EMPAX-CGE
Model Documentation

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1. Introduction

Computable general equilibrium (CGE) models are widely used in policy analysis, including analyses of environmental issues. For environmental policies that are expected to impact many sectors either through direct compliance costs or indirectly through linkages between sectors of the economy (i.e., industries, households, government, trade), it may be important to account for these interactions and constraints. General equilibrium models account for these linkages and are more appropriate than partial equilibrium analysis of large regulations that are expected to have measurable impacts on the economy. This report describes the Economic Model for Environmental Policy Analysis – Computable General Equilibrium version (EMPAX-CGE), a CGE model specifically designed for use in analysis of large-scale environmental regulations.

1.1 The EMPAX-CGE Model

EMPAX-CGE is a regional CGE economic model developed by RTI for the Environmental Protection Agency's (EPA's) Office of Air Quality Planning and Standards (OAQPS). EMPAX-CGE is designed to estimate regional macroeconomic impacts of environmental regulations on the U.S. economy. Many major regulations directly affect a large number of industries and/or substantially impact markets for key factors of production. In either case, there may be substantial indirect impacts resulting from changes in production, input use, income, and consumption patterns for directly affected markets. EMPAX-CGE offers the ability to trace economic impacts resulting from policies such as large-scale environmental regulations as the impacts are transmitted throughout the economy. This type of model provides critical insight to policymakers evaluating the magnitude and distribution of costs associated with environmental policies.

The Economic Model for Environmental Policy Analysis (EMPAX) was first developed in 2000 to support the economic analysis of EPA regulations controlling emissions from three categories of combustion sources (reciprocating internal combustion engines, boilers, and turbines). A national multi-market partial equilibrium model with linkages between manufacturing industries and the energy sector was constructed to capture the effects that these combustion rules will have on other sectors of the economy through impacts on energy prices and output. Modified versions of EMPAX have subsequently been used to analyze the impacts of strategies for improving air quality in the Southern Appalachian mountain region and will be used for analysis of the National Ambient Air Quality Standards (NAAQS) for particulate matter as well as other upcoming EPA analyses.

Over time, EMPAX has been greatly enhanced through the addition of multiple U.S. regions, more manufacturing and non-manufacturing sectors, linkages between all sectors, more detailed energy and economic data, an improved characterization of production and consumption, and, in 2003, conversion to a general-equilibrium framework (EMPAX-CGE). A key factor common across all versions of the model is the emphasis on capturing interactions between the energy sector and the rest of the economy.

1.2 History of CGE Modeling

Over the last several decades, CGE modeling has emerged as a widely accepted method for conducting empirical economic analyses because it provides the ability to integrate economic theory with real-world data. The theoretical foundation of these models is a Walrasian general equilibrium structure (Arrow and Debreu, 1954). A "general equilibrium", as described by an Arrow-Debreu model (see Arrow and Hahn, 1971), includes components such as: households in the economy have an initial endowment of factors of production and a set of preferences for goods, market demands are the sum of all agents' demands and depend on prices, Walras' law is satisfied (expenditures equal income for any set of prices), producers maximize profits and have constant- or decreasing-returns-to-scale production functions. An equilibrium solution in a CGE model is characterized by prices and production levels such that demand equals supply for all commodities, and production activities break even at solution prices (in the case of constant-returns-to-scale production). By combining this theoretical structure with numerical methods, CGE models can be used to estimate the effects of policy changes on all parts of the economy. Advances in numerical simulation techniques have allowed modelers to move from simple partial equilibrium models to general equilibrium (GE) models with many more sectors and complex behaviors. This research began with Leontief (1936, 1951, 1953) who developed static input-output (IO) models. The IO approach employed "fixed coefficients" that did not allow production technologies to change in response to different policies. Johansen (1960) was the first to develop an applied GE model that moved away from this fixed-coefficients assumption to production functions that allow substitution among inputs and technical change. Since then, ever more complex models have been used to investigate a wide variety of policies, from taxes to trade to the environment.

Analyses of the incidence and efficiency effects of taxes are based on the seminal works of Harberger (1959, 1962, 1966, 1974). The 1962 work laid out a two-sector GE model of taxes using standard neoclassical assumptions: supplies of capital and labor are fixed, factors are perfectly mobile across industries, and perfect competition exists in product and factor markets. Shoven and Whalley (1972, 1973) were the first to analyze taxes using a full GE structure. Subsequent works, notably Ballard et al. (1985), extended previous models by adding more sectors and modeling dynamic consequences of policies for household savings behavior. Recent works (e.g., Bovenberg et al. [2003] and Babiker et al. [2002]) have examined how existing tax distortions in an economy may interact with economic policies and alter their effects.

Trade policies are another area in which CGE models have been applied extensively due to their ability to examine implications for many industries and countries simultaneously. Deardorff and Stern (1981) developed one of the first large-scale CGE trade models. It had 34 countries and 29 industries and was used to investigate the effects of changes in tariff and nontariff barriers in the Tokyo Round. Analysis of more recent trade agreements, such as the North American Free Trade Agreement (NAFTA) and the Uruguay Round of trade negotiations have relied heavily on CGE models for assessments of impacts (e.g., U.S. International Trade Commission, 1992; Francois and Shiells, 1994; Martin and Winters, 1995; Robinson et al., 1991; Burfisher, Robinson, and Thierfelder, 1994).

Environmental issues ranging from the Clean Air Act to potential climate change policies have also been investigated using CGE models. These applications are discussed in more detail in the following section.

1.3 Application of CGE Models to Environmental Policies

As in other branches of economics, the use of CGE models in environmental policy applications has been growing in recent years as improvements in model structures, databases, and computer technology have reduced the costs of using these models and increased the benefits (see Adkins and Garbaccio [1999] for a bibliography of CGE models applied to environmental issues; IEC [2001] and Appendix A of EPA [2003] for comparisons of selected CGE models used in environmental analysis). Regulations may affect the economy through their influence on rates of technological innovation, the level of private investment and trade, and the location decisions of firms and workers. A major strength of CGE models for regulatory analysis is their ability to implicitly take these effects into account. Regulations that directly raise costs of production and/or prices in an industry can indirectly discourage both investment in and exports from that industry as well as industries that rely on that sector for productive inputs. In CGE models, regulatory compliance costs lead to reductions in investment as a result of lower returns to capital while exports are discouraged by higher terms of trade (the ratio of domestic to world prices).

The energy sector plays a unique role as an input into essentially every other sector of the economy while simultaneously being one of the largest contributors to air pollution. As a result of its importance, one of the earliest areas of application of CGE models to environmental issues, beginning in the mid- to late-1980s, was to energy policy modeling (e.g., Bergman, 1988; Despotakis and Fisher, 1988). There has subsequently been an emphasis on the energy sector in almost all CGE models used to analyze large-scale environmental regulations. Often, the energy sector bears a large share of the direct costs and resulting changes in prices and quantities in the energy market can have a substantial impact on the rest of the economy.

Another early application of CGE models to environmental policy (and still one of the most common) was in the analysis of economy-wide impacts associated with restrictions on emissions of pollutants. Environmental standards, taxes, or tradable permits lead to direct costs including payments to government (in the case of taxes or auctioned permits), permit trade expenditures, and abatement expenditures. However, direct costs do not capture social costs that are important to policy makers/agencies who seek to design optimal policies from a societal viewpoint. In order to estimate the social costs of environmental programs, one must capture the sum of direct, indirect and induced costs. This means modeling all relevant linkages, substitution possibilities, technical changes, and dynamic processes that are impacted by environmental programs throughout the economy. The CGE framework has proven to be a valuable tool for capturing these kinds of complex effects because of its ability to model individual agent behavior, while at the same time depicting the workings of an entire economy. The Jorgenson/Ho/Wilcoxen Intertemporal General Equilibrium Model (IGEM) is an example of a CGE model that has been used in many different studies of the impact of environmental regulations on economic growth since the early 1990s (e.g., Ho and Jorgenson, 1998; Jorgenson, 1998; Jorgenson and Wilcoxen, 1990a, 1990b, 1993a, 1993b, 1993c, 1993d, 1997, 1998) as well as an assessment of the social costs associated with the Clean Air Act (EPA, 1997). Hazilla and Kopp used a model that is very similar to IGEM in an analysis of the social costs of the Clean Air and Clean Water Acts (Hazilla and Kopp, 1990).

Another major area where CGE models have routinely been applied is in analysis of climate change policy. Studies of the impacts of climate policy using CGE models include Rose and Oladosu (2002), Bernstein et al. (1999), Harrison and Rutherford (1998), Jorgenson and Wilcoxen (1993b), McKibbin, Ross, Shackleton, and Wilcoxen (1999), Manne and Richels (1997), and Bovenberg and Goulder (1996), among others. Most of these models provide results at the national level, but there are also efforts to model impacts separately for different regions of the U.S. The Multi-Region National (MRN) model, which is a dynamic CGE model that has been used primarily to estimate impacts associated with various energy policies and hypothetical carbon target policies (Balistreri and Rutherford, 2000; Balistreri *et al.*, undated), is capable of providing results down to the state level through a decomposition of estimation into three separate models solved sequentially.

Since the mid-1990s, there have been numerous studies relying on CGE models to examine the interaction between environmental regulations and tax-induced distortions in the labor market, often referred to as tax-interaction effects (TIEs). Parry (1997), Goulder et al. (1999), and Fullerton and Metcalfe (1997) are notable examples of this literature. If one performs single-market analysis of a tax, say, or an environmental regulation, then one assumes that there are no other-market distortions or that the exacerbation and amelioration of other-market distortions caused by the intervention in question cancel one another out. The tax interaction effects literature argues that, in the case of environmental policy (as well as agricultural policy and trade policy; see Parry [1999] and Williams [1999]) the other-market effects do not cancel out. In particular, the nature of environmental regulation—through command and control, pollution taxes, or quota restrictions on pollution—systematically worsens the distortion in the labor market that arises from the existing income tax. This literature has potentially important implications for the way that social costs of environmental regulations are calculated. The findings in this literature argue for the use of CGE models rather than single-sector models in estimation of the social costs associated with regulation to account for the potentially large tax interaction effects that may result.

Some more recent studies are attempting to account for environmental benefits within CGE models. Perroni and Wigle (1994) argue that it is essential to build the benefits of environmental improvement into CGE models. In their model, there is an initial endowment of environmental quality, some of which is consumed by activities that generate pollution. Firms can abate pollution by substituting other inputs (e.g., machinery) for emissions. The household utility function in this model includes environmental quality as a consumption good with increasing marginal utility as income rises. They use the model to explore the interactions between trade policy and environmental policy. Another example of this line of research is Smith et al. (2003), where the benefits of ozone reductions in the Los Angeles Air Basin are estimated in a general equilibrium framework.

1.4 Overview of a Standard CGE Model

CGE models explicitly capture all of the flows of factors and commodities in an economy. Unlike IO analyses, which focus on the production side of the economy and rely on exogenous multipliers to estimate demand effects, CGE models include income flows and distributional effects along with production technologies. Modeling both producer and consumer behavior allows CGE models to estimate how policy effects will ripple through the entire economy.

Figure 1 illustrates a simplified version of the circular flows in an economy that are considered by a CGE model.[1] Households own factors of production (capital, labor, and natural resources) and supply them to firms. These factor sales generate income for households. Firms produce output by combining productive factors with intermediate inputs of goods and services from other industries. Output of each industry is purchased by other industries and consumers using the income received from sales of commodities or factors. Goods and services can also be exported to generate foreign exchange earnings that can be used to purchase imports from other countries.

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[1] Although this diagram ignores government, investment, and some features of foreign agents for the sake of simplicity, CGE models usually cover these interactions as well.

Figure 1. Circular Economic Flows

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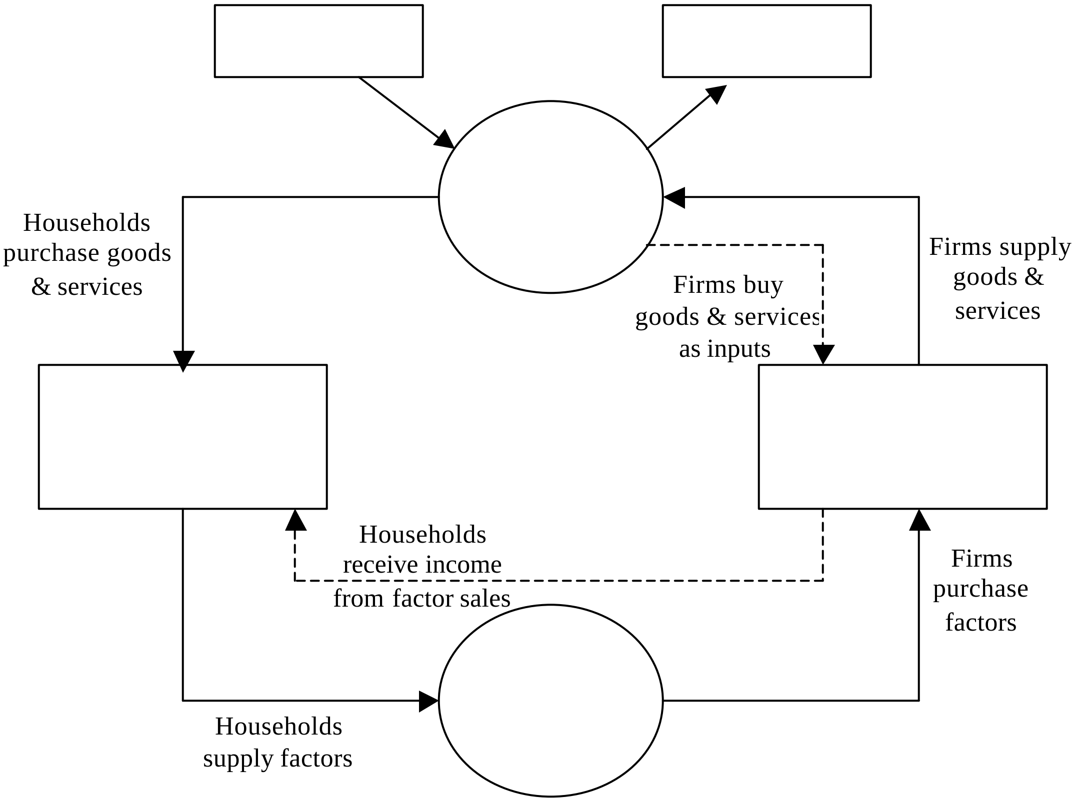

The “general equilibrium” component of CGE modeling implies that all sectors in the economy must be in balance and all flows must be accounted for. Every commodity that is produced must be purchased by firms or consumers within the U.S. or exported to foreign nations. Prices of these goods reflect all costs of production. Households receive payments for their productive factors and transfers from the government (not shown in Figure 1), and this income must equal consumer expenditures. In aggregate, all markets must clear, meaning that supplies of commodities and factors must equal demand, and the income of each household must equal their factor endowments plus any net transfers received.

Firms in a CGE model are assumed to maximize profits, which are the difference between revenues from sales and payments for factors of production and intermediate inputs. Profit maximization is done subject to constraints imposed by available production technologies. According to economic theory of producer behavior, firms will use each type of input up to the point where the marginal revenue received from employing an additional unit of an input is equal to the marginal cost of purchasing that input.

Typically, production technologies are specified using constant-elasticity-of-substitution (CES) functions that describe how different types of inputs can be substituted for each other (discussed in Section 3). The extent of these substitutions are determined by elasticities that control how easily tradeoffs among inputs can be made. Unlike input-output models, or partial-equilibrium models using fixed coefficients in production, this model structure allows producers to change the technology they use to manufacture goods. If, for example, energy prices rise, an industry can shift away from energy by employing more capital, labor, or intermediate inputs. This allows a CGE model to consider energy efficiency improvements as businesses substitute away from energy and into less energy-intensive methods.

Household behavior is generally modeled in a fashion similar to firm behavior. Consumers are assumed to maximize utility received from consumption of goods and services, subject to their budget constraint. CES functions are used to describe these utility functions, which show how willing and able households are to substitute among consumption goods in response to price changes. Because utility functions employed by CGE models are based on neoclassical economic theory, it is generally possible to estimate how a policy will affect consumers' standard of living as measured by changes in welfare, or Hicksian equivalent variation (EV). Models without a strong theoretical basis are only able to examine changes in variables like Gross Domestic Product (GDP), which may be unrelated to consumers' standard of living.

1.5 Current EMPAX-CGE Model and Planned Future Extensions

Two versions of EMPAX-CGE have been developed: first, a static version was built that could be used to investigate long-run policy effects on a wide range of industries; subsequently, a dynamic version was constructed in order to examine policies with varying effects over time. Theoretical structures of the two versions are similar, although the dynamic version has additional features needed to model investment decisions and energy markets over time. Both versions are described in detail in the following sections.

The model structure and underlying database of both EMPAX-CGE models are designed to be capable of estimating macroeconomic impacts of environmental regulations on different regions of the U.S. economy. While the theoretical structure of EMPAX-CGE is similar to other CGE models looking at energy policies, it includes additional regional information and utilizes a wide range of sources to provide the energy data used in the model. The regional disaggregation is essential since many environmental policies can have substantially different impacts across areas of the country. Use of the most complete data sources to characterize energy production and consumption by firms and households is also critical when modeling policies that may have significant implications for energy markets.

Aside from dynamics, the main difference between the static and dynamic versions of EMPAX-CGE is the level of aggregation. Static EMPAX-CGE has 41 commodities (7 of which are types of energy) and 10 regions, while dynamic EMPAX-CGE has 10 commodities (5 of which are types of energy) and 5 regions. Both models are built using the same dataset and characterizations of firm and household behavior. However, computational issues limit the size of the dynamic model to fewer industries and regions than the static model since it must solve for multiple time periods. Responses in the static version are intended to represent long-run changes in the economy, while the dynamic version is able to examine transitional effects as the economy responds to policies over a period of years.

A number of new features are going to be incorporated in EMPAX-CGE in the near future. The most important extensions planned for EMPAX-CGE include:

- Incorporation of Taxes – Tax distortions can have significant implications for the costs and effects of environmental policies. A wide range of theoretical and empirical literature has examined these "tax interactions" and found that they can substantially alter policy costs. Consequently, it is important for EMPAX-CGE to consider how tax distortions may interact with policies when estimating macroeconomic results. The economic database used by EMPAX-CGE (see Section 5) includes information on several types of taxes, but additional modeling work is needed to cover some of the most important distortions such as those from capital and income taxes.
- Multiple Households – Environmental policies can also potentially influence income distributions and affect households in substantially different ways. By including several household types, EMPAX-CGE will be able to provide additional information on how policies impact different groups of consumers. The economic database used by EMPAX-CGE distinguishes among a variety of households classified by income, but more work is required to model policy implications for different types of households.

These two extensions are discussed in Sections 8 and 9, respectively.

1.6 Outline of Subsequent Sections

Section 2 presents background information on the development of EMPAX-CGE. Section 3 summarizes the EMPAX-CGE model structure, scope, and types of policy evaluations that can be conducted. Section 4 discusses additional details of producer and consumer behaviors and presents more information on production technologies of different industries. Section 5 examines the data sources used by EMPAX-CGE and how the energy data is integrated with the economic data. Section 6 describes the use of EMPAX-CGE for policy applications. It also presents information on how EMPAX-CGE allocates environmental protection expenditures across types of equipment purchases and factor inputs by businesses in order to reduce emissions. Finally, Section 7 discusses the extensions that have been made to the static version of EMPAX-CGE to incorporate dynamic responses over time.   The last two sections describe future extensions to EMPAX-CGE (taxes and multiple households).

2. Background of EMPAX-CGE Model (to be provided by Tyler Fox)

3. Overview of the EMPAX-CGE Model

This section of the documentation provides a general overview of the model. Additional detail on the structure and data of the current version of the static model is provided in Sections 4 through 6. Section 7 provides more detail on the dynamic version of the model and Sections 8 and 9 discuss model extensions planned for the near future.

3.1 General Structure

The theoretical framework utilized by EMPAX-CGE is an Arrow-Debreu general equilibrium. Firms maximize profits subject to technology constraints, and consumers maximize utility subject to budget constraints. All markets must clear so that supply of good and services are equal to demand. In addition, income of each agent must equal their factor endowments plus any net transfers.

EMPAX-CGE combines a variety of economic and energy data sources[2] in order to characterize energy production and consumption decisions by firms and consumers with sufficient regional and industry detail to allow investigation of policies that may alter these decisions. These data are contained in a social accounting matrix (SAM) that shows current production technologies and demands by agents in the economy. The economic data in the SAM come from state-level information provided by the Minnesota IMPLAN Group,[3] while the energy data come from the Energy Information Agency (EIA) at the Department of Energy.

The static version of EMPAX-CGE uses these sources to describe 39 industries and 41 commodities. It also includes ten regions in the United States, which are combinations of states selected to approximate regions defined as distinct electricity markets by the North American Electric Reliability Council (NERC). Although the dynamic version of EMPAX-CGE contains fewer industries and regions, the underlying database and model structure are the same. Consequently, while the discussions in Sections 3 and 4 focus on the static version, the model structure for the dynamic version is substantially similar (differences are highlighted in Section 7).

The baseline data used by static EMPAX-CGE is benchmarked using EIA forecasts to represent the economy in a particular year in the future, usually 2010, 2015, or 2020. From this starting point, it estimates long-run economic effects for a policy in question. The dynamic model utilizes baseline data representing the economy in 2005 and solves in 5-year increments

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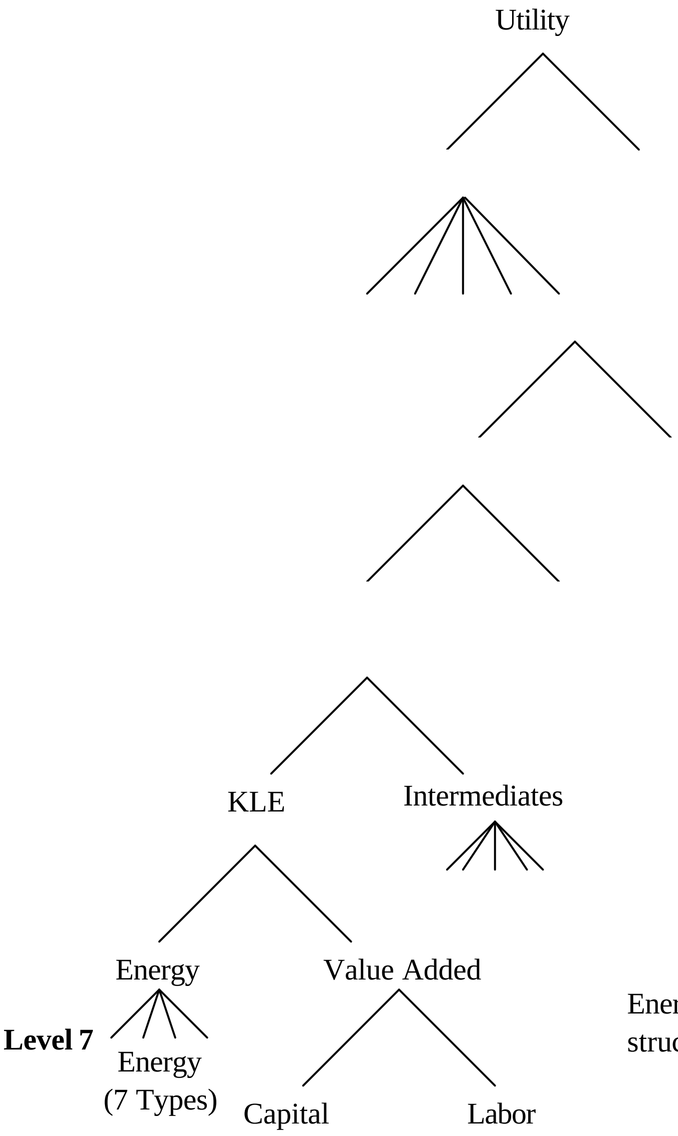
[2] See Section 5 for a detailed discussion of these data sources.

[3] See http://www.implan.com/index.html for a description of the IMPLAN Group and their data.

out to 2050. For years following 2005, the dynamic version incorporates energy consumption and production forecasts generated by EIA.

Both versions of EMPAX-CGE employ a nested CES model structure. These types of nested equations are used by CGE models to portray the types of substitution possibilities available to producers and consumers. Figure 2 illustrates this general framework and gives a broad characterization of the model.

Figure 2. General EMPAX-CGE Structure



Energy is a CES composite of 7 types of fuel. The structure of this function varies across industries.

3.2 Households

Each of the ten regions in EMPAX-CGE contains a representative household (Figure 3 shows this regional disaggregation of the U.S. economy). As shown at the top of Figure 2 (Level 1), the household maximizes utility received from consumption of goods and leisure time. Income used to purchase goods comes from sales of factors owned by the households, which include capital, labor and natural resources. In Level 2, households decide among various consumption goods according to a Cobb-Douglas specification. This structure allows households to shift consumption of goods and services in response to policies. If a good's price increases, consumers can purchase less of that good and more of other types of goods. Effects of a policy on households' standard of living (or, more formally, their welfare as measured by changes in Hicksian equivalent variation) are determined by how willing and able they are to alter their consumption patterns.

3.3 Trade

Goods and services consumed by households (and the intermediate materials used by firms) are a composite bundle of goods made up of locally manufactured commodities, commodities from other regions in the U.S., and foreign (non-U.S.) goods. As in most CGE models, these composite goods are formed using the Armington (1969) assumption that goods are differentiated by source. In other words, agents have different preferences for a commodity produced by a foreign firm than for a similar commodity produced in their home region or other parts of the U.S.

The CES nesting structure behind the Armington assumption is illustrated in the third and fourth levels of Figure 2. The third level in Figure 2 combines domestically produced goods from U.S. firms with foreign imports. This allows consumers and firms to express preferences for domestic goods over foreign goods, and vise versa. Level 4 combines local commodities produced within a region with commodities made by firms in other regions of the U.S. By using this type of nesting structure, a CGE model can express, for example, how household purchases of a total number of cars are made up of both domestic and foreign cars, and describe how willing consumers are to switch among manufacturers.

3.4 Production Activities

The production activities used by most industries[4] are illustrated in Levels 5-7. Each industry maximizes profits, equal to the difference between revenues from sales and payments for factors and intermediate inputs, subject to technology constraints. This nested CES structure is similar to those employed by other CGE models designed to investigate the effects of energy/environmental policies. Its purpose is to characterize how inputs used by industries will change in response to policies.

This structure allows producers to change the technology they use to manufacture goods. If, for example, electricity prices rise, an industry can shift away from electricity and into other

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[4] Natural resources (coal, crude oil, and natural gas) and agriculture have slightly different production structures in order to represent limits imposed on production by use of resources that are in fixed supply. These differences are discussed in Section 4.

types of energy. It can also elect to employ more capital or labor in place of electricity, which allows EMPAX-CGE to model improvements in energy efficiency.

The manner in which energy efficiency improvements can be achieved is controlled by the nesting structure of the production activities. Level 5 in Figure 2 shows how the capital-labor-energy composite good (KLE) is combined with intermediate materials inputs to produce final output. The assumption typically made in CGE models is that this is done in fixed proportions, which implies that businesses must either invest in more capital goods (i.e. new equipment) or hire more workers to achieve energy efficiency improvements. Level 6 controls these improvements by specifying how value added (the combination of capital and labor) can be substituted for energy. The final level in Figure 2 then determines how capital and labor can be substituted for each other and, in the nest of the seven different types of energy, specifies how one type of fuel can be used in place of another.[5]

The ease with which firms can switch among production inputs is controlled by elasticities of substitution. Elasticities relating to energy consumption are particularly important for the types of policies investigated by EMPAX-CGE. If, for instance, an industry is able to substitute away from energy with relative ease, the price of its output will not change much when energy prices vary. These elasticity assumptions, which are based on empirical estimation and modeling research by Massachusetts Institute of Technology's (MIT's) Joint Program on the Science and Policy of Global Change, are discussed in more detail in Section 4.

3.5 Government and Investment

Government purchases and investment are tracked in the IMPLAN economic data and EIA's Annual Energy Outlook (AEO) forecasts used by EMPAX-CGE (discussed in detail in Section 5). While investment behavior plays an important role in the dynamic version of EMPAX-CGE (see Section 7), in the static version of EMPAX-CGE investment decisions are not linked to the formation of capital for future production. Therefore, investments and government expenditures are determined from the IMPLAN and AEO data and maintained at their original levels, but do not enter the optimization decisions of households and businesses in the static version of the model.

3.6 Industries in EMPAX-CGE (Static Version)

The static version of EMPAX-CGE includes 39 industries and 41 commodities – there are more commodities than industries because the petroleum refining industry produces distillate

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[5] Specification of the energy nests depends on the industry in question - discussed in Section 4.

fuel, motor gasoline, and other petroleum. Table 1 presents the industries in the static version and their associated North American Industry Classification System (NAICS) codes.

These industries have been selected based on two factors: the desire to distinguish segments of the economy most likely to be affected by energy/environmental policies, and availability of energy consumption data. Several small industries (e.g., glass and cement) have been kept separate because they are relatively energy intensive and may respond to policies differently than other types of firms classified under the same 3-digit NAICS code. The number of industries is also controlled by available energy data. As is discussed in Section 5, the energy production and consumption data in EMPAX-CGE comes from a variety of government sources including the AEO forecasts and the Manufacturing Energy Consumption Survey (which gives current energy consumption by industries). This information is combined with the IMPLAN economic data to preserve as much industry detail as is feasible.

Table 1. Industries in EMPAX-CGE (Static Version)

General Classification	EMPAX Industry	NAICS
Energy	Coal	2121
	Crude Oil	211111[*]
	Electricity	2211
	Natural Gas	211112, 2212, 4862
	Petroleum Refining	324 [1]
Non-Manufacturing	Agriculture	11
	Construction	23
	Mining	21[**]
	Services	42, 44-45, 51-56, 61-62, 71-72, 81, & 22[***]
	Transport by Air	481
	Transport by Freight Truck	484
	Transport by Railroad	482
	Transport by Water	483
	Transport by Other	485, 486[****], 487, 488
Manufacturing	Food	311
	Beverages and Tobacco	312
	Textile Mills	313
	Textile Product Mills	314
	Apparel	315
	Leather	316
	Lumber and Wood	321
	Paper	322
	Printing and Publishing	323
	Chemicals	325
	Rubber and Plastic	326
	Glass	3272
	Cement	3273
	Other Nonmetallic Minerals (not including Glass or Cement)	327
	Iron and Steel	3311
	Aluminum	3313
	Other Primary Metals (not including Iron/Steel or Aluminum)	331
	Fabricated Metal	332
	Machinery	333
	Computer and Elec Equipment	334
	Electronic Equipment	335
	Transportation Equipment (except Motor Vehicles)	336
	Motor Vehicles	3361-3363
	Furniture	337
	Miscellaneous	339

[*] Although NAICS 211111 covers crude oil & gas extraction, the gas component of this sector is moved to the Natural Gas industry.

[**] Mining does not include coal, crude oil, or natural gas (which are covered by separate industries).

[***] The NAICS 22 component of the Services industry does not include electricity or natural gas.

[****] The NAICS 486 component of Other Transportation does not include NAICS 4862 (natural gas distribution), which is part of the Natural Gas industry.

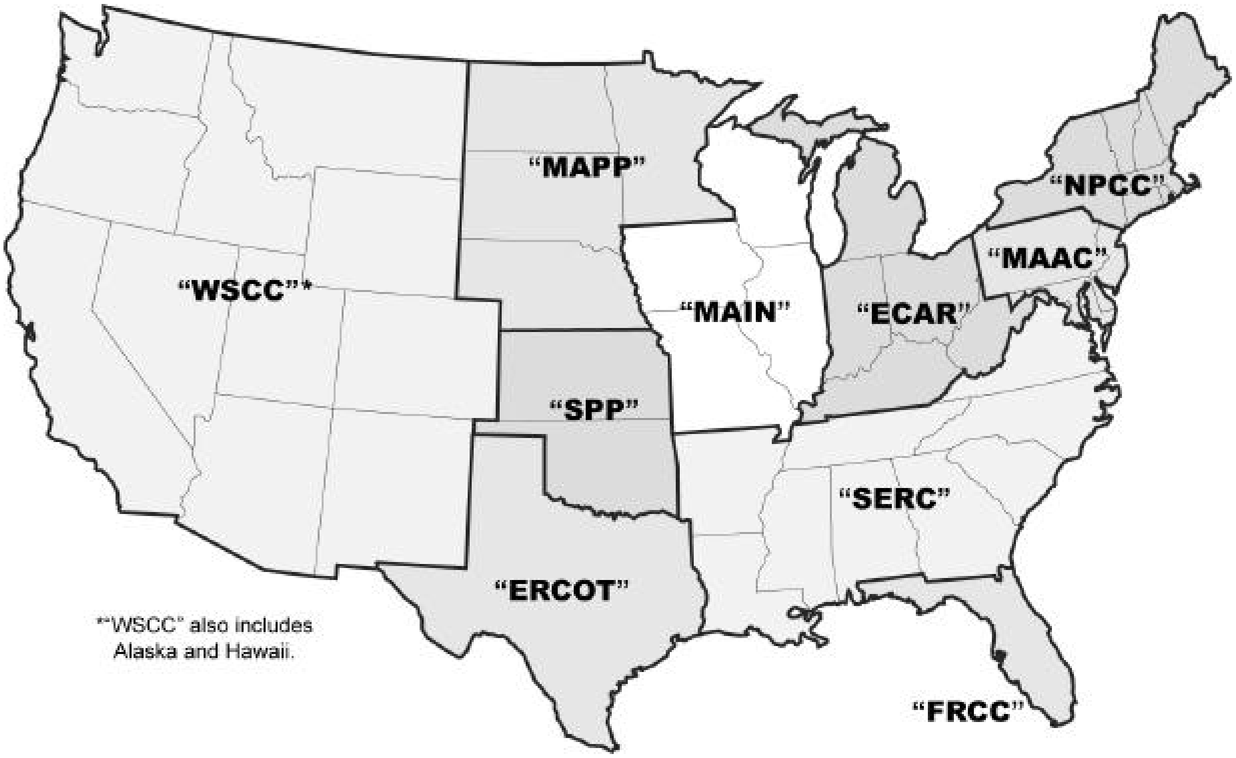
1 Output of the petroleum refining industry is classified as either distillate, motor gasoline, or other petroleum.

3.7 Regions in EMPAX-CGE (Static Version)

The static version of EMPAX-CGE contains ten regions (the dynamic version contains five regions – see Section 7). These regions have been defined based on a variety of considerations: expected regional distribution of policy impacts investigated by EMPAX-CGE, computational limits on model size, and availability of economic and energy data.

Many environmental policies have significant implications for methods of generating electricity. In addition, existing generation technologies vary substantially across the U.S., implying that regions will experience differing effects from new policies. Given these considerations, EMPAX-CGE regions have been designed to follow, as closely as possible, the electricity market regions defined by NERC. Unfortunately, economic data and information on non-electricity energy markets are generally only available at the state level (see Section 5 for a discussion of EMPAX-CGE data sources). This necessitates an approximation of NERC regions in EMPAX-CGE that follows state boundaries, as shown in Figure 3.

Figure 3. Regions in EMPAX-CGE



3.8 Social Accounting Matrix

EMPAX-CGE, like many other CGE models, relies on a social accounting matrix (SAM) to provide the baseline economic data for the model. These data describe initial economic conditions in a given year. A SAM shows values of output, payments by firms for factors of production and intermediate inputs, household income and consumption, government purchases, investment, and trade flows. It characterizes existing production technologies available to industries in the economy by showing what inputs are utilized to produce output.

By combining this information on current technologies with the production nesting structure and elasticities discussed above, EMPAX-CGE is able to estimate how firms will respond to changes in prices of their inputs by substituting among productive factors in order to manufacture output in the least-cost manner. In addition, data in the SAM, together with households' utility functions, portray initial consumer demands and how they will change in response to policies.

The SAM used by the static version of EMPAX-CGE is calibrated to represent a specific point in time, which is selected based on the policy year of interest. It is calibrated to represent the economy for the year in question through a process described in Section 5. The main focus of the calibration process is to ensure that data in the SAM reflect energy production and consumption patterns that are expected in the economy in the baseline forecast. Without an adequate characterization of initial energy use, it would be infeasible to estimate effects of policies that will alter these patterns.

3.9 Policy Evaluation

The EMPAX-CGE model can be used to analyze a wide array of policy issues, including such items as analyses of the economic costs of environmental regulations, distributional effects of policies across different industries and regions of the U.S., the effects of energy efficiency improvements, and comparisons between command and control policies and market incentives, among many other possibilities. The use of comprehensive EIA data on the energy sector and energy use by the industrial, commercial, and residential sectors allows for detailed examinations of items such as:

- how changes in electricity prices affect business and consumer choices
- the implications of changes in fuel use by firms for fuel markets
- how changes in non-electricity energy prices affect industry and consumer behavior

An essential component of EMPAX-CGE's ability to analyze environmental policies is its inclusion of information on environmental protection expenditures made by firms. These data show how businesses allocate compliance costs across purchases of emission control equipment and other necessary inputs (see Section 6 for details). By tracking these purchases, EMPAX-CGE is able to move beyond a generic application of "costs" and consider how these expenditures affect other parts of the economy in a general equilibrium setting.

Along with the energy data, production nesting structures, and elasticities designed to portray behavioral responses to environmental policies, EMPAX-CGE has the capability of being used in conjunction with the Integrated Planning Model (IPM)[6] where appropriate. IPM is a detailed model of electricity generation and transmission. It provides results on electricity prices, fuel use, and generation costs to EMPAX-CGE for policies where it is important to reflect disaggregated unit-level results that cannot be readily modeled in a CGE model (see Appendix C).

In order to evaluate policy implications, EMPAX-CGE provides results for an extensive list of macroeconomic variables at the regional level including (among others):

- households' standard of living (utility)
- Gross Domestic Product (GDP)
- energy prices
- fuel use by utilities and other businesses
- prices of goods
- output of firms
- employment
- wage rates
- capital earnings
- exports and imports

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[6] See http://www.epa.gov/airmarkt/epa-ipm/ for complete IPM documentation.

4. EMPAX-CGE Modeling Framework

Three components of a CGE model control many of the effects that are estimated for a policy: (1) the model nesting structure that controls which types of inputs can be substituted for each other in production and consumption, (2) the elasticities that determine the ease with which these substitutions can be made, and (3) the baseline dataset that describes the economy prior to implementation of a new policy. This section discusses the derivation of the nesting structure and elasticities and how they are specified in EMPAX-CGE, while Section 5 presents the data sources used by EMPAX-CGE.

In EMPAX-CGE, the nesting structure and elasticities are generally based on Massachusetts Institute of Technology's CGE model called the Emissions Prediction and Policy Analysis Model, or EPPA.[7] Although the applications of the two models are quite different (EPPA is an international model with a single region for the U.S. that is mainly used to examine global climate change policies),[8] both are intended to estimate how producers and consumers will respond to energy/environmental policies. Given this basic similarity in the objectives of the two models, EMPAX-CGE has adopted a comparable structure.

4.1 Production

Following the Arrow-Debreu general equilibrium structure, firms in EMPAX-CGE are assumed to be perfectly competitive, i.e., they are price takers and are unable to influence market prices. Their production technologies exhibit constant returns to scale with the exceptions of agriculture and natural resource sectors that have decreasing returns to scale due to use of factors in fixed supply (land and inputs of primary fuels, respectively). These assumptions interact with the three features listed above when examining policies.

In this section, the elasticity values and complete CES nesting structures for firms and households in EMPAX-CGE are presented. These model features are largely based on MIT's EPPA model, although the underlying dataset and other parts of EMPAX-CGE are dissimilar (as noted). The elasticity values shown below in Tables 2-5 were derived by MIT from Burniaux et. al. (1992), Nainar (1989), Nguyen (1987), Pindyck (1979), and expert advice. The nesting

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[7] See http://web.mit.edu/globalchange/www/MITJPSPGC_Rpt71.pdf for documentation of the EPPA model.

[8] EPPA and EMPAX-CGE also differ in their handling of dynamics. The static version of EMPAX-CGE models long-run responses to policies, but does not attempt to examine the transition path an economy takes to reach a new long-run equilibrium. The dynamic version of EMPAX-CGE is an intertemporally optimizing model that assumes agents can respond in the present to expected future policies, while EPPA is a recursive dynamic model that assumes agents do not react until a policy is actually instituted.

structures of the CES functions are based expert advice received by MIT, and are designed to reflect input substitution possibilities from “bottom-up” engineering models.

Table 2 shows elasticity values used in EMPAX-CGE by most manufacturing and service industries, and the following diagrams illustrate how substitution possibilities are characterized. In the diagrams used to illustrate production and consumption functions below, straight lines are used to show which types of inputs can be substituted for each other, according to which inputs are listed at the end of each straight line. The ease with which substitutions can be made is indicated by the elasticity of substitution (s) at the end of the curved lines. Inputs shown at the end of the lines are combined together to form a composite good at the next higher level in the diagram using these CES elasticities.

Table 2. General Production Elasticities

Variable	Variable Type	Value	Application
s_{mat}	Elasticity of substitution among material inputs	0	All sectors (includes inputs of goods to production, not factors or energy)
s_{eva}	Elasticity of substitution between energy and value added	0.5	All sectors except electricity
		0.4	Electricity
s_{va}	Elasticity of substitution between labor and capital	1.0	All sectors except nuclear/renewable generation (assumed to be fixed)
s_{enoe}	Elasticity of substitution between electric and non-electric energy	0.5	All sectors

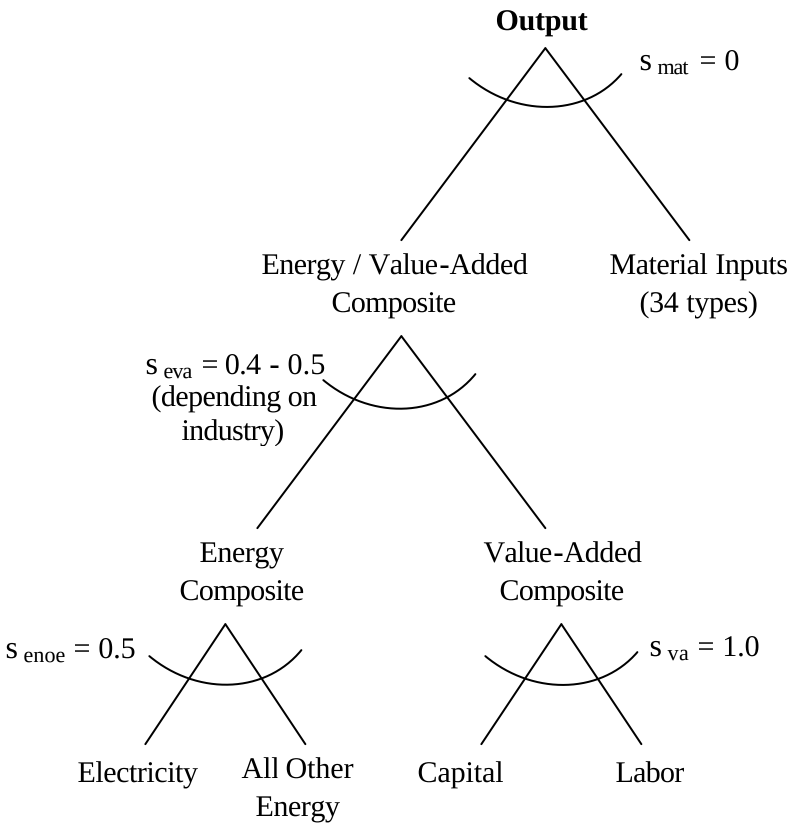
Figure 4 illustrates the general production structure used by most industries in EMPAX-CGE. The only industries not utilizing this structure are the natural resource sectors (coal, crude oil, and natural gas), petroleum refining, and agriculture. Some differences among industries also exist in the manner by which types of energy can be substituted for each other to form the “energy composite” good shown in Figure 4 (these assumptions are highlighted in Figures 5 and 7).

The inputs of “materials” in Figure 4 cover all intermediate inputs other than energy, factors of production (capital and labor), and natural resources. Materials enter production using fixed coefficients in the production structure, or a Leontief structure. The implication of Leontief technology is that producers (households) can adjust their energy consumption by: (1) changing total output (consumption), (2) substituting one type of energy for another, or (3) using additional labor or capital to achieve energy-efficiency improvements. Intermediate materials inputs are Armington goods – meaning that, prior to being used in production, domestic and imported goods are combined to produce composite "Armington" goods that are used by firms.

Materials are combined with an energy/value-added composite good that covers all capital, labor, and energy use by firms. The ability to substitute between value-added and energy varies slightly across industries (s_{eva}). The lower value for electricity reflects the fact that energy is an essential input to generation and substitution possibilities are more limited than for other industries.

Following standard modeling conventions, EMPAX-CGE assumes that capital and labor are combined using a Cobb-Douglas function (s_{va} equal to 1) to form the value-added composite good. Value-added is combined with the energy composite, which is made up of all available types of energy. Within the energy composite, another elasticity, s_{enoe}, controls the ability of firms to shift between electricity and other types of energy.

Figure 4. General Production Structure



There are some differences across industries in how the “energy” composite is formed from various energy inputs, which are illustrated in Figures 5 and 7 below.

4.1.1 Electricity Generation

The CGE model formulation used to represent electricity generation will have important effects on the results of environmental policies investigated by EMPAX-CGE. Electricity generation is unique from most other types of production in that it depends critically on energy inputs in order to create its output. There are also established theoretical and engineering bounds on how efficiently generators can convert fossil energy into electricity, which must be taken into consideration when designing the model. As the result of these considerations, the CES nesting structure used for electricity generation is different than those used for other industries.

Table 3 shows several elasticities related to energy inputs, some of which are used exclusively by the electricity sector and others that are occasionally applied to other industries as well.

Table 3. Elasticities Related to Energy Use in Electricity and Manufacturing/Services

Variable	Variable Type	Value	Application
s_{cog}	Elasticity of substitution between gas and coal-oil in fossil generation	1.0	Electricity only
s_{co}	Elasticity of substitution between coal and oil in fossil generation	0.3	Electricity only
s_{oil}	Elasticity of substitution among types of petroleum (distillate, motor gasoline, and other petroleum)	1	All sectors and households
s_{en}	Elasticity of substitution between non-electric energy sources	1.0	All sectors except electricity

The nesting structure by which fossil fuels can be substituted for each other is unique for electricity generation (Figure 5). The most important tradeoff is between coal and natural gas since these are the two main fossil-fuel options available to utilities, and many environmental policies of interest are likely to cause a shift between these fuels. Although use of distillate and other petroleum in generation is included in EMPAX-CGE,[9] the share of oil in total fuel use is quite small and will not have as much influence on results as coal and natural gas.

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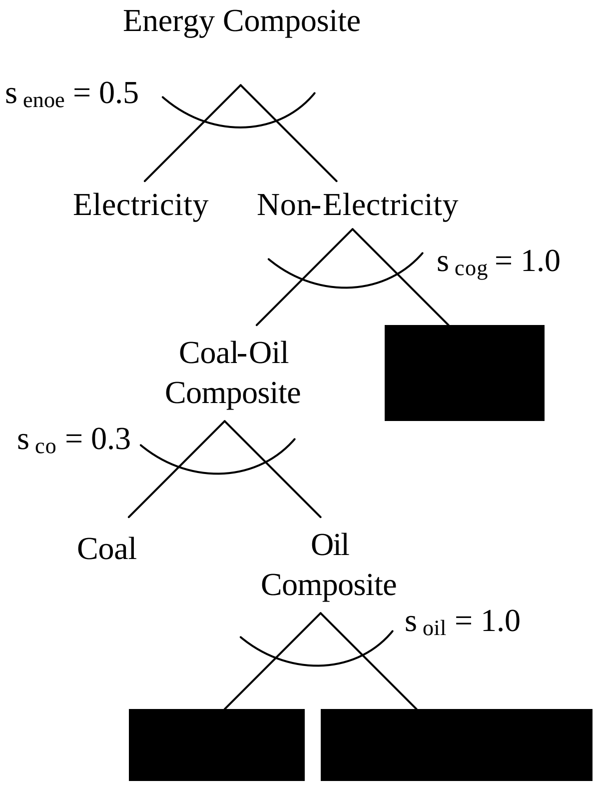
[9] The EPPA model includes oil generation, but does not distinguish among types of petroleum.

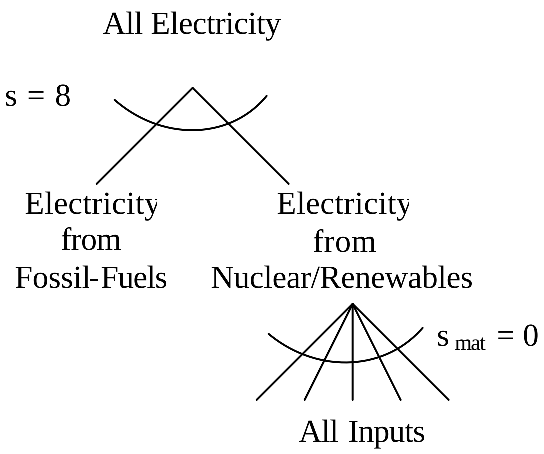
Figure 5. Energy Use in Fossil-Fueled Electricity Generation



In EMPAX-CGE, natural gas is combined with a coal-oil composite (s_{cog}) using a Cobb-Douglas formulation. Following that, coal is combined with oil (s_{co}), where the oil composite is made up of distillate and other types of petroleum (composed primarily of residual fuel in the electricity generation sector).

As illustrated by the technology structure in Figure 6, electricity in EMPAX-CGE can be generated either by the fossil-fuel nest discussed above or by non-fossil sources. The two types of generation are separated so that EMPAX-CGE can track heat rates in fossil generation (btus of energy input per kWh of electricity output) to ensure that fuel use per unit of electricity is consistent with theoretical limits and available technologies. There is an infinite elasticity of substitution at the top of the CES nest that combines electricity from the two sources, indicating that no distinction is made between electricity produced from these two methods.

Figure 6. Electricity Generation from Nuclear/Renewable Sources



EMPAX-CGE currently assumes that the amount of nuclear and renewable generation will not be affected by the policies being investigated.[10] Consequently, this generation is fixed at the levels given in the Energy Information Agency's Annual Energy Outlook forecasts. The implications are that policies investigated by EMPAX-CGE will not have large enough cost impacts to overcome existing cost differentials between fossil and renewable generation and additional nuclear units will not be built as the result of the policies. Data from the EPPA model showing the ratios of inputs in nuclear and coal generation have been used to characterize inputs to EMPAX-CGE's non-fossil generation. Use of these data gives nuclear/renewable generation a higher capital-labor ratio than fossil generation, which reflects the general cost structure of the two technologies.

4.1.2 Manufacturing, Non-Manufacturing and Services

Manufacturing, non-manufacturing, and services (including transportation services) use the general production nesting structure shown in Figure 4; however, the energy-value added elasticity (s_{eva}) is higher than for electricity. This indicates that it is relatively easier to achieve energy efficiency improvements in manufacturing than in the electricity sector, which relies heavily on energy for generation purposes.

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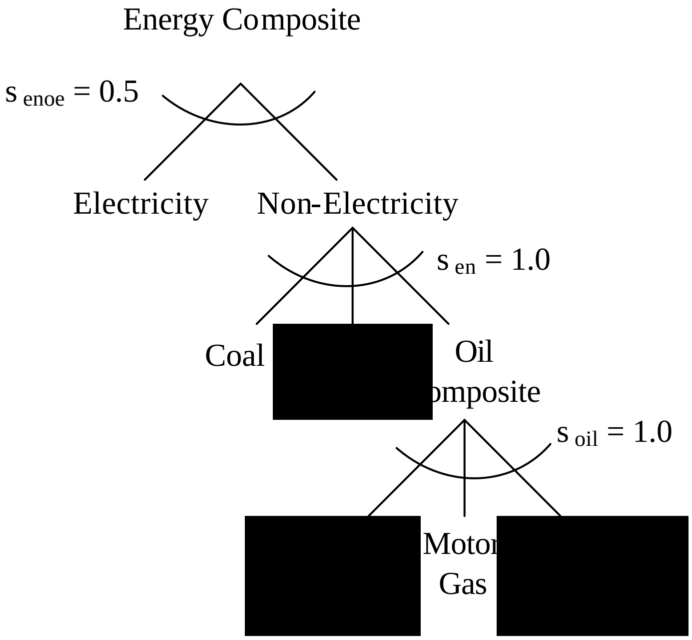
[10] In contrast, because of its focus on long-run climate policies that can cause dramatic shifts in generation technologies, the EPPA model allows for some limited substitution in nuclear generation between value added (i.e., capital and labor) and nuclear resources, and also permits building of new carbon-free (i.e. renewable) generation at a substantial cost markup over other forms of generation.

Some differences between these industries and the electricity sector exist in the substitution possibilities among energy types. Figure 6 shows how the energy composite good is formed for industrial and service sectors. The nesting structure draws fewer distinctions among types of energy than in electricity generation since the main tradeoffs in non-electricity industries are between natural gas and refined petroleum, rather than between coal and natural gas (electricity generation consumes around 90% of all coal used in the U.S., and coal is a much less important energy source for other parts of the economy).

Figure 6. Energy Use in Manufacturing, Non-Manufacturing, and Service Sectors



4.1.3 Fixed Resource Sectors (Agriculture and Fossil Fuels)

The CES nesting structures used for agriculture and natural resource industries are designed to reflect the presence of a factor of production that is available in fixed, or limited, supply. In the case of agriculture, this fixed factor is land. Similarly, production of fossil fuels relies on inputs of natural resources that are available in limited supply. Table 4 shows the elasticities that are included in the production functions describing these sectors, which are discussed separately below.

Table 4. Elasticities Related to Resource Sectors

Variable	Variable Type	Value	Application
s_{erva}	Elasticity of substitution between energy-resource and valued added	0.6	Agriculture only
s_{er}	Elasticity of substitution between energy-material bundle and resource	0.6	Agriculture only
s_{ae}	Elasticity of substitution between materials and energy	0.3	Agriculture only
s_{gr}	Elasticity of substitution between natural resource input and other inputs to resource production	0.6	Crude oil, coal, and natural gas production
s_{toil}	Elasticity of transformation in production of petroleum products from crude oil and other inputs	1	Petroleum refining sector

Agriculture

The agriculture sector is designed to reflect the presence of land in production.[11] In the top nest, value added is substituted against a resource-energy bundle. This substitution maintains a distinction between output per unit of land and output per unit of labor and capital, and allows agricultural output to be increased by additions of land (if possible), materials and energy, or value-added factors of production. This top-level nest (s_{erva}) allows agricultural efficiency per unit of land to be improved by using additional capital or labor. Energy and materials (s_{ae}) can be substituted with some difficulty for the fixed land resource (s_{er}) indicating that land can be made more productive by the use of materials (e.g., fertilizer) or energy (e.g., heating greenhouses or running farm equipment). Substitutions among energy types to form a composite energy good have the same structure as in manufacturing and services.

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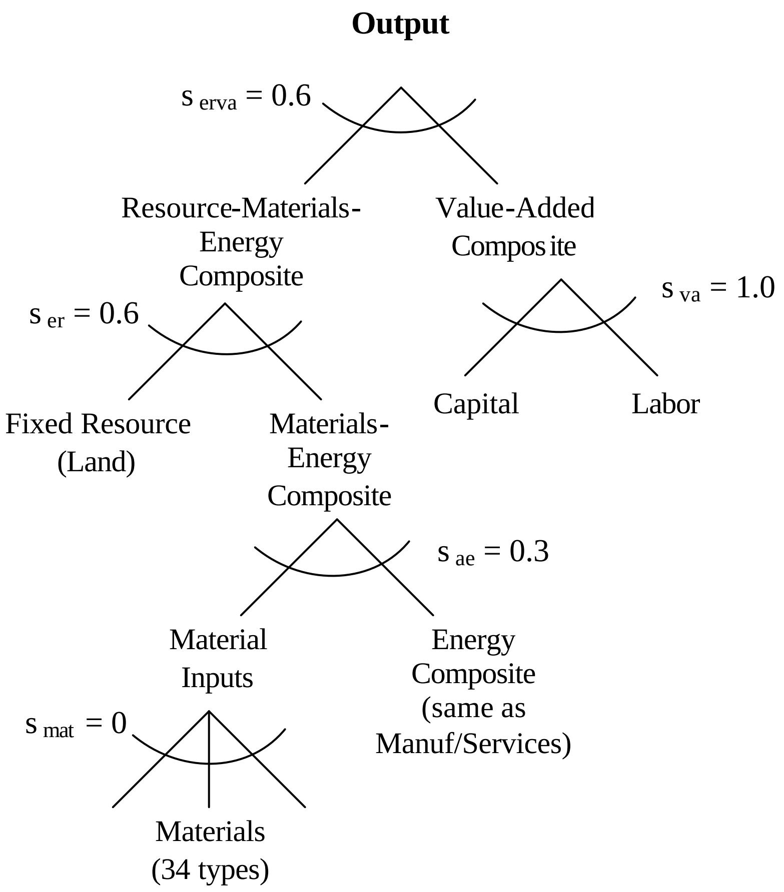
[11] EMPAX-CGE assumes that the fixed resource (land) earnings represent 1/3 of the capital payments shown in the IMPLAN data for the agricultural sector (see Section 5 for a discussion of these data).

Figure 3. Structure of Agricultural Production

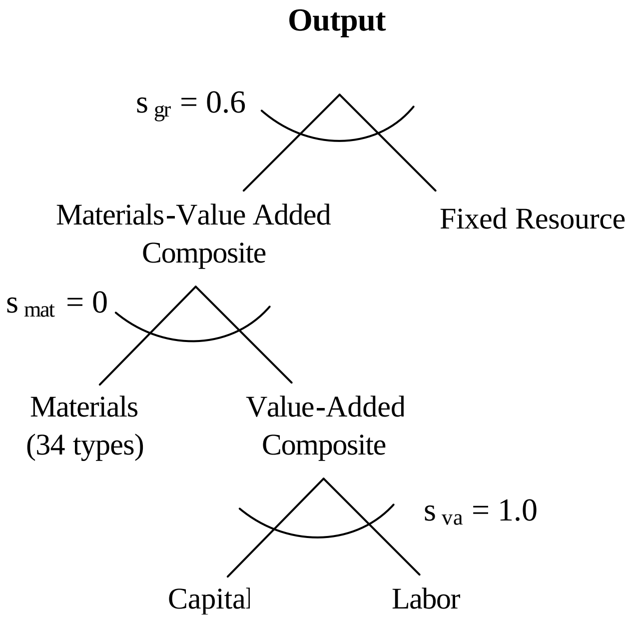


Natural Resources

Production of natural resources (coal, crude oil, and natural gas) is handled in a manner similar to agricultural goods. Output of these sectors is limited by the availability of the natural resource, hence, the use of a fixed factor in production to approximate resource constraints and give the production function decreasing returns to scale. This captures the idea that, while it is possible to develop more efficient mining equipment or invest in discovering new mines, it is not possible to produce natural resources using only factors like capital/labor or intermediate inputs. In the production nesting structure, coal in the ground, for example, is combined with other inputs in order to make it available for use by other industries. Some increase in output is allowed by use of additional factors or materials, but these must be combined (s_{gr}) with the fixed factor at the top of the nest.

The values of the rents earned by natural resources are based on MIT data from the EPPA model. For the U.S., the shares of total production costs attributed to payments to resource owners are: 10% for coal, 33% for crude oil, and 25% for natural gas. It is assumed that these payments are included in capital payments shown in the IMPLAN data[12] and, consequently, EMPAX-CGE separates out resource earnings from the more general payments to capital owners in the economic data.

Figure 4. Structure of Natural Resources Production (Coal, Crude Oil, and Natural Gas)



Petroleum Refining

Petroleum refining is not a natural resource sector. However, its production is similar in that it depends on inputs of crude oil, which can not be replaced by other types of materials. The elasticity of substitution s_{va} captures the idea that some factor substitution is possible in refining technology. However, crude oil and materials enter the production structure in fixed proportions to ensure it is necessary to use crude oil to produce petroleum products.

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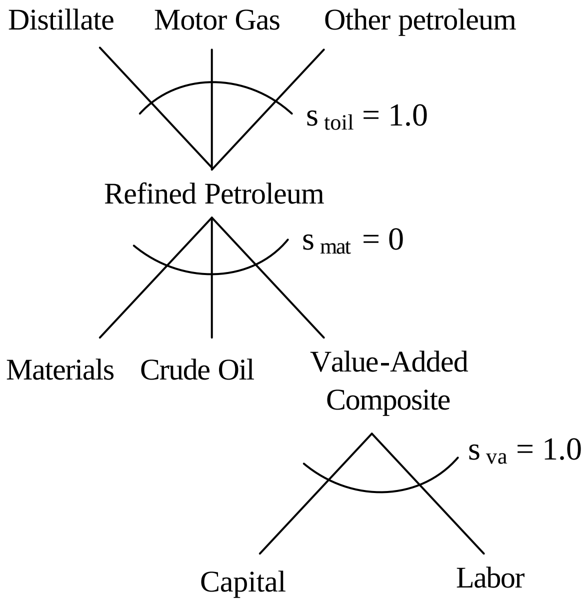
[12] Capital payments are typically calculated as the residual of all other payments, and hence would include these resource earnings.

Figure 5. Petroleum Refining Structure



EMPAX-CGE tracks three types of petroleum products: distillate fuel, motor gasoline, and “other” petroleum. The elasticity of transformation, s_{toil}, illustrates that it is possible to convert crude oil into a variety of petroleum products (transformation functions are shown as lines pointing up, rather than down). In the absence of other information, this transformation elasticity is assumed to be Cobb-Douglas, which is the typical default assumption in CGE models.

4.2 Household Consumption

EMPAX-CGE uses a nested CES structure to model consumer preferences for a representative household in each of the ten regions in EMPAX-CGE (static version). As shown in Figure 6, all consumption goods are combined using a Cobb-Douglas structure to form an aggregate consumption good. This composite consumption good is then combined with leisure time to produce household utility, or welfare. The elasticity of substitution between consumption goods and leisure (s_{cl})[13] indicates how willing households are to trade off leisure

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[13] The elasticity of substitution s_{cl} is calculated using assumptions about the portion of total available time that is devoted to labor or leisure and the static compensated labor supply elasticity:

1) The proportion of leisure (L_{LEIS}) to total labor endowment ($\overline{L}$) is: $? = 0.4$
2) $L_{LEIS} = \overline{L} * (?/(1 - ?)$
3) This gives a leisure value share in total consumption of:
   $? = L_{LEIS} / (L_{LEIS} + ?(consumption\ goods))$

time for consumption. Consequently, it controls how consumers will respond to changes in goods prices and changes in wage rates. Table 5 shows the elasticities related to household consumption and to traded goods, which are combined using the Armington assumption to form these consumption goods.

Table 5. Elasticities Related to Household Consumption and Trade

Variable	Variable Type	Value	Application
s_{cl}	Elasticity of substitution between consumption and leisure	1	Household trade-off between consumption and leisure
s_{c}	Elasticity of substitution among consumption goods	1	All goods consumed by households
s_{dm}	Armington elasticity of substitution between domestic and imported goods	3	All sectors except electricity (0.3)
s_{mm}	Armington elasticity of substitution among imports	5	Non-energy goods
		4	Energy goods except refined oil (6.0) and electricity (0.5)
s_{t}	Elasticity of transformation between goods for domestic consumption and exports	2	All sectors

The structure of household utility in EMPAX-CGE allows measurement of welfare changes from a policy in a convenient manner. Welfare changes capture a wide variety of effects that influence how consumers are affected by a policy including: changes in income, changes in the costs of consumption goods, and changes in work effort. The method for measuring welfare normally used by economists involves calculating Hicksian equivalent variation. This is the amount of income that would be needed to compensate households for economic effects of a policy. Because EMPAX-CGE includes a utility function, it is able to estimate this variable, instead of merely calculating income effects of policies or GDP changes, which ignore important consequences of policies for consumers.

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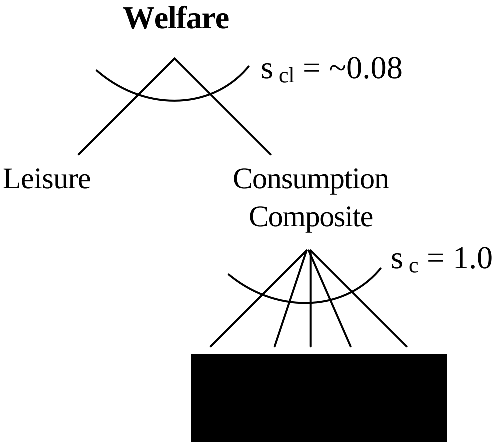
4) The static compensated labor supply elasticity is: ? = 0.4
The elasticity of substitution between leisure and consumption is: s_{cl} = ? * ((1- ?) / ?) / (1- ?)

Figure 6. Household Utility Function



The representative household in each region is endowed with factors of production including labor, capital, natural resources, and land inputs to agricultural production. The value of factors owned by each representative household depends on factor use implied by production within each region. Income from sales of these productive factors are allocated to purchases of consumption goods in order to maximize welfare

Savings are not included in consumers' utility functions in the static version of EMPAX-CGE since it is not attempting to model adjustment dynamics over time (savings do not usually play a role in static models).[14] In the dynamic version of EMPAX-CGE (see Section 7), savings provide the basis for capital formation and are motivated through people's expectations about future needs for capital.

4.3 Trade

Regions constructed in CGE models are often assumed to be small, open economies that are unable to influence import and export prices. In this case, pure trade theory suggests that each region would produce and export only those goods in which it has a comparative advantage and import all other tradable goods. However, empirical trade data routinely reveals "cross-hauling," which is the simultaneous import and export of the same type of goods. CGE models typically try to avoid the "all or nothing" specialization effects that trade theory implies because it is not consistent with empirical data and can exaggerate the effects of policies. The majority of multi-region CGE models represent trade among regions employing an assumption that goods

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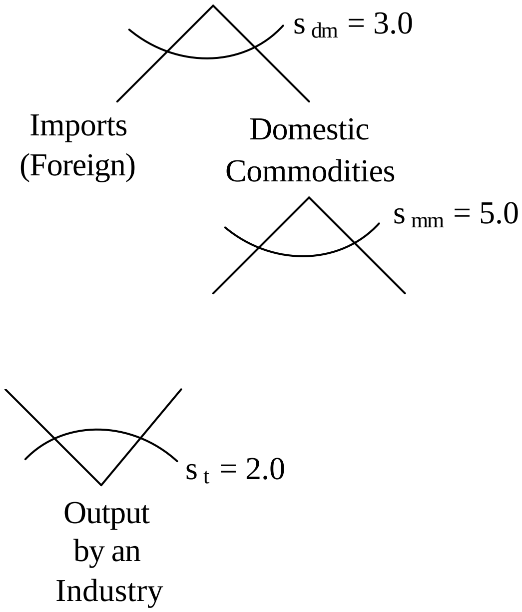
[14] Note: this assumption about the role of savings in the utility function is different than that utilized in the MIT EPPA model. Since EPPA is a recursive dynamic model, it assumes that savings provide utility to households in order to motivate savings for future time periods.

produced in different regions are imperfect substitutes for one another (i.e., Armington good represented by CES functions).

In EMPAX-CGE, goods and services consumed by households (and the intermediate materials used by firms) are composite goods made up of locally manufactured commodities, commodities from other regions in the U.S., and foreign (non-U.S.) goods. This Armington formulation is illustrated in Figure 7. At the bottom of this nesting structure, output of local industries is differentiated into output destined for local consumption by producers or households and output destined for exports using a CES transformation elasticity, s_t. Following the model's Armington structure, local output and regional imports are then combined using a relatively high elasticity, which indicates that agents make relatively little distinction between output from firms located within their region and output from firms in other regions within the U.S. This domestic composite good is finally aggregated with imports from foreign sources using a lower elasticity to capture the fact that foreign imports are more differentiated from domestic output than are imports from other regional suppliers in the U.S.

Figure 7. Trade Functions



EMPAX-CGE assumes that any trade deficits or surpluses indicated by the original data are maintained during policy simulations in the model. It has also been assumed that the representative agent in each region owns the natural resources located in that region, as well as all other businesses. Other assumptions could be made about this point, for example, EMPAX-

CGE could use an assumption that ownership of capital and resources is spread across the U.S. using a mechanism like the New York Stock Exchange. However, data to accomplish this sharing out of ownership are not readily available. Similarly, foreign ownership of businesses and resources has been ignored. If ownership were shared out across regions and foreign agents, it would tend to smooth out welfare changes across regions as the income impacts of policies would be spread more broadly across households in the U.S. However, the impact on industrial output and energy use from assuming broad ownership of factors and resources would be much less substantial.

Following standard conventions used in general-equilibrium models, factors of production are intersectorally mobile within regions, but trade in productive factors is not allowed among regions of the U.S. or with foreign agents. This assumption is necessary in order to calculate welfare changes for representative households in each of the ten regions in EMPAX-CGE. It is also currently assumed that policies investigated by EMPAX-CGE do not influence world prices of goods.[15]

4.4 Government and Investment

Government purchases and investment are exogenous variables in the static version of EMPAX-CGE. Since investment decisions in the static version are not linked to formation of capital for future production, investment purchases are determined from the IMPLAN data and are tracked in EMPAX-CGE, but do not enter the optimization decisions of households. Government purchases of goods and services are also shown in the economic data and are included in EMPAX-CGE, but do not adjust in response to policies. Currently, government expenditures are financed by non-distortionary transfers from households, rather than distortionary direct and indirect taxes imposed on goods and factors. In the near future, tax distortions will be added to EMPAX-CGE so that it will be possible to consider tax interaction effects (how environmental policies interact with existing taxes and the implications for policy costs).

4.5 Market Clearance

All markets for factors and goods must clear simultaneously in order to find a general equilibrium solution in EMPAX-CGE, i.e., supply must equal demand for all commodities. This market clearance determines equilibrium prices for factors and goods. The model solution occurs at a point where the marginal costs of production are equal to the marginal benefits from

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[15] This assumption could be changed to incorporate foreign export demand and import supply elasticities.

an additional unit of output as measured by the prices that firms and households are willing to pay for commodities. Factor prices are equal to the marginal revenue received by firms from employing an additional unit of labor or capital. Values of these factors are determined by demand by firms within each region, implying that there are regional differences in factor prices. Alternatively, EMPAX-CGE could be adjusted to assume that returns to labor and capital are equalized across the U.S., rather than assume regional productivity differences exist.

5. Database and Calibration

This section discusses the data sources used in EMPAX-CGE and the methodology for integrating the economic and energy data. EMPAX-CGE relies on a wide variety of data sources to provide the data necessary to develop a SAM that characterizes the U.S. economy at a regional level. The SAM combines information on the economy with several types of energy data.

5.1 Social Accounting Matrix

CGE models are typically based on a social accounting matrix (SAM), which is an economywide dataset that shows how resources flow through the economy at a specific point in time.[16] The framework for these data comes from traditional input-output analyses, originally developed by Leontief (1936). An IO table represents the value of economic transactions at a particular point in time. As such, it shows how firms combine intermediate inputs and factors of production to produce output. This output is directed towards intermediate and final uses, where intermediate uses are the goods and services employed by other firms to manufacture their output and final uses are the ultimate destination of consumer goods purchased by households and government.

A SAM is an expanded version of the traditional IO table. Unlike IO data, a SAM contains information on ownership of factors of production, which allows CGE models to estimate policy effects on the distribution of income. In addition, a SAM contains data on direct taxes that are removed from income received by agents and transferred to the government, and vise versa. IO tables, which ignore income, typically only include indirect taxes that are levied on purchases of intermediate production inputs or on expenditures for final goods of production. By covering all economic flows among agents, a SAM provides the basis for building a static CGE model or for providing a benchmark dataset for a dynamic CGE model.

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[16] See Shoven and Whalley (1992), *Applying General Equilibrium.*

Table 6. Basic SAM

RECEIPTS	EXPENDITURES Activities	Commodities	Factors	Households	Government	Savings / Investment	Rest of World (ROW)	Total
Activities		Gross Output						Gross Output
Commodities	Intermediate Inputs			Household Consumption	Government Consumption	Investment	Exports	Demands
Factors	Capital and Labor						Factor Income from ROW	Factor Income
Households			Household Income from Factor Ownership		Government Transfers to Households		Household Transfers to ROW	Household Income
Government	Output Taxes, Factor Taxes	Sales Taxes, Export Taxes	Government Income from Factor Ownership / Taxes	Household Transfers to Government (Direct)			ROW Transfers to Government	Government Income
Savings / Investment				Household Savings	Government Savings		Foreign Savings	Savings
Rest of World (ROW)		Imports	ROW Income from Factor Ownership		Government Transfers to ROW			Capital Outflows to ROW
Total	Activity	Supply Expenditures	Factor Expenditures	Household Expenditures	Government Expenditures	Investment	Capital Inflows from ROW	

Table 6 presents an aggregated version of a typical SAM. The table illustrates the circular flow in an economy – demand for goods and services leads to production activities, which generate income that leads back to demand. The "Activities" column shows how intermediate inputs, factors, and taxes paid by producers are combined to produce output. The other columns show how expenditures are made by agents in the model. Rows in the SAM give demands for commodities and income sources for agents. For example, demand for the gross output of a commodity (the "Commodities" row) is divided among intermediate input purchases by enterprises, household consumption, government purchases, use of commodities to make investment goods, and exports. Similarly, income for households comes from sales of factors to firms and transfers to households from the government or foreign agents (the "Households" row). This income is used to purchase private consumption goods, for direct transfers to the government, and to save (the "Households" column).

In a balanced SAM, corresponding row and column sums are equal. This means that supply equals demand for all goods and factors, tax payments equals tax receipts, there are no excess profits in production, the value of household expenditures equals the value of factor income plus transfers, and the value of government tax revenue equals the value of transfers.

5.2 IMPLAN Economic Data

Economic data necessary to develop a SAM for EMPAX-CGE are provided by the Minnesota IMPLAN Group. State-level information from IMPLAN shows how goods are manufactured using various intermediate inputs and factors of production. It also shows demands for goods and services by agents such as households and government. In addition, IMPLAN contains information on how these expenditures are financed by households' sales of factors to businesses and by government tax collections.

Table 7. EMPAX-CGE Economic Data Sources

Data Source	Data Table	Data Elements
IMPLAN	State-level economic data for year 2000	Output by industry Inputs to industries Consumer purchases and income Exports and imports
Commodity Flow Survey (Bureau of Economic Analysis)	Trade flows in 1997	Interstate trade data by commodity

IMPLAN contains data on production and consumption of 528 different types of commodities for the year 2000. These data have been developed from a variety of federal government sources including:

- US Bureau of Economic Analysis Benchmark I/O Accounts of the US
- US Bureau of Economic Analysis Output Estimates
- US Bureau of Economic Analysis REIS Program
- US Bureau of Labor Statistics Covered Employment and Wages (ES202) Program
- US Bureau of Labor Statistics Consumer Expenditure Survey
- US Census Bureau County Business Patterns
- US Census Bureau Decennial Census and Population Surveys
- US Census Bureau Economic Censuses and Surveys
- US Department of Agriculture Crop and Livestock Statistics
- US Geological Survey

Computational limitations of CGE models and available energy data (discussed below) were considered when determining the size and scope of EMPAX-CGE. As a result of these factors, the 528 sectors in IMPLAN have been aggregated into 39 industries (shown in Table 1). These industries have been selected based on their relevance to the types of energy/environmental policies that EMPAX-CGE has been designed to investigate, in conjunction with the availability of complete energy and economic data.

Although IMPLAN provides exports and imports of goods and services for each state, the data do not include information on the nature of interregional trade flows. In order to determine the origin of a state's imports and the destination of a state's exports, the IMPLAN data is combined with the Commodity Flow Survey conducted by the Bureau of Economic Analysis at the Department of Commerce. The Survey shows the origin and destination of each state's trade flows of goods and services. These statistics are used to apportion IMPLAN's general export and import data into state-to-state trade data.

Once the economic data have been aggregated into the 39 industries used in EMPAX-CGE and trade flows have been established, the state-level data are aggregated into the regions used in EMPAX-CGE.

5.3 Energy Data Sources

The IMPLAN economic data are supplemented by additional data sources on energy production and consumption for two reasons: (1) since the policies being investigated by EMPAX-CGE focus on energy markets, it is essential to have the best possible characterization of these markets in the model, and (2) EMPAX-CGE utilizes a baseline starting year that is different than the year 2000 data provided by IMPLAN (discussed in Section 5.5 on data integration).

Although IMPLAN relies on government information when creating their datasets, the focus of IMPLAN is not energy/environmental policies. This leads, in some instances, to differences between the IMPLAN economic data and the energy data collected by the Energy Information Agency (EIA) at the Department of Energy. Where these differences occur, EMPAX-CGE is based on EIA data. These sources are shown in Table 8, which lists the data source and specific table of data used and gives a description of the tables.

Information on energy production at the state level comes from EIA's annual industry profiles that collect data on coal, electricity, natural gas, and petroleum production. Energy consumption data in EMPAX-CGE are based on the Manufacturing Energy Consumption Survey (MECS) produced by EIA and historical data from EIA's Annual Energy Outlook (AEO), which shows industry-level consumption of different types of energy. The Commercial Buildings Energy Consumption Survey by EIA is also used to supplement energy consumption information from the MECS.

In addition, since EMPAX-CGE is used to investigate the effects of policies in the future, it requires a dataset that reflects changes that are expected to occur in energy markets in the absence of the policies under investigation. For this reason, EMPAX-CGE incorporates the forecasts from the AEO into its baseline dataset.

Table 8. EMPAX-CGE Energy Data Sources

Data Source	Data Table	Data Elements
Annual Energy Outlook (EIA) – Historical and forecast data (2000-2025)	Table 1	Total Production, Imports, and Exports (& some Prices) by Fuel
	Table 2	Consumption by Sector and Fuel (Quad Btu)
	Table 3	Prices by Sector and Fuel ($/MMBtu)
	Table 16	Coal supply, disposition, and prices
	Table 20	Macroeconomic variables
	Tables 23-32	Components of AEO Industrial Sector (output, fuel use)
	Table 34	Transportation energy use by use and type of fuel (Quad Btu)
	Tables 60-72	Electricity generation, fuel consumption, and trade by NERC region
State Energy Data Report, 1999 (EIA)	State-level energy consumption data (historic)	Energy consumption data by state, 1999 Categories – residential, industrial, commercial, transportation, electric utilities (physical units and Btus)
State Energy Price and Expenditure Report, 1999 (EIA)	State-level energy consumption data (historic)	Energy consumption data by state, 1999 Categories – residential, industrial, commercial, transportation, electric utilities (Dollars and $/MMBtu)
Coal Industry Annual 2000 (EIA)	Table 10	Coal production by state and coal rank (tons)
	Table 65	Coal trade from state to state (tons)
	Table 85	Coal price (mine mouth) by state and coal rank (tons)
Electricity Power Annual 2000 (EIA)	Table A7	Generation by state (MkWh)
Natural Gas Annual 2000 (EIA)	Table 6	Wellhead value and marketed production (MMCF and dollars)
	Table 12	Interstate and foreign trade by state (MMCF)
Petroleum Supply Annual 2000 (EIA)	Table 14	Crude oil production by PADD and state (barrels)
	Table 20	Imports of crude oil and petroleum from foreign sources (barrels)
	Table 32	Crude oil and refined petroleum trade between PADDs (barrels)
	Table 36	Refinery capacity by state
Manufacturing Energy Consumption Survey, 1998 (EIA)	Table N1.2 – First Use of Energy for All Purposes	Industrial energy use by NAICS code and type of fuel (trillion Btu)
Commercial Buildings Energy Consumption Survey, 1995 (EIA)	Table 1. Total Energy Consumption Major Fuel	Energy use by Government-owned and non-government buildings (Btu)
Natural Gas Transportation – Infrastructure Issues and Operations Trends (EIA)	Table 1. Interregional Pipeline Capacity and Average Daily Flows, 1990 and 2000	Gas flows among regions of U.S. (MMCF)

5.4 Energy Data Calibration

In order to integrate the EIA energy data and the IMPLAN economic data, it is necessary to have state-level energy data to combine with the economic data. The starting point for this process is the national-level (or, in the case of electricity, NERC-level) energy forecasts in the AEO. These forecasts are combined with the state-level historical data sources shown in Table 8 to produce state-level energy consumption, production, and trade forecasts. A variety of steps are necessary to accomplish this (while retaining overall energy market forecasts at the levels given in AEO):

1. Estimate how energy use by five broad categories in the AEO national forecasts corresponds to the wider array of activities in EMPAX-CGE.
2. Determine national-level forecasts for energy consumption, production, and trade.
3. Use EIA state-level energy data to share out the national AEO forecasts to states.
4. Aggregate state-level data into EMPAX-CGE regions and balance interregional energy trade flows.

Step 1

The AEO forecasts of energy consumption in quantity and price terms (Tables 2 and 3, respectively) are given for five broad categories: Residential, Commercial, Industrial, Transportation, and Electricity Generation. For two of these categories, Industrial and Transportation, AEO provides additional details on the parts of the economy that comprise the broader sectors. Energy use in electricity generation is available at the NERC-region level in separate tables (Tables 60-72). The remaining two categories, Residential and Commercial, distinguish energy use by type of equipment, but not in a fashion that is consistent with industries in EMPAX-CGE.

The Residential Sector in AEO gives household energy use, but only includes energy consumption for household appliances, heating, etc. In order to find total household energy consumption that corresponds with the households in EMPAX-CGE, it is necessary to include energy use for private transportation. This information comes from AEO Table 34, which gives petroleum use by type of vehicle. Motor gasoline use by light-duty, non-commercial, vehicles is assigned to household consumption in EMPAX-CGE.

The Commercial Sector in AEO contains energy data on service-providing facilities and equipment. This corresponds to the Service sector in EMPAX-CGE, since energy use by industrial facilities is included in AEO's Industrial Sector. One exception is that government buildings are included in the Commercial Sector. The most recent Commercial Buildings

Energy Consumption Survey (1995) by EIA is used to separate energy consumption by the Commercial Sector into public and private consumption.[17]

The Industrial Sector in AEO covers energy use by manufacturing facilities. Separate forecasts are available for a variety of energy-intensive industries and other sectors such as agriculture and mining (Tables 24-32).[18] Other industries such as fabricated metal products, machinery, and equipment (NAICS 332-336) that are separate sectors in EMPAX-CGE have been aggregated into a single "Metals-Based Durables" category in the AEO forecasts. For those industries which have a direct correspondence between AEO and EMPAX-CGE, the individual energy consumption forecasts from AEO have been utilized. For other industries in AEO like "Metals-Based Durables" that cover several sectors in EMPAX-CGE, information on industrial energy consumption from the MECS is used to share out the broader AEO category into individual industries.

The Transportation Sector in AEO covers all energy use by vehicles whose primary purpose is moving people and goods from one location to another. After assigning household and military fuel use to the appropriate sectors in EMPAX-CGE, the remaining energy consumption shown in Table 34 is separated into five modes of transportation: air, freight trucks, railroad, water, and other transportation. This fuel use is assigned to the same categories in EMPAX-CGE.

<u>Step 2</u>

After energy consumption forecasts are assigned to sectors in EMPAX-CGE, the next step is to determine national level forecasts for production, exports, and imports that balance energy markets for each type of fuel in both physical units and value terms (price times quantity). This is done using the accounting identity:

production = consumption plus exports minus imports.[19]

Consumption has been determined by the steps taken above. Exports and imports of energy are given in the AEO forecasts. This leaves production as the residual component of the equation that balances supply and demand.

<u>Step 3</u>

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[17] Military fuel use from Table 34 on the transportation sector is also assigned to the government sector in EMPAX-CGE.

[18] See pg. 39 of EIA's publication "Assumptions to AEO 2003" http://www.eia.doe.gov/oiaf/aeo/assumption/pdf/0554(2003).pdf for the list of industries.

[19] In the case of crude oil, available data (Table 1 in AEO) is for production and trade. Since all crude oil is consumed by the petroleum refining sector to produce different types of refined petroleum, the identity is reversed: consumption = production + net imports.

Once national forecasts are determined for each sector and type of fuel in EMPAX-CGE, it is necessary to determine how to share out the national totals for production, consumption, and foreign and domestic trade to states. The various energy-industry annual publications shown above in Table 8 give state-level production in quantity and price terms, which are used to share out national production data.[20] Energy consumption by sector at the state level comes from EIA publications: State Energy Data Report and State Energy Price and Expenditure Report. Consumption data are shared out to states based on both expenditures in dollars and energy use in Btus to maintain differences in energy prices across states. Foreign and domestic energy trade data also come from these industry annuals where available and are proxied where not available.

Coal trade data among states are the most complete of the energy trade data series and can be used without approximations. While the Natural Gas Annual reports flows among states, it only gives figures for all gas that moves across borders, rather than an initial origin and final destination of the gas. For this reason, gas flows from EIA's "Natural Gas Transportation – Infrastructure Issues and Operations Trends" are used. In the absence of other data, petroleum trade is shared out to states based on state production levels. Electricity trade is available at the NERC-region level in Tables 60-72 of the AEO so those levels are used after the state-level data has been aggregated.

Upon determining state-level energy forecasts, the energy data is aggregated into EMPAX-CGE regions, and interregional trade flows are balanced. Once this is done, the energy data is ready to be integrated with the economic data.

5.5 Data Integration in the SAM

Integrating the energy data with the economic data to produce a balanced SAM requires several steps: (1) estimating future economic activity starting from the historical IMPLAN data, (2) combining the economic and energy data, and (3) generating a balanced SAM with interregional and foreign trade flows.

While the process of calibrating the energy data produces balanced energy markets for each year in the AEO forecast (2000-2025), the IMPLAN economic data is for the year 2000. Therefore, before it can be integrated with the energy data, it must be projected forward to the baseline year used by EMPAX-CGE. The AEO forecasts provide economic projections for industrial output and macroeconomic variables like GDP and consumption (Tables 23 and 20, respectively). Industrial output forecasts are used to grow the manufacturing sectors in EMPAX-

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[20] The exception to this is the Petroleum Supply Annual, which only gives refinery capacity by state, rather than production. In the absence of production data, refinery capacity is used as a proxy for production at the state level.

CGE out to the baseline year. Other sectors in EMPAX-CGE like services are assumed to grow at AEO's GDP growth forecast in the absence of other information. Consumption, government, and trade are assumed to expand at the rates given in AEO's macroeconomic forecast (Table 20).

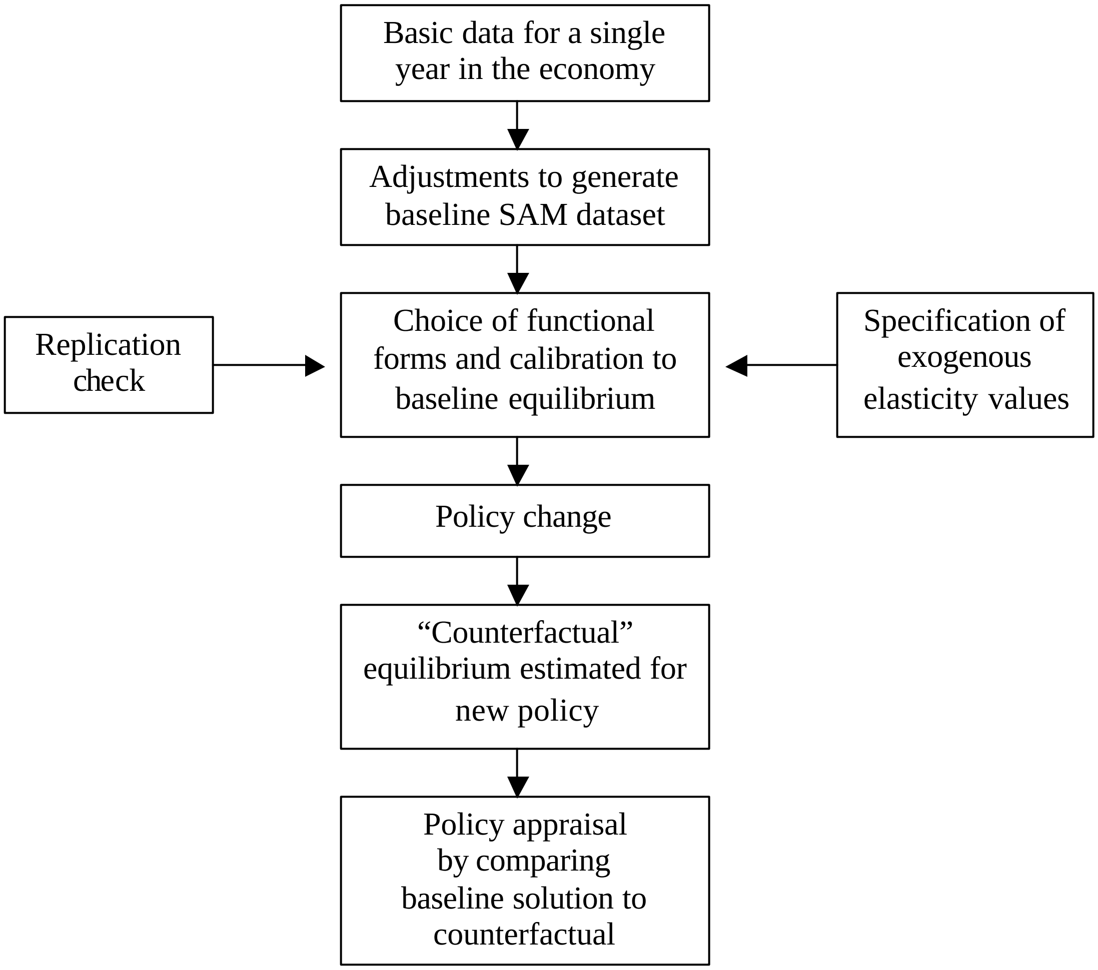
As discussed in Section 5.3, the IMPLAN data do not always adequately represent energy markets since they are not based on data sources such as those used to develop energy statistics for EMPAX-CGE. Consequently, the two types of data (economic and energy) must be integrated after they have been collected. EMPAX-CGE uses a procedure developed by Babiker and Rutherford (1997) and described in Rutherford and Paltsev (2000) to combine these data. This procedure was originally applied to data gathered by the Global Trade Analysis Project (GTAP) at Purdue University and used by many CGE modelers to investigate international energy policies such as climate change.

The methodology involves preserving the energy data and adjusting the economic data to integrate the two datasets. As done in the GTAP project, standard optimization techniques are used to maintain the calculated energy statistics while minimizing the changes necessary to combine them with the economic data. Once the data are integrated, a balanced SAM is generated that matches AEO forecasts for GDP, output, consumption, investment, and government spending.

6. Policy Evaluation

In order to use a CGE model to evaluate policies, the various components discussed in Sections 3-5 on functional forms and data must be integrated together, the model must be checked for errors, and the analyst must ensure that the economy is initially in equilibrium. Figure 8 summarizes these steps as they apply to the development of EMPAX-CGE (and other CGE models).

Figure 8. Flow Chart of Steps in Developing a CGE Model[21]



Development of a typical CGE model begins with specification of baseline data that represents the economy in a single year. Normally, datasets used for this purpose are not consistent with the conditions necessary for the economy to be in equilibrium (e.g., output is not equal to consumption, inputs to production do not equal the value of output). Because of these factors, adjustments must be made to “calibrate” a baseline SAM that is consistent with these

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[21] This chart is adapted from Shoven and Whalley’s (1992) flow diagram of a typical CGE model.

types of general equilibrium conditions. Once the underlying dataset has been constructed, functional forms are chosen that describe substitution possibilities available to firms and households. Then, since the calibration process only involves a single year's data, it is necessary to specify exogenous elasticity values, which control the ease of substitutions in the functional forms. Technically, the calibrated data determine the starting point for the production and utility functions, and the elasticities describe the curvature of the production isoquants and utility indifference curves around that starting point. When this process is complete and a replication check is run to ensure that the CGE model is fully specified and is initially in equilibrium, it is ready to be used for policy analyses.

The process of developing EMPAX-CGE has followed these steps, although additional calibration work was necessary, as discussed in Section 5, to allow the model to utilize a baseline dataset that accounts for expected economic growth and projected changes in energy markets between the year 2000 data and the starting year of the model. The figures and tables in Section 4 presented the functional forms and exogenous elasticity values in EMPAX-CGE. Based on these pieces of information, a baseline equilibrium is established by running a replication check of the model to ensure that all markets clear in the absence of new policies (supply equals demand, the value of inputs equal the value of output, etc.). At this point, a new "counterfactual" equilibrium can be computed for a policy change, which can be compared to the baseline solution to determine how the policy has altered the economy.

In evaluating policies, the static version of EMPAX-CGE considers approximately four thousand non-linear equations, which must be solved simultaneously to determine the baseline and counterfactual equilibriums. The model is solved as a mixed complementarity problem (MCP)[22] using MPSGE software (Mathematical Programming Subsystem for General Equilibrium) [23] running within the GAMS[24] language (Generalized Algebraic Modeling System). The PATH solver from GAMS is used to solve the MCP equations generated by the MPSGE software.

EMPAX-CGE is capable of being applied to a wide range of environmental policies, and estimating how a change in a single part (or multiple parts) of the economy will influence economic behavior of firms and consumers across the U.S. Along with the model structure shown in Figure 8, an essential component of its ability to analyze environmental policies is its

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[22] Solving EMPAX-CGE as a MCP problem implies that complementary slackness is a feature of the equilibrium solution. In other words, any firm in operation will earn zero economic profits and any unprofitable firms will cease operations. Similarly, for any commodity with a positive price, supply will equal demand, or conversely any good in excess supply will have a zero price.

[23] See Rutherford (1999) for MPSGE documentation.

[24] See Brooke, Kendrick and Meeraus (1996) for a description of GAMS (http://www.gams.com/).

inclusion of data on environmental protection expenditures made by firms. In order to reduce pollution, businesses typically must purchase emission control equipment and other production inputs from the rest of the economy. Accounting for these purchases is important because, in many cases, industries with high compliance costs will receive offsetting benefits as other types of companies buy more of their product, which partially reduces the burden of environmental regulations. For example, utilities have high environmental expenditures, but they also supply the electricity used by other firms to meet their own environmental standards. In addition, as expenditures on the goods and services necessary for compliance increase, firms producing these items may actually experience net benefits from regulatory action.

The importance of environmental protection activities in an economy has been investigated in previous studies (Schafer and Stahmer [1989], and Nestor and Pasurka [1995]). The goal of these papers was to improve estimates of environmental expenditures so that their contribution to gross national product could be more accurately measured. This was accomplished by developing input-output matrices showing the types of purchases made by firms in order to abate pollution. Schafer and Stahmer estimated an IO matrix for Germany using 1980 data, and Nestor and Pasurka categorized environmental protection expenditures for the U.S. economy using a similar IO framework based on 1977 and 1982 Census data.

EMPAX-CGE distributes estimated environmental protection (EP) costs across industries using data from Nestor and Pasurka. This study, which is based on data from an EPA report (U.S. EPA, 1995b), provides a detailed IO matrix of EP expenditures by 41 industries in 1982. It shows how each industry's costs are allocated across purchases from other industries and also gives data on how much labor and capital were used. Table 9 displays these environmental protection activities for selected industries (chemicals, petroleum refining, and electric utility industries) as an example of the information available. The columns of the table represent industries required to comply with environmental regulation, while the rows represent the industries from which they purchased environmental protection goods and services.

There are substantial differences in the distribution of costs between inputs across industries. For instance, the electric utility sector spends a very large proportion (47 percent) of their environmental protection expenditures on inputs purchased from the mining sector (most of which is low sulfur coal), while the chemicals and petroleum refining sectors do not spend any appreciable amount on these inputs. Expenditures on labor and capital generally account for a large share of environmental protection costs across all industries, but still differ substantially across sectors in the total percentage devoted to these inputs and in the distribution between labor and capital.

Table 9. Selected Distributions of Environmental Protection Expenditures

	Chemicals	Petroleum Refining	Electric Utilities
Mining	0%	0%	47%
Construction	7%	7%	4%
Textile mill products	0%	1%	0%
Chemicals and allied products	5%	3%	3%
Petroleum refining	1%	6%	2%
Stone clay and glass products	4%	5%	2%
Machinery except electrical	0%	1%	0%
Electric utilities	8%	15%	6%
Gas utilities	0%	1%	0%
Finance insurance and real estate	1%	2%	1%
Other services	17%	22%	7%
Water supply ("environmental")	2%	1%	0%
Sewerage systems	3%	0%	0%
Solid waste management services	10%	4%	4%
Labor	16%	18%	15%
Capital	24%	13%	11%
Total	100%	100%	100%

EMPAX-CGE assumes, in the absence of any other information, that additional expenditures to meet new regulations (such as the operating costs estimated by IPM or any compliance costs experienced by other industries) follow the patterns shown in the Nestor and Pasurka study.[25] Compliance costs are allocated across industries supplying EP goods and services based on an assumption of constant shares. The only exception to this allocation approach is that electric utilities' purchases from the mining sector are ignored when determining the shares since these purchases (mainly of low-sulfur coal) were specific to policies in place in 1982. Also, since EMPAX-CGE can use IPM results on fuel switching directly (see Appendix C), it is not necessary to include them in another, more indirect, fashion.

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[25] Ideally, environmental protection IO tables more recent than 1982 would be available. The levels in dollar values for baseline expenditures are probably quite different now than when the study data were collected. However, EMPAX-CGE uses expenditure shares, rather than the 1982 dollar values.

7. Dynamic EMPAX-CGE

The dynamic version of EMPAX-CGE is designed to investigate policies that have variable effects over time. By modeling the future path of the economy, it is able to consider transitions that occur as the economy adapts to new policies. Dynamic EMPAX-CGE is based on the same data sources, production technologies, and household utility functions as the static version, but includes additional features to allow it to model economic growth, investment decisions, and intertemporal behavior by households.

There are four sources of economic growth in Dynamic EMPAX-CGE: technological change from improvements in energy efficiency, growth in the available supply of labor from population growth and changes in labor productivity, increases in stocks of natural resources, and capital accumulation. Changes in energy use per unit of output are model through exogenous variables called autonomous energy efficiency improvements (AEEI), which are used to specify energy consumptions by fuel type and industry to replicate energy forecasts from EIA. Labor force growth, changes in available natural resources, and resource prices are also based on the AEO forecasts. Decisions regarding capital formation also control many of the dynamic aspects of the model.

The representation of savings-investment decisions by households determine behavioral responses to policies. Dynamic EMPAX-CGE models these decisions using a forward-looking, full intertemporal optimization approach in which households have perfect foresight and maximize the present value of all future consumption.[26] This is in contrast to other dynamic CGE models that assume savings and investment are based only on the current time period's characteristics and that households are not forward looking.[27] By allowing agents to anticipate new policies, the EMPAX-CGE model shows how people will begin to prepare for policies that are announced today, but that will not begin until sometime in the future.

In order to investigate the dynamic implications of policies, the model must first establish a baseline path for the economy that incorporates economic growth and technology changes that are expected to occur in the absence of any new policies. Dynamic EMPAX-CGE begins from a balanced SAM that reflects economic conditions estimated by EIA for the year 2005. From this starting point, it solves in 5-year time intervals into the future and uses a variety of mechanisms (discussed in this section) to replicate the AEO energy and economic projections through the year 2025. Once this baseline is established, it is possible to run "counterfactual" policy experiments.

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[26] The theoretical basis for these types of models comes from Ramsey (1928), Cass (1965), and Koopmans (1965).

[27] Non-forward looking models are classified as recursive dynamic, e.g. MIT's EPPA model.

Section 7.1 discusses how the industry and regional data employed in the static version of EMPAX-CGE have been aggregated in order to allow the dynamic version to find solutions for multiple time periods while remaining within computational modeling limits. Section 7.2 describes the energy production and consumption forecasts utilized by the model and how they are replicated. Section 7.3 covers similar issues related to natural resources. Section 7.4 discusses the approach to modeling capital formation. Section 7.5 discusses household decisions and labor supply issues. Finally, Section 7.6 describes how a baseline equilibrium is established for the model.

7.1 Data Utilized by Dynamic EMPAX-CGE

The dynamic version of EMPAX-CGE relies on the same data sources as the static version of EMPAX-CGE, and employs the same techniques discussed in Section 5 to generate an initial SAM for the economy based on AEO forecasts for the year 2005. From this starting point, it determines a growth path for the economy in the baseline by adjusting energy production and consumption, along with resource and labor changes, as discussed in following sections.

Table 10 shows how industries in Dynamic EMPAX-CGE correspond to the wider array of sectors in the static model. The five main types of energy (coal, crude oil, electricity, natural gas, and petroleum) are maintained as separate industries due to their importance to environmental policies, although the petroleum refining sector only produces one type of oil instead of the original three categories (distillate fuel, motor gasoline, and other petroleum). Agriculture is also kept separate since it does not fit in the other categories. An "energy-intensive manufacturing" industry is defined that covers the types of businesses defined as high energy users according to EIA's classification in "Assumptions to AEO 2003." The remaining, less energy-intensive, manufacturers are grouped together in a single category. Service industries are left as a distinct category due to the overall size of the service side of the economy, even though they use relatively little energy and are generally less affected by environmental policies. Transportation services are grouped together to reduce the size of the model, but have not been merged with other types of services since they consume significant amounts of fuel and are vital for moving goods and people around the country.

Table 10. Industries in Dynamic Version and Correspondence to Static Version

Dynamic Version	Static Version
Coal	Coal
Crude Oil	Crude Oil
Electricity	Electricity
Natural Gas	Natural Gas
Petroleum Refining *	Petroleum Refining
Agriculture	Agriculture
Energy-Intensive Manufacturing	Food
	Paper
	Chemicals
	Glass
	Cement
	Iron and Steel
	Aluminum
Other Manufacturing	Construction
	Mining
	Beverages and Tobacco
	Textile Mills
	Textile Product Mills
	Apparel
	Leather
	Lumber and Wood
	Printing and Publishing
	Rubber and Plastic
	Other Nonmetallic Minerals (not including Glass or Cement)
	Other Primary Metals (not including Iron/Steel or Aluminum)
	Fabricated Metal
	Machinery
	Computer and Elec Equipment
	Electronic Equipment
	Transportation Equipment (except Motor Vehicles)
	Motor Vehicles
	Furniture
	Miscellaneous
Services	Services
Transportation	Transport by Air
	Transport by Freight Truck
	Transport by Railroad
	Transport by Water
	Transport by Other

* The petroleum refining industry produces only one type of oil, rather than the three types in the static version (distillate fuel, motor gasoline, and other petroleum).

A similar aggregation has been applied to regions in the model (see Figure 9). The goal of this process is to reduce the size of the dynamic model while keeping a regional categorization that maintains important differences in electricity generation and manufacturing industries across parts of the nation. In the northeast, midwest, and southern parts of the U.S., two regions from the static model have been combined into a single more aggregated region. In the middle of the country, three regions have been merged. The western region remains the same as in the static version of EMPAX-CGE.

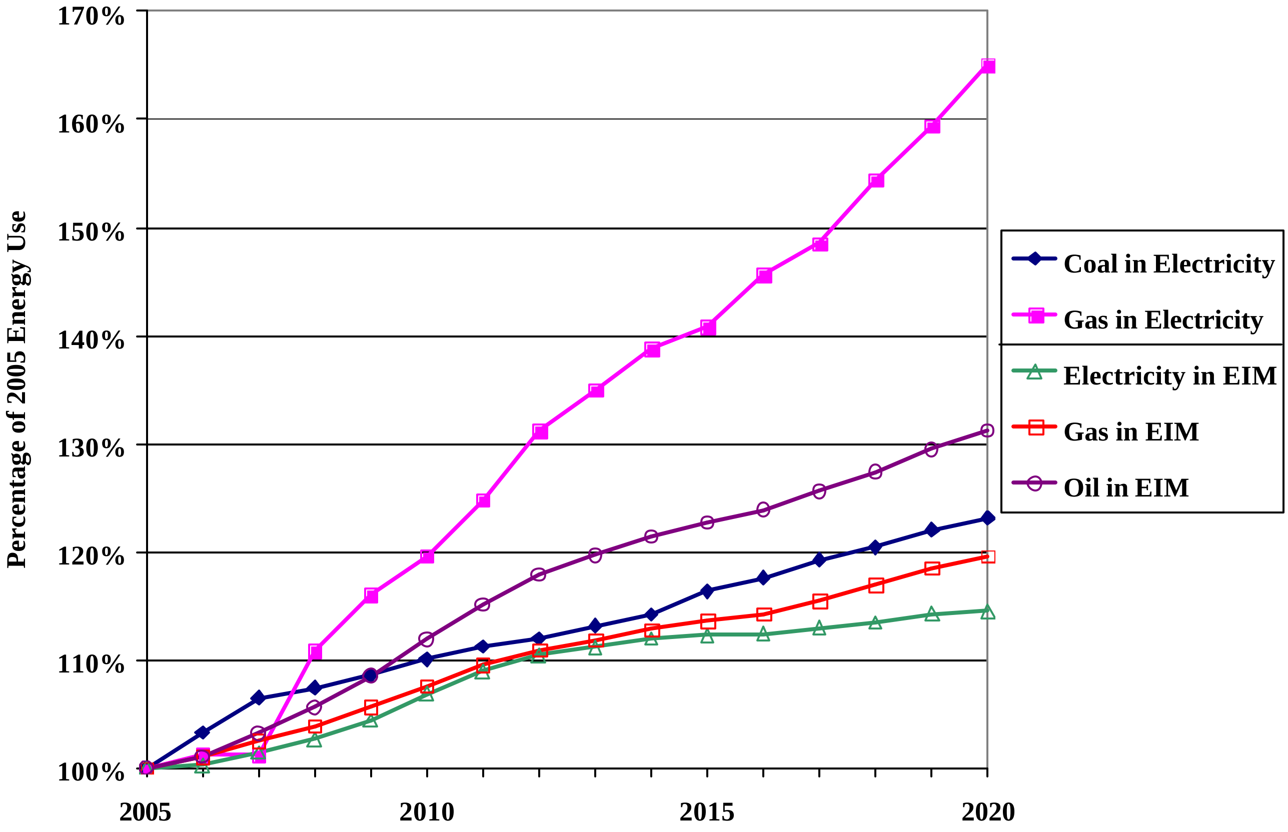
Figure 9. Regions in EMPAX-CGE (Dynamic Version)

7.2 Energy Use

The baseline model solution for EMPAX-CGE needs to reflect the fact that energy consumption per unit of output tends to decrease over time through improvements in production technologies and energy conservation. Not incorporating these changes would cause the model to estimate unrealistically large costs for energy/environmental policies since the initial energy use would be too high. In addition, the baseline equilibrium must consider how industries shift from one energy source to another over time.

Figure 10 shows EIA estimates for fuel-use changes in two industries that rely heavily on energy: electricity generation and energy-intensive manufacturing (EIM). Utilities mainly use coal and gas to generate electricity, in addition to non-fossil sources. Consumption of both types of fuel is expected to increase in the future as demand for electricity grows, but there is a significant shift into gas-fired generation over the next two decades for a variety of reasons.[28] Similarly, EIM firms consume more energy in the future, but are inclined to switch into oil, rather than other fuels.

Figure 10. AEO's Changes in Energy Use for Selected Fuels/Industries



To capture these types of shifts in consumption, along with changes in energy efficiency, an autonomous energy efficiency improvement (AEEI) index for each fuel and each industry is

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[28] In additional to variations in fuel use patterns expected from changes in prices and technologies, the AEO forecasts include effects that are expected to occur from legislation on the books at the time the forecasts are generated. This contributes to the shift away from coal and into gas as firms comply with existing environmental regulations.

developed that specifies the rate of decline in energy use per unit of output.[29] AEEIs provide the means for matching expected trends in energy consumption that have been taken from the AEO forecasts. They alter the amount of energy needed to produce a given quantity of output by incorporating improvements in energy efficiency and conservation.

Another important method of establishing baseline energy consumption patterns in the dynamic version of EMPAX-CGE is setting electricity generation by nuclear and renewables sources. The AEO forecasts provide estimates for future generation by these two sources, and EMPAX-CGE fixes non-fossil electricity output at these levels. This implies that the types of policies investigated by EMPAX-CGE will not be of a magnitude sufficient to overcome cost differentials between fossil and renewable generation, and that additional nuclear units will not be built as the result of these policies.

7.3 Natural Resources

The final component of Dynamic EMPAX-CGE that controls the energy side of the economy is the modeling of how natural resources (coal, crude oil, and natural gas) evolve over time in price and quantity terms. AEO forecasts show prices and production quantities expected in the future, but do not provide any information on the amount of the resources available in the ground for extraction or the costs associated with extracting additional materials. To overcome this limitation, EMPAX-CGE generates resource supply elasticities around the forecasted production paths.[30]

Resource supply elasticities reflect the fact that production costs rise as more is extracted and resources are depleted. By selecting the elasticities of substitution between the natural resources and other production inputs in these industries (elasticity s_{gr} in Figure 4), the supply elasticity can be determined.[31] Price paths from AEO are also matched in EMPAX-CGE by adjusting the growth rates for the fixed factor inputs to resource production so that their prices in the baseline solution are calibrated to the desired forecasts.

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[29] Edmonds and Reilly (1985) were the first to outline this approach. See Babiker et al. (2001) for a discussion of how this methodology was used in the EPPA model (EPPA assumes that AEEIs are the same across all industries in a country, while the AEEIs in EMPAX-CGE are industry specific).

[30] See Babiker and Rutherford (1997) and Rutherford and Paltsev (2000) for a discussion of how these techniques were used to incorporate the International Energy Agency energy data in the GTAP economic data.

[31] EMPAX-CGE uses an approach to natural resources that is similar to the EPPA model. Algebraic calculations can demonstrate that the resource supply elasticity ($?^s$)is equal to the substitution elasticity (s_{gr}) adjusted by the share of inputs of natural resources used to produce output from the resource industry (S_{nr}): $?^s = s_{gr} * (1 - S_{nr}) / S_{nr}$.

7.4 Capital Stock and Adjustment Dynamics

Savings and investment decisions made by households determine aggregate capital stocks in the economy in Dynamic EMPAX-CGE. Characteristics of the formation of these stocks is described by the IMPLAN dataset, which provides details on the types of goods and services used to produce investment goods. The model uses this information to specify an aggregate investment sector that produces capital used by the economy. The data sources, however, do not contain a representation of initial capital stocks so it is necessary to calibrate them from observed earnings generated by the unobserved capital stock.[32] Typically, capital stock data, even if available, is not considered as reliable as capital earnings data so the calibration approach may be employed even if stocks are provided.[33]

Starting from the initial capital stock in the economy, the model has to specify how the stock evolves over time. These "adjustment dynamics" associated with formation of capital control the transition path the economy takes in response to new policies. In Dynamic EMPAX-CGE, these dynamics are controlled through the use of quadratic adjustment costs associated with installing new capital, which imply that real costs are experienced in order to build and install new capital equipment.

Following Uzawa (1969), EMPAX-CGE assumes that capital installation costs depend on the rate of gross investment in relation to the existing stock of capital. Costs of new capital decrease as the capital stock rises and vice versa. The installation cost function is given by:

$$I_t = J_t\left(1 + f\frac{J_t}{2K_t}\right)$$

where I_t is gross investment (in period t), J_t is net investment, K_t is the existing capital stock, and f reflects the speed of adjustment. The formulation implies that rapid changes in capital stocks are expensive and that the rate of adjustment will decline as adjustment costs increase.

Overall capital stocks are a function of this new net investment and depreciation (d) of existing capital. The amount of capital available in the economy in the future is controlled by this equation:

$$K_{t+1} = K_t(1-d) + J_t$$

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[32] The rate of return to capital earnings includes the interest rate (r) plus the depreciation rate (d). This is equal to the ratio of capital earnings (K_e) in the economy divided by the capital stock (K), allowing the stock to be calculated as: $K_S = K / (r + d)$.

[33] See Babiker et al. (2001) for a discussion of the EPPA model's calibration of capital stocks, which was done even though the underlying GTAP data included information on stocks.

which shows how depreciation lowers available capital and net investment increases it. Net investment has to be sufficient to cover both economic growth (generating a need for additional capital in the future) and depreciation of existing capital. The capital stock generated in the model is perfectly malleable across industries within each of the five regions.

7.5 Households

As in the static version of EMPAX-CGE, each region in the dynamic version contains a representative household that maximizes utility subject to their budget constraint. In the dynamic version of EMPAX-CGE, however, households have perfect foresight and maximize intertemporal utility over all time periods in the model. Within each period, intratemporal utility received by a household is formed from consumption of goods and leisure time according to the CES nesting structure shown in Figure 6. Over time, households consider the discounted present value of utility received from all periods' consumption of goods and leisure.

Since it is not computationally feasible to model an infinite number of time periods, EMPAX-CGE approximates an infinite horizon. This is done by separating the household's maximization decisions into two optimization problems, within model horizon (t=0 to t=T) and post horizon (t=T+1 to infinity).[34] The two problems are connected by the desired capital stock in T+1. In each time period, *t*, households maximize intratemporal utility. Across time periods, the intratemporal utility, U_t (shown in Figure 6), is combined using a CES function to form intertemporal utility:

$$\max U = \left(\sum_{t=0}^{T} \left(\frac{1}{1+g} \right)^{t} \left[U_t \right]^{r} \right)^{1/r}$$

where *?* is the effective discount rate and the intertemporal elasticity of substitution, *s*, is equal to *s=1/(1-?)*. This intertemporal utility maximization is done subject to an intertemporal budget constraint:

$$\sum_{t} \left(p_t^c C_t + w_t LEIS_t \right) = \sum_{t} w_t L_t + pk_0 K_0 - pk_T K_T$$

where p^c is the average price of consumption goods, *C* is total consumption, *w* is the wage rate, *LEIS* is leisure time, L_t is the total labor endowment in time t, pk_0 is the price of capital in the initial time period, K_0 is the initial capital stock, pk_T is the price of capital in the terminal model period, and K_T is the supply of capital in the terminal period.

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[34] See Lau, Pahlke, and Rutherford (2002) for discussion of this approach.

Labor earnings arise from an endowment of labor to households. This endowment grows over time as population and labor productivity grow. The model does not attempt to distinguish between these two sources of growth. Instead, it relies on exogenously specified growth rates in effective units of labor available to the economy. Using the assumption of Harrod-neutral technical change to represent increases in labor productivity allows EMPAX-CGE to include a labor augmentation parameter that covers both population growth and improvements in per-unit labor effectiveness. The growth parameter is based on AEO forecasts of overall economic growth.

At the beginning of the model horizon, in addition to labor endowments, households also own the existing capital stock, the value of which reflects expected future capital earnings generated from that stock. However, since the model solves an finite horizon problem it is necessary to remove the value of capital stocks remaining at the end of the model horizon.

7.6 Generation of a Baseline Model Solution

Before Dynamic EMPAX-CGE can be used to investigate a new policy, a baseline solution must be established for the model. In a dynamic model, this involves more steps than those discussed in Section 6 for the static model. Starting from the initial dataset representing the year 2005, the functional forms are chosen and exogenous elasticities are specified as before. Then a "steady-state" growth path is specified for the economy that is used as a replication check to ensure there are no errors in the model. Finally, the economy's growth and energy variables are matched to desired forecasts.

A steady-state growth path involves allowing all variables in the model to grow at a constant rate from the initial year out into the future. Labor and natural resource endowments grow at this constant rate (assumed to be 3% per year, based on the average GDP growth in the AEO forecasts). Output, inputs to production, and consumption also grow at this rate. If the model has been properly specified, the "steady-state" replication check will show that the economy is in an equilibrium along this constant-rate growth path. Once the model is able to replicate a steady-state growth path, desired forecasts can be applied to move the economy to a new baseline equilibrium that is based on expected future economic conditions.

Dynamic EMPAX-CGE incorporates a variety of forecasts to allow it to reflect expected future economic conditions (as given by the AEO forecasts). These include:

- Energy consumption by industry and fuel type
- Nuclear/renewable electricity generation
- Natural resource prices
- Labor endowments

Growth paths for energy are matched by the use of AEEI’s that adjust the amount of fuel consumed by industries and households. These are calculated for each of the ten industries, and ten households, for each type of energy (coal, crude oil, electricity, natural gas, and petroleum). A series of iterative solves are conducted by the model in order to find AEEI coefficients that replicate the energy consumption and production forecasts. Each model solve estimates what the appropriate AEEI needs to be in order to match the forecasts. The model is then solved to determine the resulting energy uses, and these findings are compared to the desired result. The differences between the model solution values and the desired forecasts are used to adjust the AEEI’s, and the model is resolved again until the baseline model solution is within a small percentage of the initial forecasts (generally within 0.1% - 1.0% of AEO’s projections).

The amount of electricity generated by nuclear/renewable sources are easier to match to forecasts due to the assumption of fixed input coefficients in production. Households are endowed with a fixed factor input to non-fossil generation (e.g., some fraction of the capital used in generation) that is required in order to produce the electricity. By allowing this endowment to grow along the desired path, output from non-fossil sources is constrained to match forecasts.

Price paths for natural resources (coal, crude oil, and natural gas) are established using the process described in Section 7.3, which allows the model to replicate prices off the steady-state growth path. Labor endowments of each household in Dynamic EMPAX-CGE grow at exogenously specified rates based on AEO forecasts of economic growth. These growth parameters cover both population growth and improvements in labor productivity and are one of the main sources of economic growth in the model.

8 Incorporation of Taxes

The next planned extension to the capabilities of EMPAX-CGE is to include taxes and their associated distortions. If existing tax rates drive a wedge between the cost of producing a good and the price paid by the purchaser, it will distort producer and consumer behaviors. These distortions can have significant implications for the costs and effects of environmental policies. Both theoretical and empirical literature has examined these "tax interactions" and found that they can substantially alter policy costs. Consequently, it is important for EMPAX-CGE to consider how tax distortions may interact with policies when estimating macroeconomic results.

One of the main goals will be to determine an appropriate characterization of the user cost of capital. In dynamic models, capital taxes can be relatively distortionary since they influence how people save and invest. This, in turn, affects how much capital is available for future production and can have significant effects on the results of policy simulations. The cost of capital depends on a multitude of factors such as interest rates, income tax rates (since households pay taxes on capital earnings), property taxes, and more. Past work by other CGE modelers (e.g., Ballard and Fullerton [1985], Fullerton and Rogers [1993], and Bovenberg et al. [2003]) provides guidance on the appropriate methods for calculating the user cost of capital.

Along with capital taxes, an important feature related to modeling tax distortions is inclusion of a labor-leisure choice - how people decide between working and leisure time. EMPAX-CGE currently incorporates a labor-leisure decision by households, in part to facilitate consideration of tax distortions in the model. The labor supply elasticities related to labor-leisure choices control a large degree of how distortionary taxes are in a CGE model.

The IMPLAN economic database used by EMPAX-CGE includes information on several types of taxes such as indirect business taxes (sales/excise taxes), Social Security taxes, property taxes, direct taxes/transfers between households and government, etc. Wedges between producer costs and purchaser prices from these taxes will be included based on the rates shown in the IMPLAN data. Additional data on average marginal income tax rates (the tax rate paid, on average, on the last unit of income earned) will need to be collected from a variety of federal and state government sources. Similarly, once an approach to determining the user cost of capital has been selected, average marginal rates for its components (e.g., property taxes) have to be determined.

After all tax distortions have been added to the model, the implied marginal excess burdens, or marginal cost of public funds (MCPF, the welfare costs associated with raising an additional dollar of tax revenue), will be examined. These MCPF will be compared to empirical estimates to validate the parameters selected for EMPAX-CGE. Prior to these investigations, equal yield constraints to hold government revenues/expenditures constant will be added.

9 Incorporation of Multiple Households

Another important extension of EMPAX-CGE to be undertaken is the inclusion of multiple types of households in place of the representative households currently utilized. Environmental policies have the potential to influence income distributions and may affect households in substantially different ways. Energy commodities typically comprise a much larger part of the budget for low-income households than for higher-income ones. This raises the possibility that environmental policies may have regressive effects if they cause energy prices to increase, i.e. people with low incomes may bear a larger part of the burden of these policies than people with higher incomes. By including several household types classified by differences in income, EMPAX-CGE will be able to provide additional information on how environmental policies impact these different groups of consumers.

The IMPLAN economic database used by EMPAX-CGE distinguishes among a variety of households classified by income. Their expenditure patterns have been developed from the U.S. Bureau of Labor Statistics' Consumer Expenditure Survey and the U.S. Census Bureau's Decennial Census and Population Surveys. The nine consumer groups include households in the following income groups:

- $0 to $4,999
- $5,000 to $9,999
- $10,000 to $14,999
- $15,000 to $19,999
- $20,000 to $29,999
- $30,000 to $39,999
- $40,000 to $49,999
- $50,000 to $69,999
- $70,000 and above

Computational limitations will control how many of these income classes can be included in EMPAX-CGE; however, the model will be expanded to include as many household types as feasible.

As with overall energy consumption data, the IMPLAN data (especially related to energy consumption by households) will need to be evaluated to determine its accuracy. In addition, trends in income and consumption patterns between the initial year of the IMPLAN data (year 2000) and the starting year for EMPAX-CGE will need to be incorporated. Projections of income growth from government sources will be used, as possible, to establish the multiple representative households in the baselines of the static and dynamic models, along with growth trends in the dynamic model.

References

Adkins, L.G. and R.F. Garbaccio. 1999. “A Bibliography of CGE Models Applied to Environmental Issues.” U.S. Environmental Protection Agency, Office of Economy and Environment. Available at http://www.ksg.harvard.edu/cbg/ptep/cge.bib.2e.pdf.

Armington, P.S. 1969. “A Theory of Demand for Products Distinguished by Place of Production.” *IMF Staff Papers 16*, pg. 159-178.

Arrow, K.J. and G. Debreu. 1954. “Existence of an Equilibrium for a Competitive Economy.” *Econometrica* 22, pg. 265-290.

Arrow, K.J. and F.H. Hahn. 1971. *General Competitive Analysis*. San Francisco: Holden-Day.

Babiker, M.H and T.F. Rutherford. 1997. “Input-output and general equilibrium estimates of embodied carbon: A data set and static framework for assessment.” University of Colorado at Boulder, Working Paper 97-2.

Babiker, M.H, J.M Reilly, M. Mayer, R.S. Eckaus, I.S Wing, and R.C. Hyman. 2001. “The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Revisions, Sensitivities, and Comparisons of Results.” MIT Joint Program on the Science and Policy of Global Change, Report No. 71.

Babiker, M.H., G.E. Metcalf, and J. Reilly. 2002. “Tax Distortions and Global Climate Policy.” MIT Joint Program on the Science and Policy of Global Change, Report No. 85.

Ballard, C.L., D. Fullerton, J.B. Shoven, and J. Whalley. 1985. *A General Equilibrium Model for Tax Policy Evaluation*. Chicago: University of Chicago Press.

Berck, P. and P. Hess. 2000. “Developing a Methodology for Assessing the Economic Impacts of Large-Scale Environmental Regulations.” Department of Agricultural and Resource Economics and Policy, University of California, Berkeley, Working Paper No. 924.

Bergman, L. 1988. “Energy Policy Modeling: A Survey of General Equilibrium Approaches.” *Journal of Policy Modeling* 12(4):671-691.

Bernstein, P.M., W.D. Montgomery, T.F. Rutherford, and G. Yang. 1999. “Effects of Restrictions on International Permit Trading: The MS-MRT Model.” *The Energy Journal (Kyoto Special Issue)*: 221-256.

Bovenberg, L.A. and L.H. Goulder. 1996. “Optimal Environmental Taxation in the Presence of Other Taxes: General-Equilibrium Analysis.” *American Economic Review* 86(4):985-1000.

Bovenberg, A.L., L.H. Goulder, and D.J. Gurney. 2003. “Efficiency Costs of Meeting Industry-Distributional Constraints under Environmental Permits and Taxes.” Stanford University working paper, http://www.stanford.edu/~goulder/Bovenberg-Goulder-Gurney%20Paper.pdf.

Burfisher, M., S. Robinson, and K. Thierfelder. 1994. "Wage Changes in a U.S.-Mexico Free Trade Area: Migration versus Stolper-Samuelson Effects." In J. Francois and C. Shiells (eds.), *Modeling Trade Policy: Applied General Equilibrium Assessments of North American Free Trade.* Cambridge: Cambridge University Press.

Burniaux, J.M., G. Nicoletti, and J. Oliveira-Martins. 1992. "GREEN: A Global Model for Quantifying the Cost of Policies to Curb CO2 Emissions." *OECD Economic Studies 19*, pg. 123-140.

Cass, D. 1965. "Optimum Growth in an Aggregative Model of Capital Accumulation." *Review of Economic Studies* 32, pg. 233-240.

Deardorff, A.V. and M. Stern. 1981. "A Disaggregated Model of World Production and Trade: An Estimate of the Impact of the Tokyo Round." *Journal of Policy Modeling* 3, pg. 127-152.

Despotakis, K.A. and A.C. Fisher. 1988. "Energy in a Regional Economy: A Computable General Equilibrium Model for California." *Journal of Environmental Economics and Management* 15(3):313-330.

Edmonds, J., and J. Reilly. 1985. *Global Energy: Assessing the Future*. Oxford University Press: New York.

Francois, J. and C. Shiells (eds.). 1994. *Modeling Trade Policy: Applied General Equilibrium Assessments of North American Free Trade.* Cambridge: Cambridge University Press.

Fullerton, D., and G.E. Metcalfe. 1997. "Environmental Controls, Scarcity Rents, and Pre-Existing Distortions." NBER Working Paper 6091.

Fullerton, D., and D. Rogers. 1993. "Who Bears the Lifetime Tax Burden?" The Brookings Institute: Washington, DC.

Goulder, L.H., I. Parry, and D. Burtraw. 1997. "Revenue-Raising Versus Other Approaches to Environmental Protection: The Critical Significance of Preexisting Tax Distortions." *Rand Journal of Economics* 28:708-731.

Harberger, A.C. 1959. "The Corporate Income Tax: An Empirical Appraisal." In *Tax Revision Compendium*, Vol. 1. House Committee on Ways and Means. Washington D.C.: Government Printing Office.

Harberger, A.C. 1962. "The Incidence of the Corporation Income Tax." *Journal of Political Economy* 70, pg. 215-240.

Harberger, A.C. 1964. “Taxation, Resource Allocation, and Welfare.” In *The Role of Direct and Indirect Taxes in the Federal Reserve System*. Princeton: Princeton University Press.

Harberger, A.C. 1966. “Efficiency Effects of Taxes on Income from Capital.” In *Effects of Corporation Income Tax*, ed. M. Krzyzaniak. Detroit: Wayne State University Press.

Harberger, A.C. 1974. *Taxation and Welfare*. Chicago: University of Chicago Press.

Harrison, G.W. and T.F. Rutherford. 1998. “Burden Sharing, Joint Implementation, and Carbon Coalitions.” In *International Environmental Agreements on Climate Change*, Amsterdam: Kluwer.

Hazilla, Michael, and Raymond Kopp. 1990. “Social Cost of Environmental Regulations: A General Equilibrium Analysis.” *Journal of Political Economy* 98(4):853-872.

Ho, M.S. and D.W. Jorgenson. 1998. “Environmental Regulation and U.S. Trade.” In D.W. Jorgenson, *Growth, Volume 2: Energy, the Environment, and Economic Growth.* Cambridge, MA: MIT Press.

Johansen, Leif. 1960. *A Multi-Sectoral Study of Economic Growth.* Amsterdam, The Netherlands: North-Holland.

Jorgenson, D.W. 1998. *Growth, Volume 2: Energy, the Environment, and Economic Growth.* Cambridge, MA: MIT Press.

Jorgenson, D.W. and P.J. Wilcoxen. 1990a. “Environmental Regulation and U.S. Economic Growth.” *Rand Journal of Economics* 21(2):314-340.

Jorgenson, D.W. and P.J. Wilcoxen. 1990b. “Intertemporal General Equilibrium Modeling of U.S. Environmental Regulation.” *Journal of Policy Modeling* 12(4):715-744.

Jorgenson, D.W. and P.J. Wilcoxen. 1993a. “The Economic Impact of the Clean Air Act Amendments of 1990.” *The Energy Journal* 14(1):159-182.

Jorgenson, D.W. and P.J. Wilcoxen. 1993b. “Reducing U.S. Carbon Dioxide Emissions: An Econometric General Equilibrium Assessment.” *Resource and Energy Economics* 15(1):7-25.

Jorgenson, D.W. and P.J. Wilcoxen. 1993c. “Reducing U.S. Carbon Dioxide Emissions: An Assessment of Alternative Instruments.” *Journal of Policy Modeling* 15(5&6):491-520.

Jorgenson, D.W. and P.J. Wilcoxen. 1993d. “Energy, the Environment, and Economic Growth.” In A.V. Kneese and J.L. Sweeney (eds.), *Handbook of Natural Resource and Energy Economics, Volume 3*. New York: Elsevier Sciences.

Jorgenson, D.W. and P.J. Wilcoxen. 1997. “Fundamental U.S. Tax Reform and Energy Markets.” *The Energy Journal* 18(3):1-30.

Jorgenson, D.W., and P.J. Wilcoxen. 1998. "The Economic Impact of the Clean Air Act Amendments of 1990." In D.W. Jorgenson, *Growth. Volume 2: Energy, the Environment, and Economic Growth.* Cambridge, MA: MIT Press.

Industrial Economics, Inc. (IEC). 2001. "Benefits and Costs of the Clean Air Act 1990-2020: Draft Analytical Plan for EPA's Second Prospective Analysis." Prepared for the U.S. Environmental Protection Agency, Office of Policy Analysis and Review.

Koopmans, T.C. 1965. "On the Concept of Optimal Economic Growth." In *The Econometric Approach to Development Planning.* North Holland: Amsterdam.

Lau, M., A. Pahlke, and T. Rutherford. 2000. "Approximating Infinite-Horizon Models in a Complementarity Format: A Primer in Dynamic General Equilibrium Analysis." University of Colorado working paper.

Leontief, W.W. 1936. "Quantitative Input-Output Relations in the Economic System of the United States." The Review of Economics and Statistics, XVIII (August 1936), 105-25.

Leontief, W.W. 1951. *The Structure of the American Economy, 1919-1939*, 2nd ed. (1st ed. 1941), New York, NY: Oxford University Press.

Leontief, W.W. 1953, ed. *Studies in the Structure of the American Economy,* New York, NY: Oxford University Press.

Manne, A. and R. Richels. 1997. "On Stabilizing CO_2 Concentrations: Cost-Effective Emission Reduction Strategies." Paper presented at the IPCC Asia-Pacific Workshop on Integrated Assessment Models, the United Nations University, Tokyo, Japan, March 1997.

Martin, W. and Winters, L. A. 1996. *The Uruguay Round and the Developing Countries*. Cambridge: Cambridge University Press.

Mathiesen, L. 1985. "Computation of Economic Equilibrium by a Sequence of Linear Complementarity Problems." *Mathematical Programming Study* 23, pg. 144-162.

McKibbin, W.J., M.T. Ross, R. Shackleton, and P.J. Wilcoxen. 1999. "Emissions Trading, Capital Flows, and the Kyoto Protocol." *The Energy Journal (Kyoto Special Issue)*: 287-333.

Nainar, S.M.K. 1989. "Bootstrapping for Consistent Standard Errors for Translog Price Elasticities." *Energy Economics 11,* pg. 319-322.

Nestor, D.V. and C.A. Pasurka. 1995. "Environment-Economic Accounting and Indicators of the Economic Importance of Environmental Protection Activities," *Review of Income and Wealth,* Series 41, No. 3, pg. 265-287.

Nguyen, H.V. 1987. "Energy Elasticities Under Divisia and Btu Aggregation." *Energy Economics 9*, pg. 210-214.

Parry, Ian W.H. 1997. "Environmental Taxes and Quotas in the Presence of Distorting Taxes in Factor Markets." *Resource and Energy Economics* 19:203-220.

Parry, Ian W.H. 1999. "Agricultural Policies in the Presence of Distorting Taxes." *American Journal of Agricultural Economics* 81:212-230.

Pindyck, R.S. 1979. "Interfuel Substitution and the Industrial Demand for Energy: An International Comparison." *Review of Economics and Statistics 61*, pg. 169-179.

Ramsey, F.P. 1928. "A Mathematical Theory of Saving." *Economic Journal* 38, pg. 543-559.

Robinson, S., M. Burfisher, R. Hinojosa, and K. Thierfelder. 1991. "Agriculture in a U.S.-Mexico Free Trade Agreement: A Computable General Equilibrium Model with Migration and Farm Programs." Giannini Foundation Working Paper No. 617.

Rose, A. and G. Oladosu. 2002. "Greenhouse Gas Reduction Policy in the United States: Identifying Winners and Losers in an Expanded Permit Trading System." *Energy Journal* 23(1):1-18.

Rutherford, T.F and S.V. Paltsev. 2000. "GTAP-Energy in GAMS: The Dataset and Static Model." University of Colorado at Boulder, Working Paper 00-2.

Schafer, D. and C. Stahmer. 1989. "Input-Output Model for the Analysis of Environmental Protection Activities," *Economic Systems Research*, Vol. 1, No. 2, pg. 203-228.

Shoven, J.B. and J. Whalley. 1972. "A General Equilibrium Calculation of the Effects of Differential Taxation of Income from Capital in the U.S." *Journal of Public Economics* 1, pg. 281-322.

Shoven, J.B. and J. Whalley. 1973. "General Equilibrium with Taxes: A Computation Procedure and an Existence Proof." *Review of Economic Studies* 40, pg. 475-490.

Shoven, J.B. and J. Whalley. 1992. *Applying General Equilibrium*. Cambridge: Cambridge University Press.

Smith, V.K., H. Sieg, H.S. Banzhaf, and R. Walsh. 2003. "General Equilibrium Benefits for Environmental Improvements: Projected Ozone Reductions under EPA's Prospective Analysis for the Los Angeles Air Basin." Working Paper.

Tobin, J. "Natural Gas Transportation - Infrastructure Issues and Operational Trends." http://www.eia.doe.gov/pub/oil_gas/natural_gas/analysis_publications/natural_gas_infrastructure_issue/pdf/nginfrais.pdf

U.S. Environmental Protection Agency. 1995a. "The U.S. Environmental Protection Industry: A Proposed Framework for Assessment." Office of Policy, Planning, and Evaluation, EPA 230-R-95-011.

U.S. Environmental Protection Agency. 1995b. "The U.S. Environmental Protection Industry: The Technical Document." Office of Policy, Planning, and Evaluation, EPA 230-R-95-012.

U.S. Environmental Protection Agency. 2003. "OAQPS Economic Analysis Resource Document." Office of Air Quality Planning and Standards, Innovative Strategies and Economics Group.

U.S. International Trade Commission. 1992. "Economy-Wide Modeling of the Economic Implications of a FTA with Mexico and a NAFTA with Canada and Mexico." USITC Publication No. 2508.

Uzawa, H. 1969. "Time Preference and the Penrose Effect in a Two-Class Model of Economic Growth." Journal of Political Economy, 77. 628-652.

Williams, Roberton C., III. 1999. "Revisiting the Cost of Protectionism: The Role of Tax Distortions in the Labor Market." *Journal of International Economics* 47:429-447.