapolate

investment data backwards to before 1980 when annual investment data by sector is not available. The smoothed data are summed over five-year intervals to create capital stock vintages.

Figure 4.3. Annual Investment: Paper Making and Paper Products in China



Production Functions

Each column (excluding final demand) in the hybrid input-output table provides a representation of the inputs to a production process. For each input, there is an associated price and quantity. All production processes are assumed to be constant-returns-to-scale, implying the rate of conversion of inputs to output is independent of scale.⁴⁹

For calibration of production functions, we model a hypothetical plant with some given output capacity. For example, we could choose to represent coal-fired electric power generating plants as having a capacity of 500 megawatts.

Physical input-output coefficients can be derived from the hybrid input-output table for each combination of input and production process. The quantity of output is found by dividing the value of output by its price. Similarly, the quantity of input is found by dividing the value of input by its price. The input-output coefficient is then the quantity of input divided by the quantity of output.

It is important to remember that the technical coefficients of an economic production function are not the same as the input-output coefficients. In the special case of fixed-coefficient production,

⁴⁹ The energy supply sectors, however, do not exhibit constant returns to scale. In energy supply, the cost of production increases due to declining quality of the energy resources as they are consumed. The resource constraint implies decreasing returns to scale for primary energy supplies.

the technical coefficients of the production function are related to input-output coefficients in a direct way that is independent of price⁵⁰.

In general, input-output coefficients are related to the technical coefficients of production functions through prices. If the relative price of an input to production rises, the derived demand for that input will fall. The rate at which one input is substituted for another, relative to the rate of change in prices of those inputs, is referred to as the elasticity of substitution among inputs to production. In a constant-elasticity-of-substitution (CES) production function; this elasticity of substitution remains constant across changes in price (hence the name of the production function). Equation (7) shows the dependence of input-output coefficients on CES technical coefficients, relative prices, and the assumed elasticity of substitution. In the SGM calibration process, we invert this relationship and solve for technical coefficients as a function of input-output coefficients, prices, and the elasticity of substitution.

As the SGM searches for equilibrium prices, technical coefficients remain invariant with respect to price. However, input-output coefficients respond to changes in price. The rate of response, governed by the elasticity of substitution, is important for climate policy. Real world production processes will respond to changes in the price of fossil fuels and the SGM reflects this behavior. There are also physical limits to the degree of substitution. For example, power plant efficiencies cannot exceed limits imposed by the second law of thermodynamics and for some technologies responsiveness is even more tightly constrained. Note that the input-output table tells us nothing about the elasticity of substitution among inputs in production. That parameter must be set exogenously using published results from econometric studies, simulations of bottom-up technology models, or expert judgment.

Elasticities

Table 4.3 provides a list of typical elasticities of substitution (for producers) and demand elasticities (for consumers). Short-run elasticities of substitution are kept small, between 0.00 and 0.10 for all producing sectors. This means that previously constructed capital has limited ability to respond to changing relative prices

⁵⁰ This is discussed in detail in the technical annex to SGM documentation.

Table 4.3. Typical Producer and Consumer Elasticities in the Second Generation Model

Production activity/ consumption good	Long-run elasticity of substitution for producers	Short-run elasticity of substitution for producers	Own-price elasticity of demand for consumers	Income elasticity of demand for consumers
Agriculture	0.30	0.10	-0.38	0.32
Services	0.40	0.10	-1.02	1.01
Crude Oil	0.28	0.10		
Natural Gas	0.28	0.10		
Coal	0.28	0.10	-0.21	0.50
Coke	0.28	0.10		
Electricity	0.10	0.00	-0.21	0.50
Refined Petroleum	0.10	0.00	-0.21	0.50
Distributed Gas	0.10	0.00	-0.21	0.50
Paper and Pulp	0.28	0.10	-1.02	1.01
Chemicals	0.28	0.10	-1.02	1.01
Non-metallic minerals	0.28	0.10	-1.02	1.01
Primary Metals	0.28	0.10	-1.02	1.01
Food Processing	0.28	0.10	-1.02	1.01
Other Industry	0.28	0.10	-1.02	1.01
Passenger Transport	0.28	0.10	-1.02	1.01
Freight Transport	0.28	0.10	-1.02	1.01

Elasticities were set using expert judgment after surveying the open literature. The range of estimates for price elasticities of demand for energy is documented in Edmonds (1978) updated and summarized in Edmonds and Reilly (1985) as well as Bohi (1981) and numerous individual studies⁵¹.

The Baseline Scenario

The first step in constructing a baseline scenario is calibration of the SGM to a base year as discussed above. The next step is to introduce values for future exogenous variables such as demographics, technology, and factor productivity trends. There are occasions when it is desirable for the SGM baseline behavior to mimic that of some externally specified profile over some period into the future. For example, the SGM-USA has on various occasions been asked to create a baseline scenario that is consistent with that of the *Annual Energy Outlook*, published by the U.S. Energy Information Administration. In practice, we have found a sequential process works best in creating a baseline scenario consistent with an externally specified trajectory. This process begins by matching labor force assumptions, proceeds to then match next gross domestic product (GDP)⁵² paths, then moves on to electricity generation, and finally fossil fuel consumption.

Various technical parameters are available in SGM to influence the time path of model output, especially autonomous time trends governing the efficiency of inputs in production processes. In matching a baseline scenario to a desired GDP path we use an exogenous estimate of the labor force and then adjust an autonomous labor efficiency improvement parameter to get the desired

⁵¹ A forthcoming study from Resources For the Future, sponsored by the Economic Analysis Branch, will update these values.

⁵² Since the SGM is a CGE model, the GDP is an output rather than an input to the model.

aggregate output level. The second step is to match projections of electricity generation, in units of billion kilowatt-hours, by adjusting an autonomous electricity efficiency improvement parameter in all model activities that use electricity. Third, the mix of fossil fuels within electricity generation is adjusted by varying the time path of the cost to produce electricity using oil, natural gas, or coal. Fourth, fossil fuel consumption outside of electricity generation is adjusted using fossil fuel efficiency improvement parameters in all model activities that use fossil fuels. These adjustments in efficiency and cost parameters are not independent, so the baseline calibration process is repeated at least once. The choice of baseline has significant impacts on estimated costs to be emissions targets and thus being able to emulate a standard baseline is important when participating in multi-model exercises such as the Stanford EMF.

Response to Carbon Prices

An important summary of the behavior of a model in terms of greenhouse gas abatement is the marginal abatement cost curve (MACC). A MACC maps the relationship between the cost of emitting the gas and the reduction in emissions relative to the reference case. Clearly, each MACC is a contingent mapping derived under *ceteris paribus* conditions. In contrast to the non-CO₂ gases, where the SGM uses exogenous estimates of the MACC to determine the impact of an inclusive carbon management policy, the SGM internally estimates the response of carbon emissions to a carbon price. Using a number of model runs, a MACC for carbon emissions can then be created and used, for example, in simple desk top systems to investigate the impact of various carbon policies.

Several key elasticities help determine the response of carbon emissions to changes in energy and carbon prices. Economic theory would suggest that the longer a price change is in effect, the greater the response. The SGM response to carbon prices exhibits precisely this behavior. Elasticities of substitution for existing vintages of capital stock are relatively small, between 0.00 and 0.10 for all producing sectors, limiting short-term response within existing capital. Over time, new plant and equipment becomes an increasingly important component of the economy. As discussed earlier, substitution opportunities are greater for new investments as a greater array of technology options are available. Thus, the responsiveness of the carbon emissions to an initial change in the price of emissions increases with the passage of time.

This behavior is displayed in Figure 4.4. This MACC's in the figure were constructed by applying carbon values of {\$10, \$20, \$30, \$40, \$50, \$100, \$150} in SGM-USA starting in the 2005 SGM time step and held constant thereafter. The "start" curve in Figure 4.4 is the reduction from baseline carbon emissions, expressed as a percentage reduction, in the beginning time step of 2005. The other marginal abatement cost curves move out to the right as new capital stocks adjust to the new set of relative prices after introduction of a carbon price. Carbon values in Figure 4.4 are reported in 1990 U.S. dollars⁵³.

MACCs constructed in this way are also useful for reduced-form analysis of various permit trading systems. They can be combined with MACCs from other countries, MACCs for non-CO₂ greenhouse gases, and MACCs for mitigation opportunities in agriculture and forests.

⁵³ A rough conversion to 2000 U.S. dollars can be made by multiplying all carbon prices by 1.25.

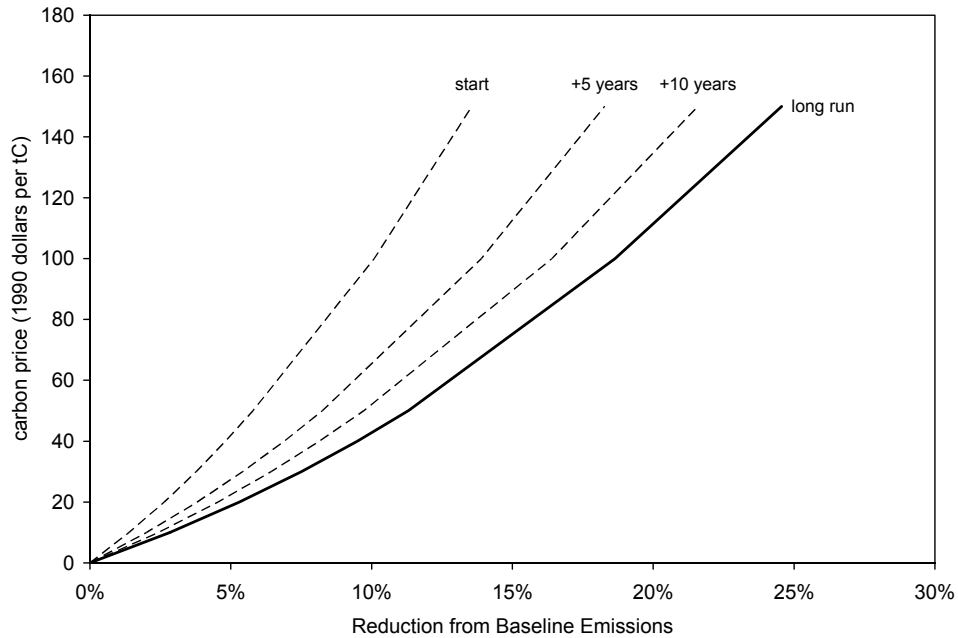


Figure 4.4. Marginal abatement cost curves for the United States energy system generated with a series of constant-carbon-price experiments.

These marginal abatement cost schedules for SGM-2004 are significantly less elastic than SGM-98. This is shown in Figure 4.5. Note that the MACCs derived from EMF runs are not the same

Cost of U.S. Carbon Emission Reductions, 2010

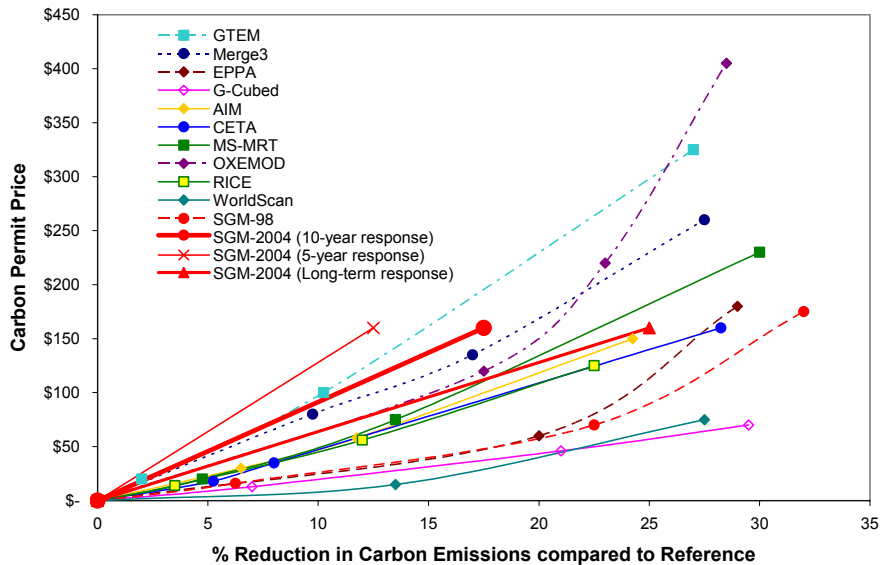


Figure 4.5: Marginal Abatement Cost Curves (MACCs) in EMF-16 including SGM-98 Compared with SGM-2004 Instantaneous, ten year, and Long-term Responses to Carbon Values

straightforward *ceteris paribus* calculation which varies price and nothing else. Rather the EMF calculations are dynamic with multiple factors varying simultaneously. Thus, while indicative of behavior, they are not truly MACCs.

Figure 4.5 shows US carbon reduction MACCs for models that participated in the EMF-16 exercise, including SGM-98 (Weyant, 1999). These results are contrasted to the results from SGM-2004. Three response periods are shown, five-year, ten-year, and long-term. The five-year response plots the percentage reduction relative to a reference case when a specific value of carbon is phased in over five years. The ten-year response case shows the percentage reduction in carbon emissions relative to a reference case when the value of carbon remains in place for another five years. The long-term response shows the percentage reduction in carbon emissions relative to a reference case when the value of carbon remains in place indefinitely. The 2010 MACCs in EMF-16 represent a case in which carbon values had existed for 10 years. The lower elasticity of response in SGM 2004 is a direct reflection of the change in the treatment of vintages in the SGM 2004. Existing vintages of capital have relatively little latitude to respond to carbon values in SGM 2004, whereas the assumed flexibility of existing plant and equipment was significantly greater in SGM 98⁵⁴.

Figures 4.6 and 4.7 show the results for the most recent EMF study, EMF-21. While the EMF-21 study focused on the combined suite of greenhouse gases, the available results do not permit showing the impact of adding the non-CO₂ and forestry mitigation options, which is to substantially reduce the marginal cost of reducing emissions. EMF-21, unlike EMF-16, did not require modelers to use a common reference case. Since cost curves are driven by the target, the reference case, and the set of management options, direct comparison between figures 4.5, 4.6 and 4.7 is not possible. Relative positions within Figure 4.5 are valid, but within 4.6 and 4.7 they are complicated by differences in the base case. In Figure 4.6, the SGM appears expensive, but it has nearly a gigatonne higher emissions in the base case than any other model. What is important to note is the wide spread in costs.

⁵⁴ The marginal value of a ton of carbon is the most comparable measure of cost across models. It is not the only measure. At least two measures of cost are available from the SGM and from other models as well. The first measure, which we call the direct cost, can be thought of as either a deadweight loss or the integral under the marginal abatement curve for carbon. Either way, direct cost can be approximately equal to one-half of the carbon price times the reduction in carbon emissions. For international trade in carbon emissions permits, direct costs are then adjusted by the value of transfer payments required to purchase or sell permits. This measure of net cost is simple to construct and is comparable across models.

Of ultimate interest, however, is the net impact on some broader measure of economic activity (such as GDP) or on economic welfare (such as real consumption). There are many reasons why the change in GDP (or real consumption) is different from the direct cost net of transfer payments. These other components of cost include the effects of pre-existing fiscal distortions, changes in terms of trade, and the ultimate disposition of government revenues. In addition, measurement of GDP (or real consumption) depends on the choice of index and base year used to construct that index. This reflects real-world problems in constructing a quantity index for GDP when relative prices are changing. The SGM reports GDP as a quantity index of net output, with base-year (1990) prices as weights.

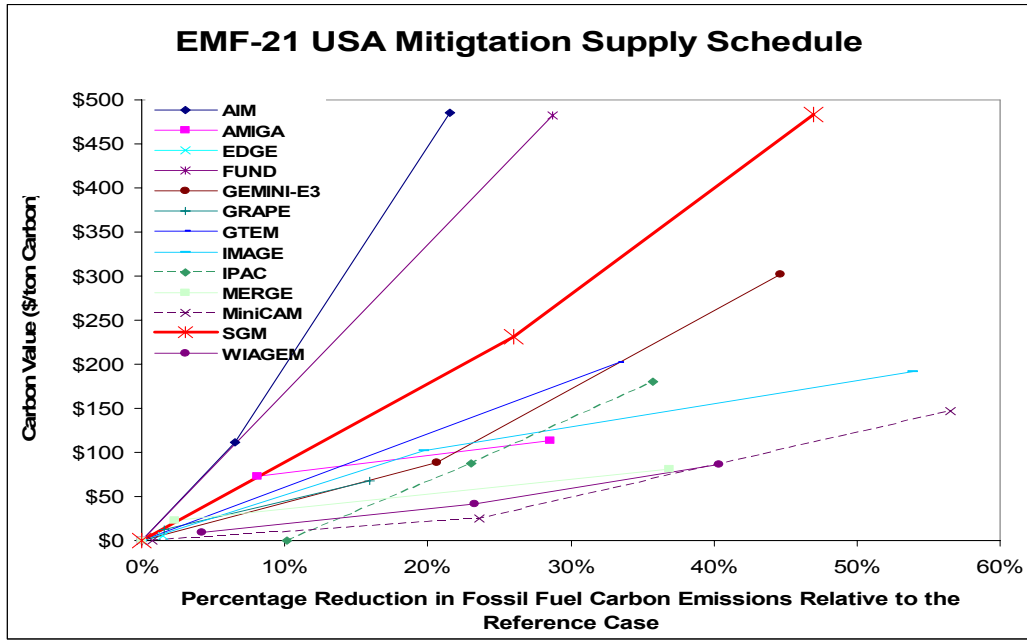


Figure 4.6 EMF 21 Marginal abatement cost curves for carbon for the United States

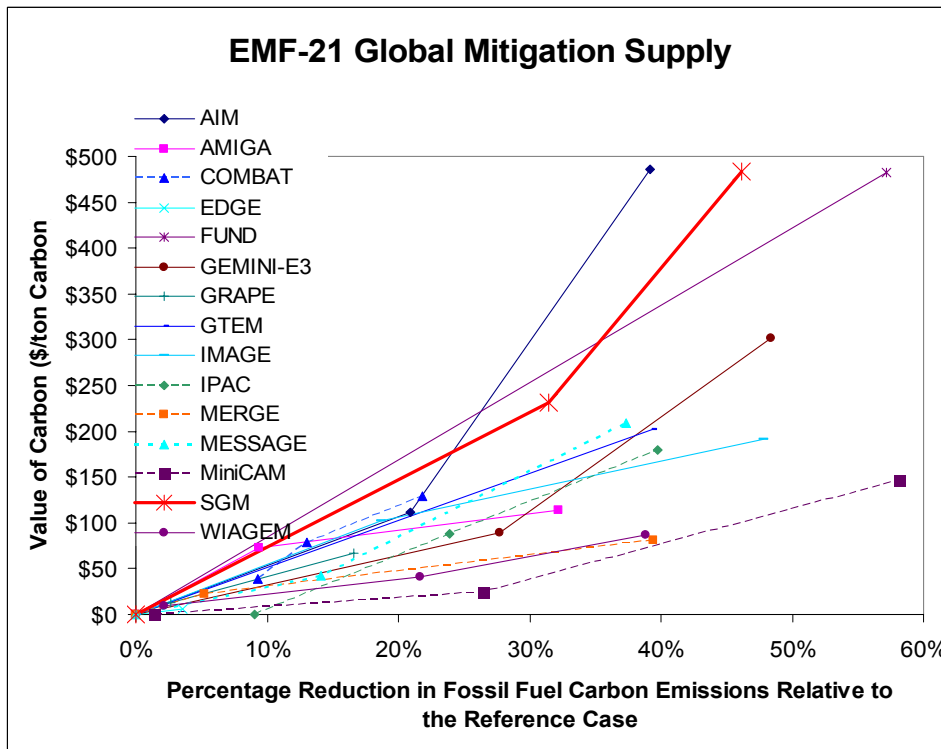


Figure 4.7 EMF 21 global marginal abatement cost curves.

V. Future Model Development

SGM 2004 is a benchmark version of the SGM. But, it is hardly the final version of the model. The SGM has evolved substantially over the period of its existence. It has remained a model designed to address the climate change issue on a time scale consistent with the transition of technology, looking forward five to fifty years. The model structure was developed to explicitly represent key features of the energy-economy-greenhouse-gas-emissions problem. In that sense it has remained true to its roots. The model has evolved significantly over time adding richness and detail in the process. Future model development is intended to continue that trend.

Perhaps the most important model development activity is the transformation of the SGM from a model coded in FORTRAN to one coded in C++. While this change in computational environment may seem arcane, it has important implications for future model development. The C++ environment means that most future changes to the model structure, e.g. the addition of technology options or new inputs and outputs, will no longer require recoding the model. Rather, such changes can be accomplished through changes in the database alone, thus accelerating the rate of model development and decreasing the potential for errors. In a C++ environment, for example, the introduction of a hydrogen market would be accomplished by simply changing the database to include hydrogen. Of course, making model expansion simpler and less error-prone doesn't solve the ongoing problem of data availability and quality. No model is immune from the problem of garbage-in-garbage-out.

Other areas in which model development is continuing include: the household sector, investment choice, expanded technology representations particularly in power generation, transportation, buildings, and manufacturing, fossil fuel supply, agriculture-land-use, and the implementation of nested CES production functions. Much of this development will take advantage of knowledge gained implementing these innovations in the simpler MiniCAM long-term analytical framework.

A high priority is the development of a more theoretically satisfying demand system for the household sector that would allow for a consistent treatment of the consumption, savings, and labor supply. Incorporating consumption, savings and labor supply into a utility function framework would allow calculation of welfare measures such as equivalent variation. This having been said, the form of the household sector model remains to be determined. Given the intergenerational nature of the time scale of the problem, an overlapping-generations model is a candidate framework in addition to a single, infinitely-lived household model.

At the same time, the SGM team continues to maintain its international collaborations. The Mexican module is being updated in collaboration with the Mexican Petroleum Institute (IMP). The Japan module is being updated in collaboration with the National Institutes for Environmental Studies (NIES) in Japan. A Germany module is under development with the German Institute for Economic Research (DIW). At the same time the SGM existing collaborations are being continued with China, India, France, Korea, and Brazil.

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