Documentation of the Applied Dynamic Analysis of the Global Economy (ADAGE) Model

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ABSTRACT

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This paper documents the *Applied Dynamic Analysis of the Global Economy* (ADAGE) model. ADAGE is a dynamic computable general equilibrium (CGE) model capable of examining many types of economic, energy, environmental, climate-change mitigation, and trade policies at the international, national, U.S. regional, and U.S. state levels. To investigate policy effects, the CGE model combines a consistent theoretical structure with economic data covering all interactions among businesses and households. A classical Arrow-Debreu general equilibrium framework is used to describe economic behaviors of these agents.

ADAGE has three distinct modules: *International*, *US Regional*, and *Single Country*. Each module relies on different data sources and has a different geographic scope, but all have the same theoretical structure. This internally consistent, integrated framework allows its components to use relevant policy findings from other modules with broader geographic coverage, thus obtaining detailed regional and state-level results that incorporate international impacts of policies. Economic data in ADAGE come from the GTAP and IMPLAN databases, and energy data and various growth forecasts come from the International Energy Agency and Energy Information Administration of the U.S. Department of Energy. Emissions estimates and associated abatement costs for six types of greenhouse gases (GHG) are also included in the model.

This paper describes features of the ADAGE model in detail. It covers the economic theory underlying firm and household behavior, the specific equations and parameter estimates used in the model, and the dynamics that control transition paths from the model's baseline economic-growth path to new economic equilibria in the presence of policies. The paper also discusses data sources used in ADAGE and presents baseline estimates of economic growth, energy production and consumption, and GHG emissions.

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1. THE ADAGE MODEL: OVERVIEW AND UPDATES

RTI International's (RTI's) *Applied Dynamic Analysis of the Global Economy* (ADAGE) model is a dynamic computable general equilibrium (CGE) model capable of examining a wide range of economic policies and estimating how all parts of an economy will respond over time to policy announcements. Among the feasible set of policies are many types of economic, energy, environmental, and trade policies that can be investigated at the international, national, U.S. regional, and U.S. state levels.[1] Of particular note is the ability of the ADAGE model to investigate climate-change mitigation policy issues affecting six types of greenhouse gases (GHG) at a range of geographic scales.

To investigate implications of policies, the ADAGE model combines a consistent theoretical structure with observed economic data covering all interactions among businesses and households. These economic linkages include firms purchasing material inputs from other businesses and factors of production (labor, capital, and natural resources) from households to produce goods, households receiving income from factor sales and buying goods from firms, and trade flows among regions. Nested constant-elasticity-of-substitution (CES) equations are used to characterize firm and household behaviors (which are intended to maximize profits and welfare, respectively), as well as options for technological improvements.

ADAGE uses a classical Arrow-Debreu general equilibrium framework to describe these features of the economy. Households are assumed to have perfect foresight and maximize their welfare (received from consumption of goods and leisure time) subject to budget constraints across all years in the model horizon, while firms maximize profits subject to technology constraints. Economic data in ADAGE come from the GTAP[2] and IMPLAN[3] databases, and energy data and various growth forecasts come from the International Energy Agency (IEA) and Energy Information Administration (EIA) of the U.S. Department of Energy.

ADAGE is composed of three modules: "*International*," "*US Regional*," and "*Single Country*." Each module relies on different data sources and has a different geographic scope, but all have the same theoretical structure. The internally consistent, integrated framework connecting ADAGE's modules allows its components to use relevant policy findings from other modules with broader geographic coverage. This allows the model to estimate detailed regional and state-level results that incorporate international impacts of policies,

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[1] RTI gratefully acknowledges partial funding of model development by the U.S. Environmental Protection Agency and the Pew Center on Global Climate Change (see http://www.pewclimate.org/). Any opinions expressed in ADAGE policy analyses are those of the authors alone.

[2] See http://www.gtap.agecon.purdue.edu/ for information on the Global Trade Analysis Project.

[3] See http://www.implan.com/index.html for information on the Minnesota IMPLAN Group.

while avoiding computational issues that preclude solving for all U.S. states and world nations simultaneously.

ADAGE incorporates four sources of economic growth: (1) growth in the available effective labor supply from population growth and changes in labor productivity, (2) capital accumulation through savings and investment, (3) increases in stocks of natural resources, and (4) technological change from improvements in manufacturing and energy efficiency. By means of these factors, a baseline growth forecast is established for ADAGE using IEA and EIA forecasts for economic growth, industrial output, energy consumption and prices, and GHG emissions. Starting from the year 2010, ADAGE normally solves in 5-year time intervals along these forecast paths, which are extended into the future as necessary for each policy investigation.[4]

This paper describes these features of the ADAGE model in detail. Among the areas covered are the economic theory underlying firm and household behavior, the specific CES equations and parameter estimates used, distortions from the existing tax structure, and the dynamics that control transition paths from the expected baseline economic growth path to a new economic equilibria in the presence of a policy. The paper also discusses data sources used in ADAGE and shows baseline estimates of economic growth, energy consumption, and GHG emissions.

The ADAGE model description and data documentation provide a context against which model results can be interpreted. These results include, among others, estimates of the following:

- Hicksian equivalent variation (a metric used in economic analyses to describe overall policy effects, considering all impacts of changes in prices, income, and labor supply);
- gross domestic product (GDP), consumption, industry output, and changes in prices;
- employment impacts and changes in wage rates;
- capital earnings and real interest rates;
- investment decisions;
- input purchases and changes in production technologies of firms;
- flows of traded goods among regions;
- energy production and consumption by businesses and households; and
- fuel and GHG permit prices.

The rest of Section 1 gives an overview of CGE modeling in general and the broad structure of ADAGE in particular. Section 2 then provides additional details on the general-equilibrium theory, model structure, and parameter estimates that control economic

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[4] Beyond the termination of policy investigations (generally around 2050), additional time periods are run to ensure that the model converges to a new steady-state equilibrium after a policy is imposed.

behavior in the model. Section 3 discusses the dynamic processes in the model that control economic growth. Section 4 describes the economic data in the model and related assumptions about taxes and labor-supply decisions, while Section 5 covers energy data sources. Section 6 provides information on GHG emissions and the methods used to model emissions abatement costs. Finally, Section 7 illustrates how these model features interact to determine economic growth and presents tables covering data from the ADAGE model's baseline forecasts.

Updates since the 2007 version of ADAGE include:

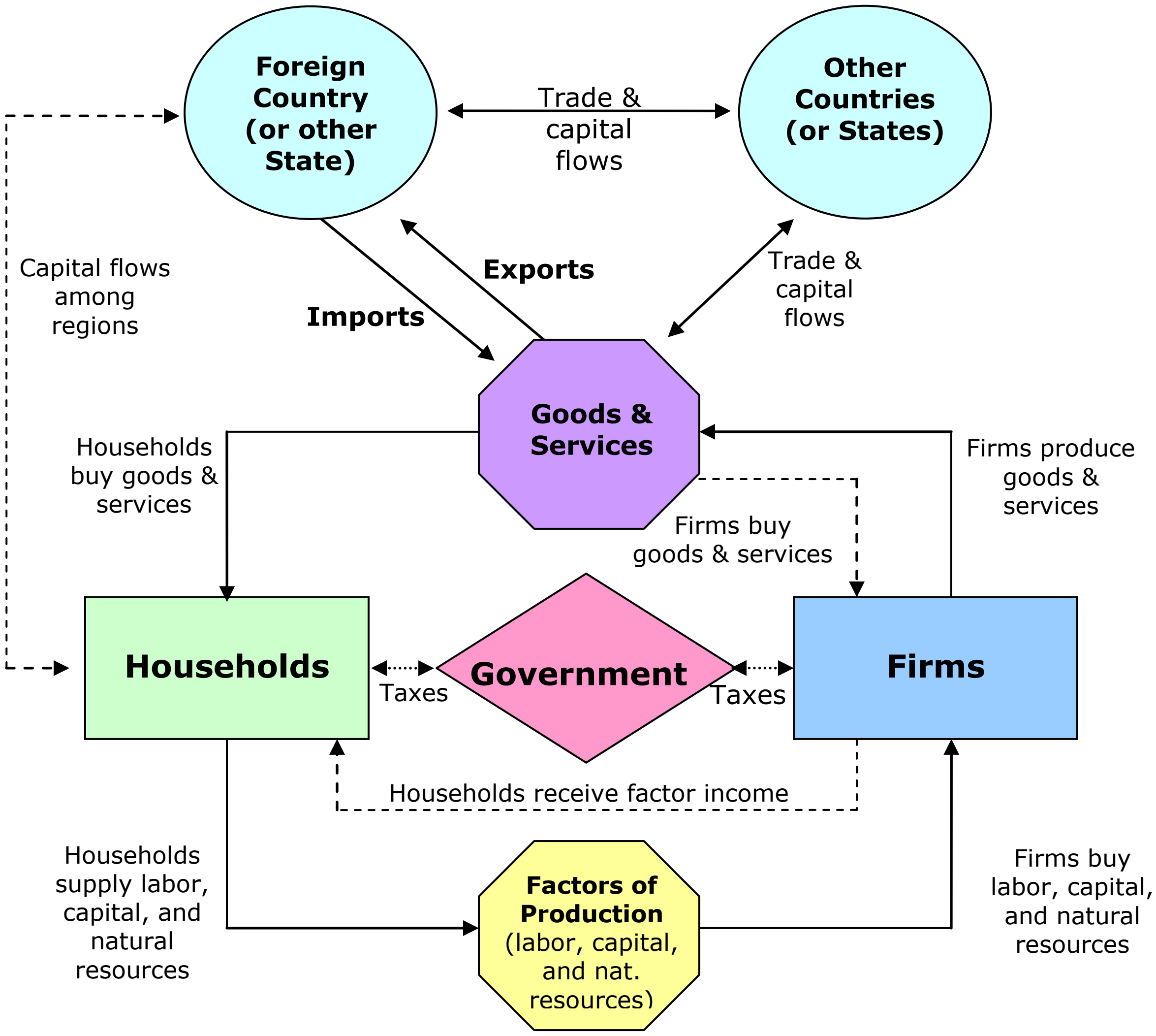
- Use of EIA *Annual Energy Outlook 2009* forecasts (March 2009 version)
- Use of IEA *World Energy Outlook 2008* forecasts
- Use of additional emissions data from EPA's *US Emissions Inventory—Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2006*. These data cover non-energy emissions of carbon dioxide not included in previous versions of the model.
- The initial year of the model has been shifted to 2010
- The capital structure of the model has been changed:
    - A putty-clay approach now controls capital movements - it distinguishes between existing capital stocks and new capital formation (compared to the previous model's use of a quadratic adjustment-cost approach).
- Capital costs for new electricity generation capacity have been updated (AEO 2009 has higher costs than in those used in forecasts several years ago)
- Supply curves for biomass electricity and offsets from FASOM-GHG have been updated (specific curves used are presented with each policy analysis).

1.1 Overview of CGE Modeling

Typically, the theoretical foundations of CGE models are based on a Walrasian general equilibrium structure. As described by an Arrow-Debreu model (Arrow and Debreu, 1954; Arrow and Hahn, 1971), this includes components such as the following: households in the economy have an initial endowment of factors of production and a set of preferences for goods; business firms maximize profits and have constant- or decreasing-returns-to-scale production functions; market demands are the sum of all agents' demands and depend on prices; and an equilibrium solution is characterized by prices and production levels such that demand equals supply for all commodities, income equals expenditures, and production activities break even at solution prices in the model (for constant-returns-to-scale production).

Within this theoretical structure, CGE models capture all flows of goods and factors of production (labor, capital, and natural resources) in the economy. The "general equilibrium" nature of these models implies that all sectors in the economy must be in balance and all economic flows must be accounted for within the model. A simplified version of these circular flows in an economy is illustrated in Figure 1-1.[5] Households own factors of production and sell them to firms, which generates incomes 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 or households using the income received from sales of factors. Goods and services can also be exported, and imported goods can be purchased from other countries. Capital flows among regions as they run trade deficits or surpluses. In aggregate, all markets must clear, meaning that supplies of commodities and factors of production must equal their demands, and the income of each household must equal its factor endowments plus any net transfers received.

Figure 1-1. Circular Economic Flows within CGE Models



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[5] Each foreign country, or state, also contains all the linkages among households, firms, and government shown in the figure.

Economic data specifying these circular flows are contained in a balanced social accounting matrix (SAM), which provides a baseline characterization of the economy that accounts for all interactions among agents in the economy (households, firms, government, and foreign countries). The SAM contains data on the value of output in each industry, payments for factors of production and intermediate input purchases by each industry, household income and consumption patterns, government purchases, investment, trade flows, and GHG emissions. These data reflect technologies currently used by firms to manufacture goods and households' preferences for consumption goods. The theoretical structure of the CGE model, along with its parameter estimates, then determines how production and consumption will change in response to new policies.

In this theoretical structure, households are assumed to maximize utility received from consumption of goods and services, subject to their budget constraints. CES functions are typically used to describe these utility functions, which show how willing and able households are to substitute among consumption goods in response to price changes. Firms are assumed to be perfectly competitive and 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, which are also typically specified using CES functions that describe how different types of inputs can be substituted for each other.[6] The extent of these substitutions is determined by elasticity parameters that control how easily trade-offs among inputs can be made.

To examine implications of climate-change mitigation policies, an additional constraint can be introduced into a CGE model that limits GHG emissions to a particular level. Based on this emissions cap, the model will estimate a shadow value on GHG emissions associated with the constraint, which can be interpreted as the price at which GHG allowances (or permits) would trade under a GHG cap-and-trade system. Allowance prices for a particular policy will be determined by emissions in the economy's baseline, the tightness of the cap, options for technological and energy-efficiency improvements, and the abilities and willingness of firms and households to switch into nonenergy goods.

1.2 Components of the ADAGE Model

The ADAGE modeling system is composed of three modules: *International*, *US Regional*, and *Single Country.* As shown at the top of Figure 1-2, this framework begins with the *International* module. This component of ADAGE allows the model to conduct international policy investigations on any set of nations included in its database (within computational limits on the total number of regions in the model). After the data and forecasts enter the

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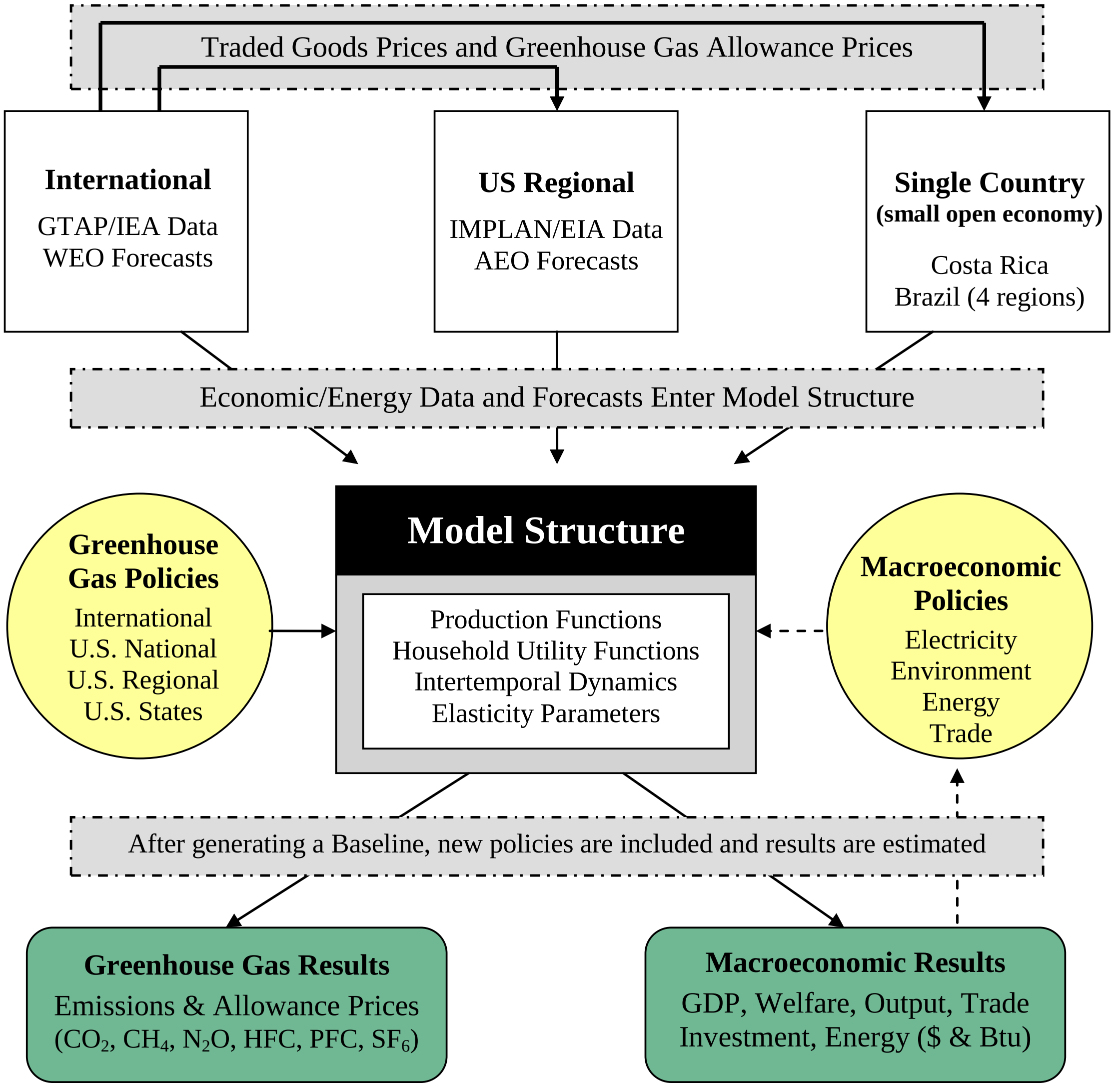
[6] Unlike input-output (I/O) models or partial-equilibrium models using fixed coefficients in production, a CGE model structure usually allows producers to change the technologies employed to manufacture goods.

model structure, policies can be examined. From these studies, findings on prices of traded goods and, in the case of climate change mitigation policies, emissions permit prices can be passed to the *US Regional* and *Single Country* modules. By passing this information down to modules with additional regional disaggregation, ADAGE is able to incorporate effects of international policies in its regional simulations (see Balistreri and Rutherford [2004] for a discussion of this type of modeling structure and its application in a climate-policy context).

Within the *US Regional* module, states are combined using a flexible regional-aggregation scheme that allows an individual state of focus to be designated and modeled relative to other regions. Typically, around five primary regions (groups of neighboring states) and an individual state (modeled as a separate sixth region) are included in policy simulations. By

Figure 1-2. The ADAGE Model: Integrated Framework of Connected Modules



running this aggregation scheme through all states of interest for a policy, findings can be obtained for multiple states in a computationally tractable, yet flexible and consistent, manner. (The same procedure can be used separate individual nations from national groupings in the *International* module). A similar CGE structure was used in Andriamananjara, Balistreri, and Ross (2006) to examine state-level impacts of international trade policies.[7]

ADAGE uses a variety of economic, energy, and emissions data sources to characterize production and consumption decisions by firms and households. These data show current production technologies and demands by agents, and are combined with economic growth forecasts and estimates of future energy production, consumption, and prices:

- ***International***—GTAP economic data, IEA energy production and consumption data, and *World Energy Outlook 2008* forecasts from IEA (2008). Carbon dioxide (CO_2) emissions related to fuel consumption are from IEA. Non-CO_2 GHG emissions are from the U.S. EPA (developed for the Stanford EMF 21 on multigas abatement).
- ***US Regional***—Economic data from the Minnesota IMPLAN Group (2005), and energy data and forecasts from EIA: *Annual Energy Outlook 2009*, *Manufacturing Energy Consumption Survey 2002*, *State Energy Reports*, and various Industry Annuals. Fuel-related CO_2 emissions are from EIA, and non-CO_2 GHG emissions are from EPA.
- ***Single Country***—Individual country data where GTAP data are less comprehensive – modeled as small open economies not affecting world traded-goods prices (currently for a regional Brazil model—International Food Policy Research Institute data[8]—and Costa Rica).

This integrated modular design (along with the flexible regional aggregations for U.S. states) has been adopted to overcome computational constraints that limit the total size of nonlinear, intertemporally optimizing CGE models such as ADAGE.

ADAGE model development would not have been possible without the MPSGE software (Mathematical Programming Subsystem for General Equilibrium; Rutherford [1999]).[9] ADAGE is solved as a mixed complementarity problem (MCP) within the Generalized Algebraic Modeling System (GAMS) language (Brooke et al. [1998]).[10] The GAMS/PATH solver is used to solve the MCP equations generated by the MPSGE software.

1.3 Data in the ADAGE Modules

ADAGE combines multiple data sources to create a balanced SAM for each module. The data are used to generate a balanced SAM for the year 2010 consistent with desired sectoral and regional aggregations.

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[7] To the best of our knowledge, this aggregation methodology was originally conceived by Thomas Rutherford. See http://www.mpsge.org/ for information on his work, and Balistreri and Rutherford (2004) for a description of this modeling approach.

[8] See http://www.ifpri.org/ for International Food Policy Research Institute (IFPRI) data and reports.

[9] See http://www.gams.com/solvers/solvers.htm#MPSGE for more information.

[10] See http://www.gams.com for more information.

The *International* module of ADAGE relies on the GTAP Version 6 database (Dimaranan, 2006). These economic data include balanced SAMs for 87 regions containing 57 sectors, with information for the year 2001 (which are extended to the base model year of 2010 using information from various sources). Within the bounds of the regional and sectoral disaggregation of these data, ADAGE is flexible in choosing regions and industries. For climate-change mitigation policy analyses, this information is combined with IEA data on historical and forecasted energy production, consumption, and price data; types of electricity generation; and GDP growth.

An international regional aggregation of the countries in GTAP is selected for an analysis based on the relevant international policy backdrop. Depending on the policy in question, it might include a group of regions such as:

- United States,
- Europe,
- Japan,
- Australia / New Zealand
- China and/or India and/or Russia,
- Rest of world.

The *US Regional* module is based on state-level economic data from the Minnesota IMPLAN Group[11] (available for the year 2004) and energy data from EIA (available for the year 2007). These data are typically used to define approximately five to six broad regions within the United States (regional definitions are flexible along state boundaries, one potential aggregation is shown in Figure 1-3). To examine a particular state of interest, that state is modeled as a separate sixth region, which interacts simultaneously with the five broader regions. When examining energy/environmental policies, the broad regions within the United States are generally selected to capture important differences across the country in electricity-generation technologies and also to approximate electricity market regions defined by the North American Electric Reliability Council (NERC). Each region typically includes between 10 and 20 industries (such as those shown below), where the total number of industries (aggregated from the IMPLAN data, which includes over 500 industries) are controlled by dimensional constraints in the CGE model.

The *Single Country* module is designed to allow ADAGE to look at nations not covered by the GTAP data and/or look at regions within non-U.S. countries if data are available. IFPRI publishes a four-region SAM for Brazil that has been adapted for use in ADAGE. Similarly, a Costa Rica SAM from Rodriguez (1994) is used to specify a module for that country, combined with World Bank data on expected economic growth. These data sources are

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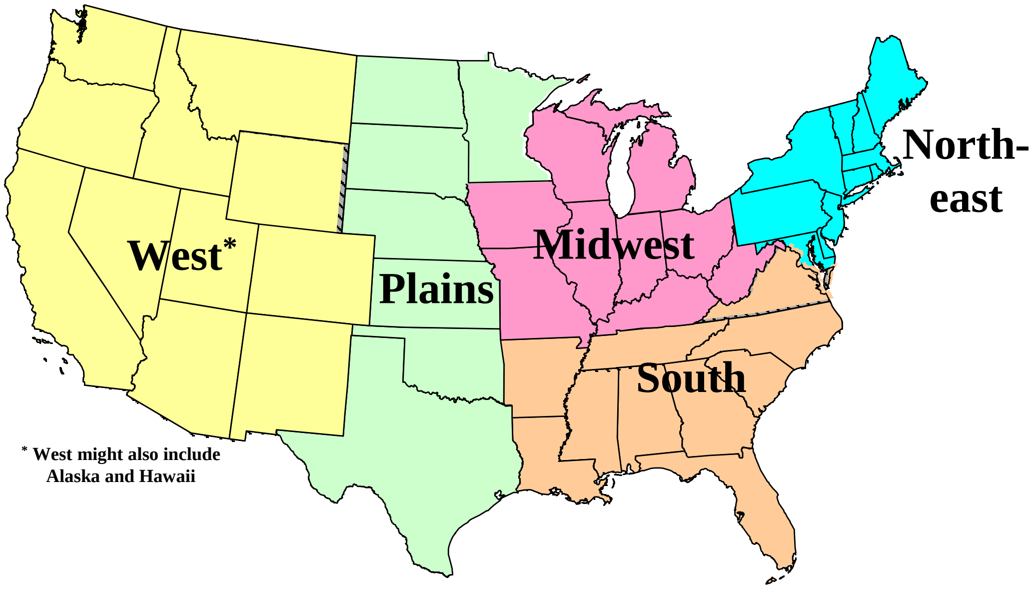
[11] Programs from Rutherford (2004) are used to organize and aggregate the IMPLAN data.

described in more detail in policy papers related to the specific countries in question and are not discussed here.

Figure 1-3. Potential U.S. Regional Aggregation (excluding specific states)



Industries represented in each module of ADAGE are aggregated from those in the underlying GTAP and IMPLAN databases to focus on the relevant economic sectors likely to be affected by the policy under investigation, while remaining within computational limits of CGE models. When using findings from one module in another, similar aggregations of industries are used across databases to ensure policy effects are translated accurately among modules. For example, when examining energy policies, data in each module are typically aggregated to five broad industries (with a focus on maintaining important distinctions in energy consumption and emissions) and five primary energy industries (with multiple forms of electricity generation, plus advanced technology options):

- agriculture
- energy-intensive manufacturing
- other manufacturing
- services
- transportation

- coal
- crude oil
- electricity (*multiple technologies*)
- natural gas
- refined petroleum

ADAGE, however, is flexible across industries (and regions) contained in the databases underlying the SAMs for each region and can be reaggregated for particular policy investigations to include specific regions and industries of interest (where the total number of regions and industries is constrained by computational considerations).

For policy investigations related to energy and climate-change mitigation, procedures are used to integrate the relevant economic and energy data. Although the GTAP and IMPLAN economic data contain information on the value of energy production and consumption in dollars, these data are replaced with IEA and EIA data for several reasons. First, when the policies being investigated focus on energy markets, it is essential to include the best possible characterization of these markets in the model, and the economic data do not always agree with energy information collected by IEA and EIA. Second, physical quantities of energy consumed are required for ADAGE to accurately estimate GHG emissions. IEA and EIA report physical quantities, while the economic databases do not. Finally, the economic data sources reflect the years 2001 and 2004, respectively, while the initial base year for ADAGE is 2010. Thus, *World Energy Outlook* (WEO) and *Annual Energy Outlook* (AEO) energy production and consumption, output, and economic-growth forecasts for 2010 are used to adjust the economic data.

1.4 General ADAGE Model Structure

Figure 1-4 illustrates the general framework of ADAGE, giving a broad characterization of the model and associated elasticities of substitution (noted by σ). At the top level, households in each region maximize intertemporal utility, or their overall welfare, across all time periods with perfect foresight. Within each time period, intratemporal household utility is a function of consumption and leisure. Below these utility functions, households distinguish between transportation services (either personal or purchased) and other types of consumption goods. These individual consumption goods are formed from domestic goods and foreign imports (plus regional domestic imports in the case of the *US Regional* module). At the bottom of the diagram, production technologies are specified that control how inputs can be substituted for each other. Although not illustrated in the figure, differences across industries exist in their handling of energy inputs, most notably between electricity generation and other manufacturing industries. In addition, the agriculture and fossil-fuel industries contain equations that account for the use of natural resource inputs.

As shown at the top of the figure, each region in ADAGE contains a representative household, which maximizes intertemporal utility over all time periods in the model subject to budget constraints based on endowments of factors of production (labor, capital, natural resources, and land inputs to agricultural production). Income from sales of factors is allocated to purchases of consumption goods and to investment. Within each time period, intratemporal utility is received by households from consumption of transportation, goods, and leisure.[12] All goods, including total energy consumption, are combined using a CES structure to form an aggregate consumption good. This composite good is then combined with leisure time to produce household utility. The elasticity of substitution between consumption goods and leisure, σ_{cl}, is controlled by labor-supply elasticities and indicates how willing households are to trade off leisure for consumption.

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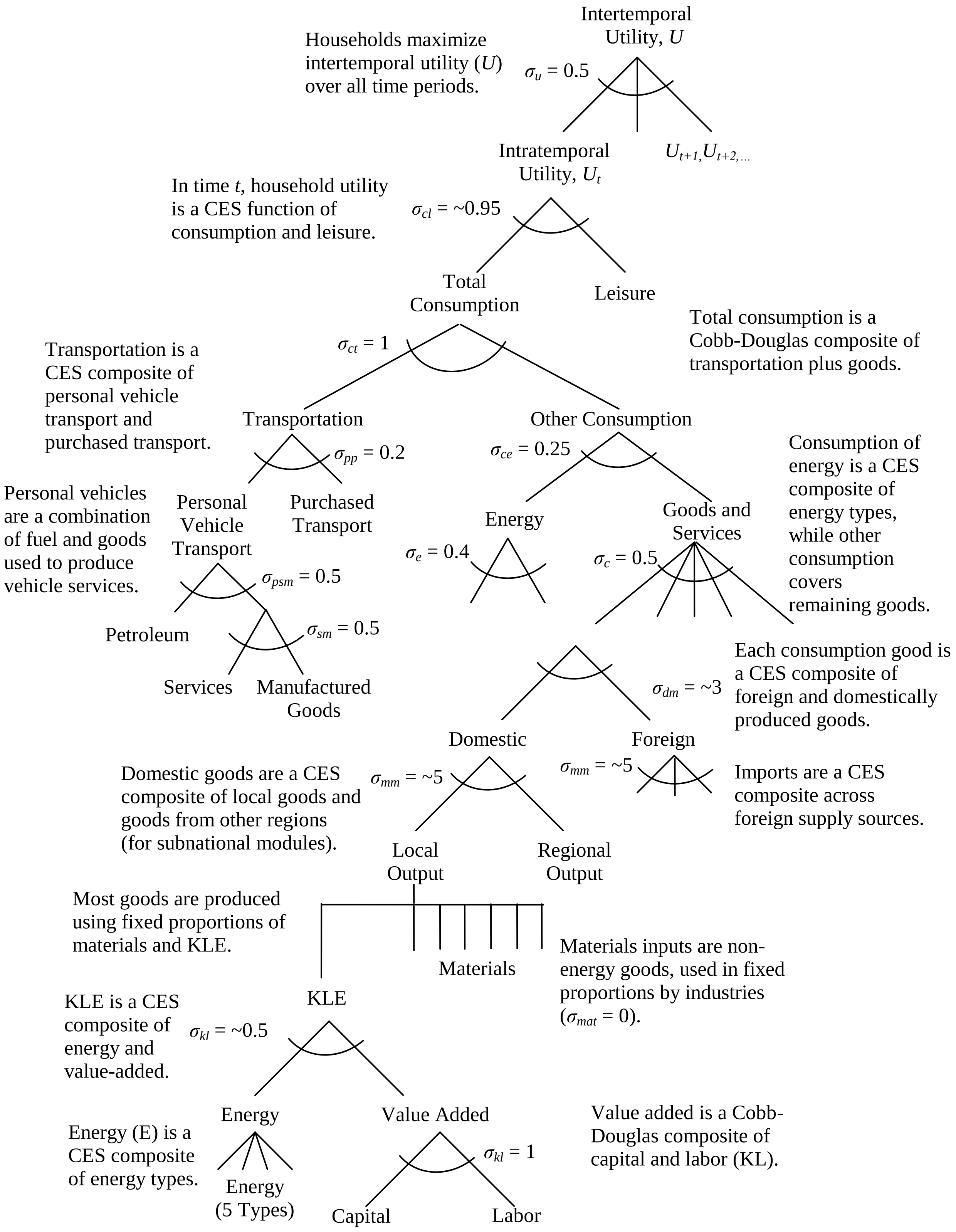
[12] Part of the utility function related to intratemporal choices among consumption goods, energy, and transportation have been adapted from the Emissions Prediction and Policy Analysis (EPPA) model developed at the Massachusetts Institute of Technology (MIT).

Figure 1-4. Consumption, Trade, and Production Structures in ADAGE



Households maximize intertemporal utility (*U*) over all time periods.

In time *t*, household utility is a CES function of consumption and leisure.

Total consumption is a Cobb-Douglas composite of transportation plus goods.

Transportation is a CES composite of personal vehicle transport and purchased transport.

Personal vehicles are a combination of fuel and goods used to produce vehicle services.

Consumption of energy is a CES composite of energy types, while other consumption covers remaining goods.

Each consumption good is a CES composite of foreign and domestically produced goods.

Domestic goods are a CES composite of local goods and goods from other regions (for subnational modules).

Imports are a CES composite across foreign supply sources.

Most goods are produced using fixed proportions of materials and KLE.

Materials inputs are non-energy goods, used in fixed proportions by industries ($\sigma_{mat} = 0$).

KLE is a CES composite of energy and value-added.

Value added is a Cobb-Douglas composite of capital and labor (KL).

Energy (E) is a CES composite of energy types.

Factors of production owned by households are assumed to be intersectorally mobile within regions, but migration of productive factors is not allowed across regions so that changes in utility for representative households located in each region can be calculated.[13] It has also been assumed in the *International* and *Single Country* modules that the representative household in each country owns the natural resources located within it, as well as all capital stocks. For the *US Regional* module, ADAGE assumes that ownership of capital stocks and natural resources is spread across the United States through capital markets.

As shown in the middle of Figure 1-4, goods and services are assumed to be composite, differentiated "Armington" goods (Armington, 1969) made up of locally manufactured commodities and imported goods.[14] Within this basic framework in ADAGE, some differences across modules exist to accommodate the fact that goods produced in different regions within the United States are more similar than goods produced in different nations. In the *US Regional* module, output of local industries is combined with goods from other regions in the United States using the trade elasticity σ_{mm}. The high values for this elasticity indicates agents make relatively little distinction between output from firms located within their region and output from firms in other regions of the United States (i.e., they are close substitutes). This module then aggregates domestic goods with imports from foreign sources using lower trade elasticities (σ_{dm}) to capture the fact that foreign imports are more differentiated from domestic output. The *International* (and some *Single Country*) module skips the interregional step, but include an aggregation across foreign supply sources.

Production technologies used by most industries and associated elasticities are illustrated in the bottom levels of Figure 1-4 (see Section 2 for industry-specific details on these equations). Within these technology constraints, each industry maximizes its profits. The nested CES structure of ADAGE allows producers to change the technology they use to manufacture goods. If, for example, petroleum prices rise, an industry can shift away from petroleum and into other types of energy. It can also choose to employ more capital or labor in place of petroleum, thus allowing ADAGE to model improvements in energy efficiency. The ease with which firms can switch among production inputs is controlled by the elasticities of substitution. Elasticities relating to energy consumption are particularly important when investigating environmental policies. 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.

For various sectors in the economy, the general nesting structure of production activities and associated elasticities have been adapted from the EPPA model developed at the MIT, a

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[13] Migration among nations and across regions of the United States is included in baseline forecasts.

[14] The one exception is crude oil, which is modeled as a homogeneous good that is identical across all regions and has the same baseline price across all regions and modules (from EIA price forecasts).

well-known CGE model designed to investigate energy and GHG policies.[15] Researchers at MIT derived their CES nesting structures and elasticity estimates from a variety of empirical literature, expert elicitations, and "bottom-up" engineering studies. Figure 1-4 shows broadly how these equations control production technologies. A capital-labor-energy composite good (KLE) is combined with materials inputs to produce final output. The assumption that this is done in fixed proportions implies that businesses must either invest in more capital goods (i.e., new equipment) or hire more workers to achieve energy-efficiency improvements – this is illustrated in the figure with the horizontal line for $\sigma_{mat} = 0$. The elasticity σ_{KLE} controls these improvements by specifying how value added (the combination of capital and labor) can be substituted for energy. The bottom level in Figure 1-4 then determines how capital and labor can be substituted for each other and, in the other nest, specifies energy substitution possibilities.

In addition to these production equations, ADAGE includes options to construct new types of electricity generation technologies that are capable of significant reductions in GHG emissions under climate-related policies. These options combine the top-down CGE approach with bottom-up engineering estimates of the cost and effectiveness of advanced technologies such as integrated coal gasification combined cycle (IGCC) with carbon capture and storage (CCS) and advanced combined cycle (CC) with CCS. Whether or not these technologies are cost effective depends on the policy in question – see Section 2.3.3 for additional discussion.

Taxes have been included in ADAGE because of the critical role that the existing tax structure can play in determining costs of a policy. If taxes drive a wedge between the cost of producing a good and the price paid by that good, producer and household behaviors are distorted, giving rise to an excess burden beyond the revenue raised by the tax. The *International* module incorporates taxes from the GTAP data, and the *Single Country* modules include any tax rates from their data sources. For the *US Regional* module, a variety of additional tax information has been integrated with the IMPLAN economic database, including marginal income tax rates from the NBER TAXSIM model. ADAGE also contains a user cost of capital formulation based on Fullerton and Rogers (1993), which estimates marginal effective capital tax rates as a function of their important components, most notably personal income and corporate tax rates.[16]

Distortions associated with taxes are a function of both marginal tax rates and labor-supply decisions of households. Thus, ADAGE includes a labor-leisure choice—how people decide between working and leisure time. Labor-supply elasticities related to this choice determine, to a large extent, how distortionary taxes are in the model. Based on a

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[15] See Paltsev et al. (2005) at http://web.mit.edu/globalchange/www/eppa.html for EPPA documentation.

[16] Marginal income tax rates and industry-specific marginal capital tax rates are around 40 percent.

literature survey by Russek (1996) and estimates used in other CGE models, ADAGE uses 0.4 for compensated and 0.15 for uncompensated labor-supply elasticities.[17]

In ADAGE, economic growth comes from four sources: growth in the available labor supply (encompassing both population growth and changes in labor productivity), capital accumulation through investment, increases in stocks of natural resources, and technological change associated with improvements in manufacturing and energy efficiency. Labor force expansions, economic growth rates, and industrial output are based on IEA and EIA forecasts. Savings, which provide the basis for capital formation, are motivated through households' expectations about future needs for capital. The GTAP and IMPLAN datasets provide details on the types of goods and services used to produce the investment goods underlying each economy's capital stocks. Dynamics associated with formation of capital are controlled by using partial "putty-clay" approach that distinguishes between existing and new capital stocks (see Phelps [1963] and Lau et al. [2002]). Existing, or clay, capital is fixed within industrial sectors with characteristics based on today's technologies. New, or putty, capital is technologically flexible and mobile across sectors, and also is used to cover depreciation of existing capital. Expected changes in energy consumption per unit of output in the putty capital portions of industries are modeled as exogenous autonomous energy efficiency improvements (AEEI). These AEEIs are used to replicate energy consumption forecasts by industry and type of fuel from IEA and EIA forecasts, which also provide the growth rates for electricity generation, natural resource production, and energy prices.

Prior to investigating policy scenarios, a baseline growth path is established for ADAGE that incorporates these economic growth and technology changes expected to occur in the absence of any new policy actions. Beginning from the initial balanced SAM dataset, a "steady-state" growth path is first specified for the economy to ensure that the model remains in equilibrium in future years, assuming all endowments and output grow at a constant rate. Next, this assumption of constant growth is replaced by forecasts from IEA and EIA. Upon incorporating these forecasts, ADAGE is solved to generate a baseline consistent with them, after which it is possible to run "counterfactual" policy experiments.

In order to investigate energy and GHG-emissions policies, the ADAGE model tracks fuel consumption in physical units (British Thermal Units or Btus), based on IEA and EIA forecasts. Since CO_2 emissions from fuel use are tied to combustion of fossil fuels, the model is able to determine emissions levels in terms of millions of metric tons of carbon (MMTC). Substitution options for, and the costs of, replacing energy inputs to production are controlled by the CES equations and substitution elasticities discussed in Section 2. Households also have the ability to switch fuels, lower overall consumption, and improve energy efficiency.

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[17] These values give an overall marginal excess burden (MEB) of approximately 0.3 and a marginal cost of funds from income taxes of around 1.25 in the *US Regional* module, measured at the baseline solution for the model.

ADAGE has also endogenized emissions abatement costs associated with five non-CO_2 gases (CH_4, N_2O, HFCs, PFCs, and SF_6), based on the approach used in the EPPA model (Hyman et al., 2002). Unlike CO_2, these gases are not emitted in fixed proportions to energy consumption, making the modeling of abatement costs more problematic. Rather than relying on exogenous marginal abatement cost functions, which ignore interactions among the economic sectors, emissions of non-CO_2 gases are modeled directly as an input to production. This allows specification of abatement cost curves representing industry-specific costs associated with achieving reductions. National baseline emissions of these gases are matched to EPA forecasts. Regional shares of EPA's national emissions for the United States are based on regional output and consumption from the IMPLAN and EIA data.

2. ADAGE MODELING FRAMEWORK

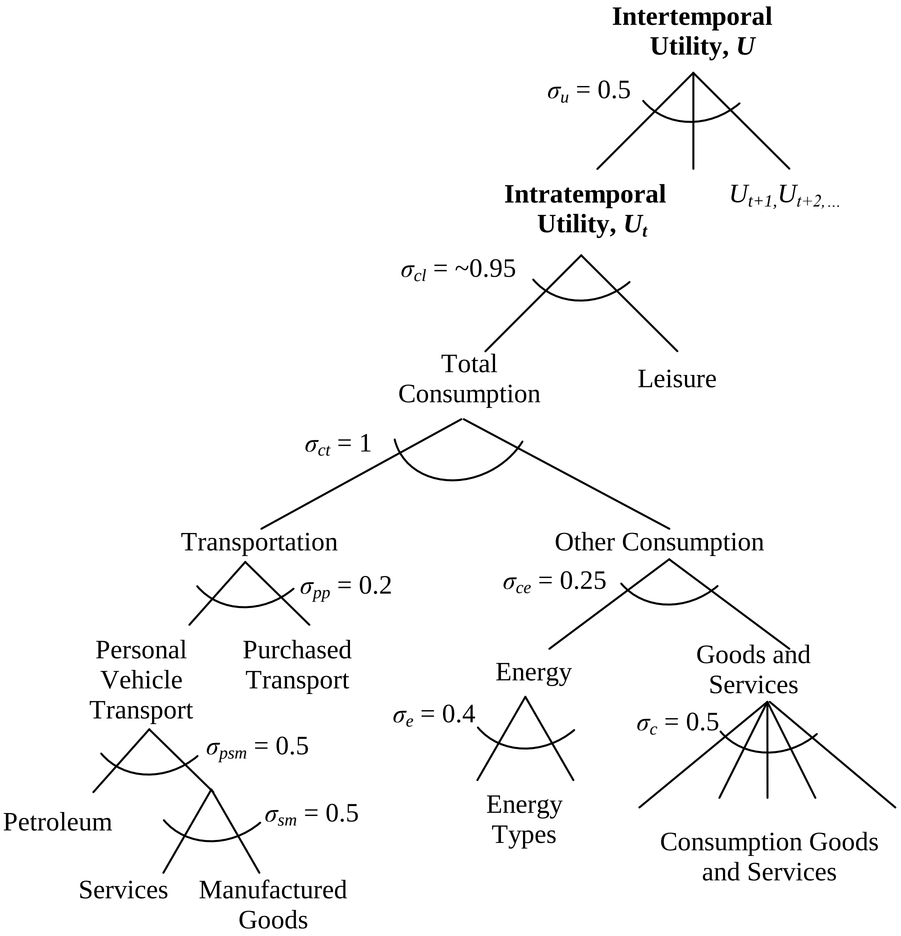
This section, which is organized along the lines of Figure 1-4, presents nesting structures detailing the CES equations used in ADAGE to describe household behavior, trade flows, and production activities. Associated elasticity parameter values that control the model's reactions during policy investigations are also given. These equations, along with the model's dynamics and its baseline economic and energy data, will determine impacts estimated for policies.

2.1 Households

Each region in ADAGE contains a representative household that maximizes intertemporal utility over time subject to its budget constraints. As shown in Figure 2-1, in determining intratemporal (within each time period), household preferences distinguish between transportation and other types of consumption goods. Overall transportation is a combination of purchased transportation and transportation provided through use of personal vehicles. Personal vehicle transport is a function of petroleum consumed in vehicles and the manufacturing and service goods that go into those vehicles. Non-transportation energy use by households is separated from other types of energy use (e.g., heating oil or electricity) and combined into a single composite energy good with a relatively low elasticity (σ_e). This reflects potential difficulties associated with households' attempting to switch among these fuel types. The energy composite good is then combined with other consumption goods using a CES structure to form an aggregate consumption good that is combined to total transportation. The final composite good is then traded off against leisure time to form period-by-period household utility. The elasticity of substitution between consumption goods and leisure (σ_{cl}) indicates how willing households are to trade off leisure time for consumption.

Over time, households consider the discounted present value of utility received from all periods' consumption of goods and leisure when attempting to maximize intertemporal utility.[18] The household utility function allows measurement of welfare changes associated with a policy, which capture a wide variety of effects influencing how households are affected by a policy (such as changes in income, changes in the costs of consumption goods, and changes in work effort). These welfare effects are measured by Hicksian equivalent variation, which is the amount of income needed to compensate households for the economic effects of a policy.

Figure 2-1. Household Utility Function



Households are endowed with the factors of production used by firms (labor, capital, natural resources, and land inputs to agricultural production). Factor prices are equal to the marginal revenue received by firms from employing an additional unit of that factor. Factors are assumed to be intersectorally mobile within regions,[19] but it is assumed that

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[18] ADAGE approximates the infinite horizon implied in Figure 2-1 using techniques described in Lau, Pahlke, and Rutherford (2002) since it is not computationally feasible to model an infinite number of time periods.

[19] Migration of labor across regions is not allowed so that welfare changes for the representative households located in each region can be calculated; however, migration among nations and across regions of the United States is included in ADAGE's baseline forecasts.

factor prices depend on their use in production within each region (i.e., there can be regional price differences). It has also been assumed in the *International* and *Single Country* modules that the representative household in each country owns the natural resources located within it, as well as all businesses. For the *US Regional* module, ADAGE assumes that ownership of capital stocks and natural resources is spread across the U.S. through capital markets. Income from sales of all productive factors by households are allocated to purchases of consumption goods to maximize welfare.

When choosing the amount of labor to supply to firms, households consider their total endowment of time, the income received from labor sales, and how leisure time affects their welfare. These choices are controlled in ADAGE by a labor-supply elasticity, which expresses how the labor supply will respond to changes in wage rates and disposable household income. Selection of this parameter is important because it interacts with tax rates in the model to determine the extent of distortions caused by the existing tax structure, with related implications for the costs of policies. If households are very willing to switch between leisure and work in response to changes in wages, existing labor taxes will have significantly distorted economic behavior from what would occur in the absence of the taxes, implying a large excess burden for labor taxes, and the reverse if households are not willing to substitute leisure time for work (and hence consumption goods).

Russek (1996) reviews the relevant literature, which cites estimates for total labor supply elasticities ranging between –0.1 and 2.3. Fuchs, Krueger, and Poterba (1998) also review estimated elasticities with similar findings. The values for labor-supply elasticities most commonly used in CGE models are in the mid-point of the range presented by Russek—typically around 0.4 for compensated elasticities and 0.15 for uncompensated elasticities (see, for example, Parry and Bento [2000], Williams [1999], Goulder, Parry, and Burtraw [1997], Bovenberg and Goulder [1996]).

The elasticity of substitution between consumption goods and leisure (σ_{cl}) and the total time endowment of households can be selected to get desired compensated and uncompensated labor-supply elasticities (Ballard, 1999). In ADAGE, the compensated labor-supply elasticity is set at 0.40 and the uncompensated labor-supply elasticity is set at 0.15, based on estimates in the CGE literature and the implications for tax distortions in the model (see Section 4 for tax rates and measurements of their distortions in ADAGE). These choices determine the elasticity between consumption goods and leisure (σ_{cl}) shown in Figure 2-1.

2.2 Trade

In each module of ADAGE, goods and services are assumed to be composite, differentiated "Armington" goods made up of locally manufactured commodities and imported goods (see Figure 2-2).[20] In this trade structure, output of local industries is initially separated into

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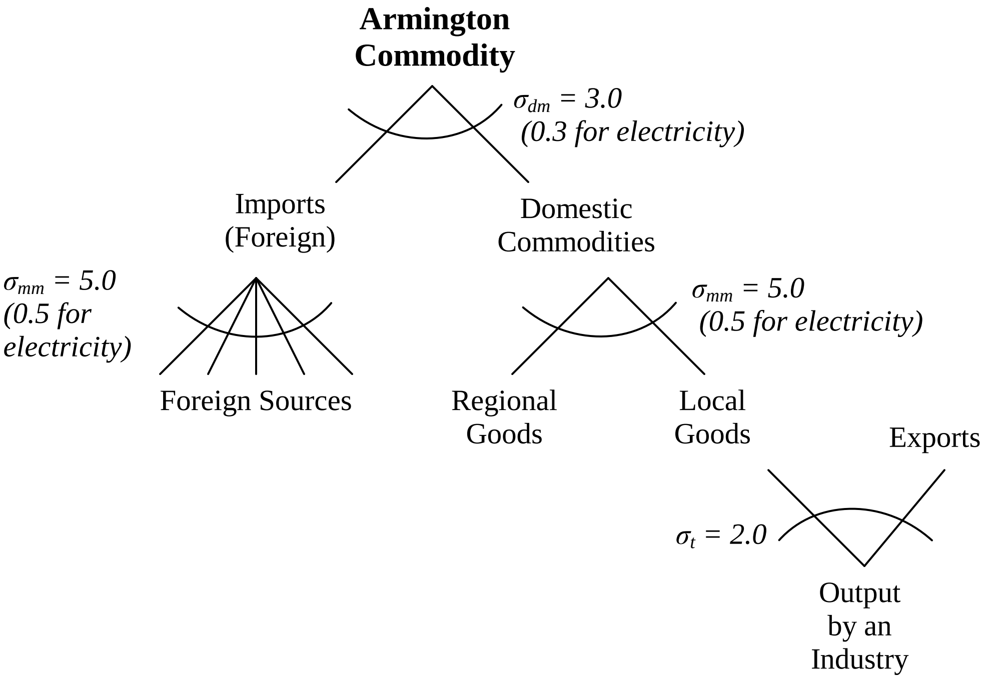
[20] Unlike other goods, crude oil is modeled as a homogeneous good that is identical across all regions.

output destined for local consumption by firms or households and output destined for export using a CES transformation elasticity, σ_t. In the *US Regional* module, this local output is then combined with goods from other regions in the United States using trade elasticities that indicate that agents make relatively little distinction between output from firms located within their region and output from firms in other regions within the United States. This module finally aggregates the domestic composite good with imports from foreign sources using lower elasticities, which indicates that foreign imports are more differentiated from domestic output than are imports from other regions of the United States.[21] The *International* and *Single Country* modules skip the interregional step but include an aggregation across different foreign supply sources.

Figure 2-2. Trade Functions[a]



[a]These Armington elasticities are generally similar to those used in the EPPA model.

The *US Regional* and *Single Country* modules are linked with the *International* module through the prices of traded goods determined by the *International* module. Findings on prices of internationally traded goods are passed down the chain so that the modules with more regional detail are able to incorporate the effects of international policies in their policy simulations (Balistreri and Rutherford, 2004).

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[21] The *US Regional* module includes additional detail on coal trade among states to distinguish among types of coal produced in different locations within the United States (see Section 5).

2.3 Production

Following ADAGE's Arrow-Debreu general equilibrium structure, firms are assumed to be perfectly competitive and are unable to influence market prices. Production technologies exhibit constant returns to scale, except for the agriculture and natural resource sectors, which have decreasing returns as a whole because of the use of factors available in fixed supply (land and primary fuels, respectively). Industries maximize profits, subject to technology constraints characterized by nested CES equations that allow firms to change the technologies used to manufacture goods. Many equations are generally adapted, with some changes, from MIT's EPPA model (Paltsev et al., 2005). Electricity production from fossil fuels is similar to Balistreri and Rutherford (2004), while advanced electricity technologies are incorporated using logic from McFarland et al. (2004) and Paltsev et al. (2005).

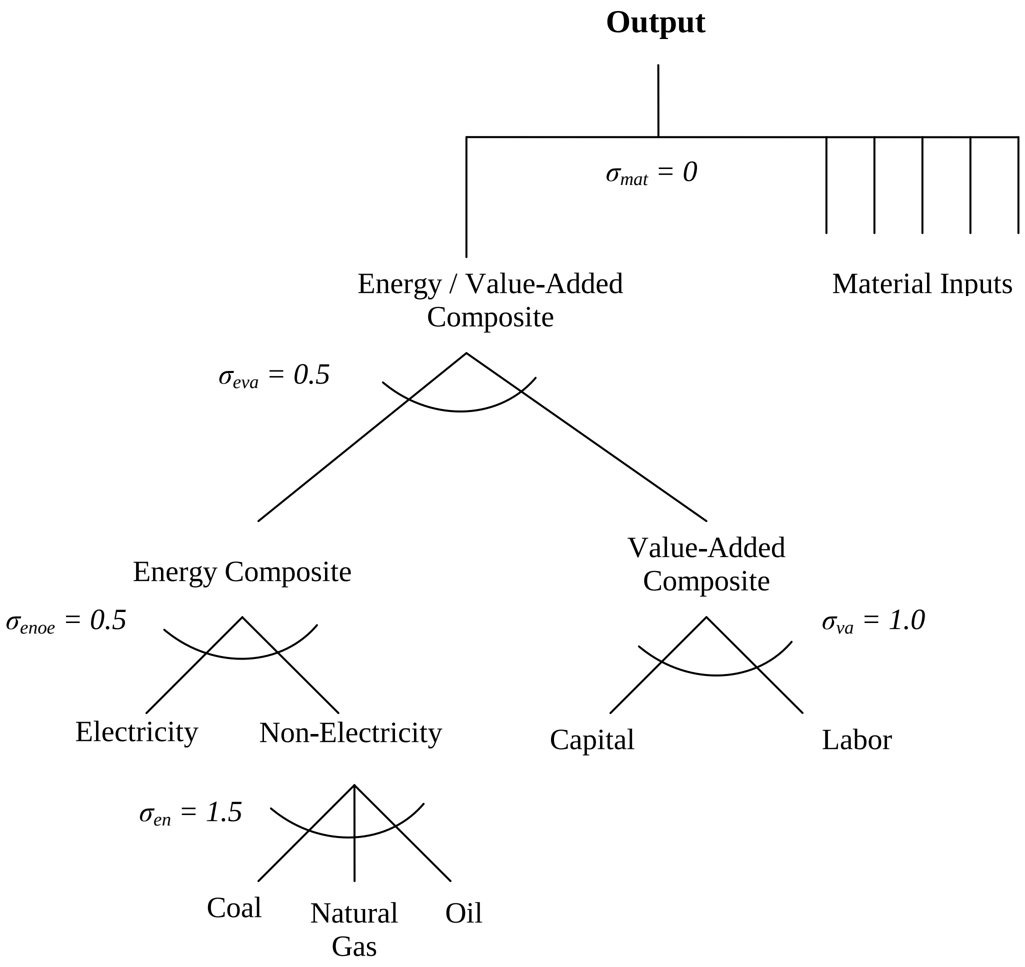
Production technologies in ADAGE allow for energy-efficiency improvements, the nature of which are controlled by the nesting structure of the production activities. Intermediate materials inputs (nonenergy, nonfactor inputs) generally enter production using fixed coefficients, or a Leontief structure. This implies that producers (or households) can adjust their energy consumption by changing total output (or consumption), substituting one type of energy for another, or using additional labor or capital to achieve energy-efficiency improvements. Along with how energy-efficiency changes are modeled, substitution elasticities related to energy consumption are particularly important when investigating energy, environmental, or climate-change mitigation policies. If, for instance, an industry is able to substitute away from energy with relative ease, or from one type of energy to another, the price of its output will not change much when energy prices vary.

2.3.1 Manufacturing and Services

All manufacturing and services industries (including transportation services), which represent the majority of gross output in most economies, use the production nesting structure shown in Figure 2-3. Intermediate materials inputs, which are Armington composites of domestic and imported goods, enter at the top of the CES nest in fixed proportions (σ_{mat}) – illustrated by the horizontal line at the top of the diagram – and can be traded off against a composite good of energy and value added (capital and labor). The energy/value-added elasticity (σ_{eva}) then controls overall energy-efficiency improvements that can be achieved by substituting capital and labor for energy in production.

ADAGE assumes that capital and labor are combined using a Cobb-Douglas function (σ_{va} of 1) to form the value-added composite good. Value-added is combined with an energy composite good made up of all available types of energy. Within the energy composite, another elasticity (σ_{enoe}) controls the ability of firms to shift between electricity and other types of energy. At the bottom of Figure 2-3, the σ_{en} elasticity shows how coal, natural gas, and refined petroleum can be substituted for each other.[22] Within this structure, the energy/valued-added elasticity and the two energy elasticities (σ_{enoe} and σ_{en}) have the most impact when examining energy and environmental policies because they control efficiency improvements and fuel switching.

Figure 2-3. Manufacturing and Services Production



2.3.2 Agriculture

The CES nesting structure used for agriculture is designed to account for the use of land inputs to agricultural output because it is an essential fixed factor and is available in limited supply. The formulation also maintains a distinction between output per hectare of land and output per unit of labor and capital and allows agricultural output to be increased by adding land (if possible), materials, and energy, or capital and labor. At the top of the nest in Figure 2-4, value added is substituted against a resource-materials-energy bundle (σ_{erva}),

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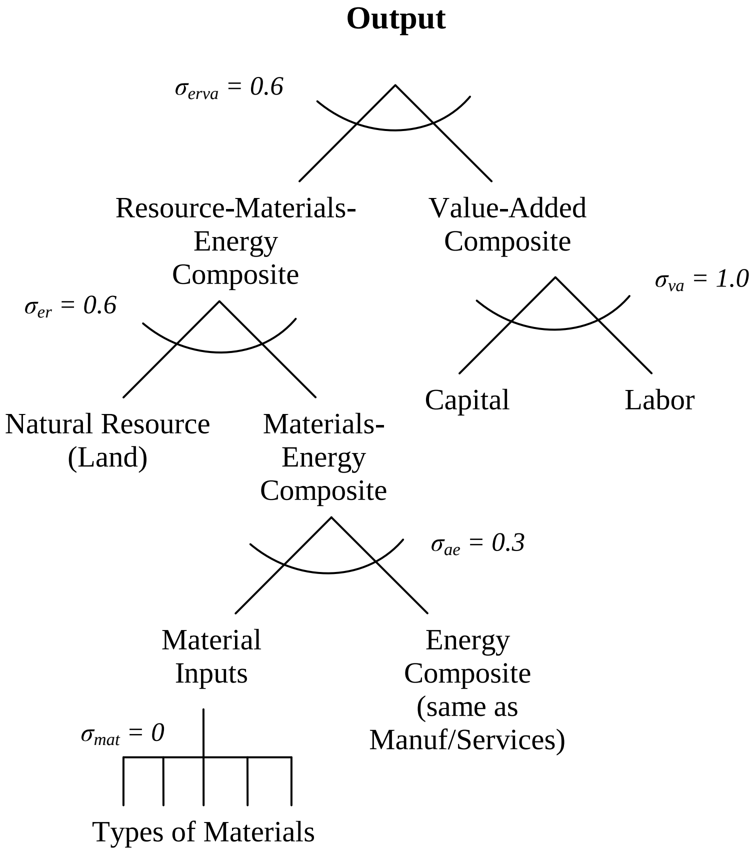
[22] This elasticity is set to 1.5 to avoid the constant value share implications of a Cobb-Douglas formulation, which allows somewhat more fuel switching than would occur in the EPPA model.

allowing agricultural efficiency per hectare of land to be improved by using additional capital or labor. Energy and materials (σ_{ae}) can be substituted with some difficulty for the fixed land resource (σ_{er}), indicating that land can be made more productive by using materials (e.g., fertilizer) or energy (e.g., heating greenhouses or running farm equipment). Substitutions among energy types to form a composite energy good are the same as in manufacturing.

Figure 2-4. Agricultural Production

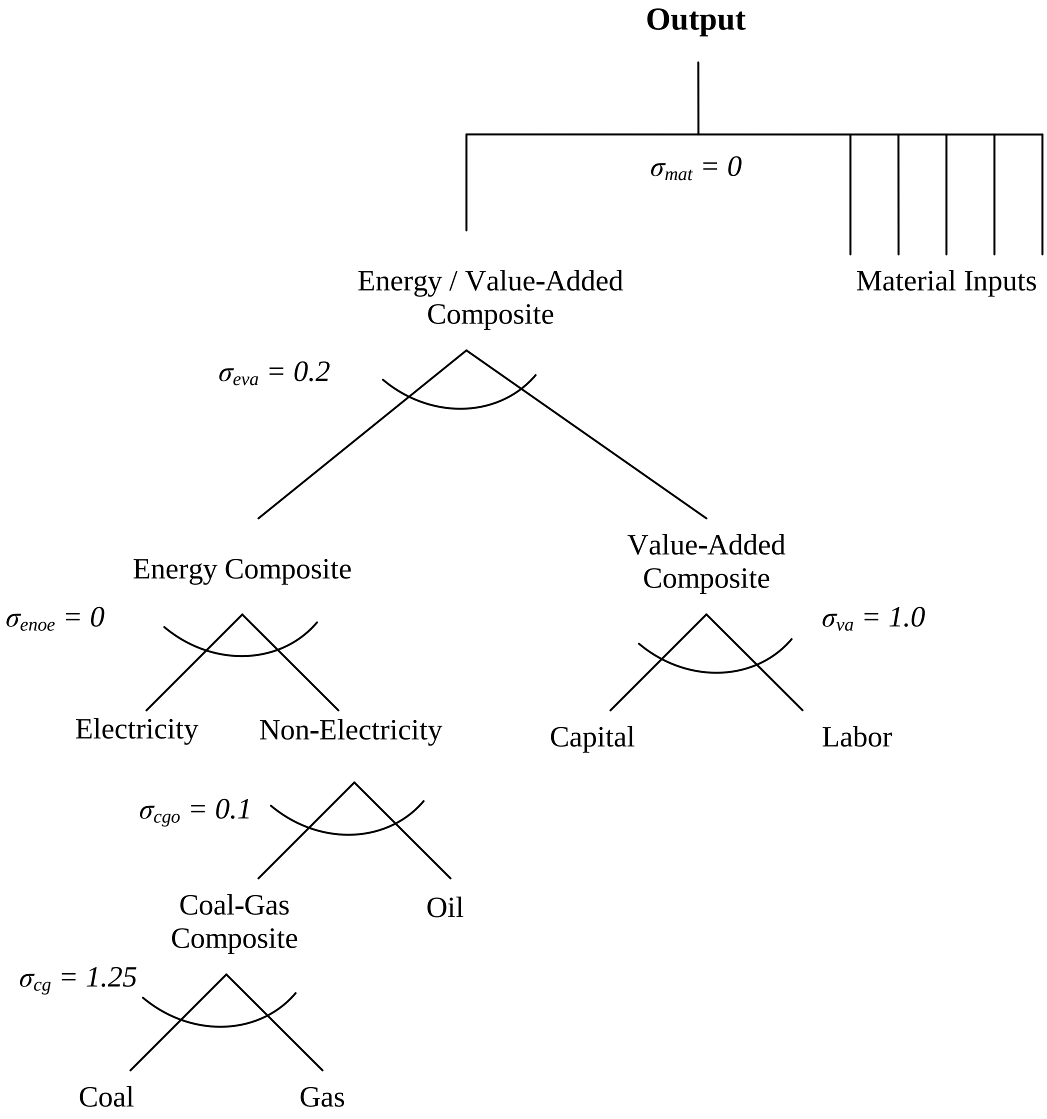


2.3.3 Electricity

Generation of electricity is unique from the manufacturing and services industries because the electricity sector depends critically on energy inputs. In addition, there are established theoretical and engineering bounds on how efficiently fossil-fuel inputs can be converted into electricity. Because of these considerations, and the importance of the representation of the electricity industry for estimated impacts of energy and environmental policies, the CES equations typically used for electricity generation are different from those in other industries.

At the top of the nested CES structure shown in Figure 2-5 (conventional fossil-fuel electricity generation),[23] materials enter in fixed proportions and can be traded off against a composite good made of capital, labor, and energy. As with other industries, ADAGE assumes that capital and labor are combined using a Cobb-Douglas function (σ_{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. The energy value-added elasticity (σ_{eva}) is lower than in manufacturing, indicating that it is harder to achieve energy-efficiency improvements in the electricity sector, which relies heavily on energy for generation purposes.

Figure 2-5. Fossil-Fuel Electricity Generation



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[23] The CES equations used for fossil generation are based on Paltsev et al. (2005) and Balistreri and Rutherford (2004).

Within the energy composite, the σ_{enoe} elasticity of zero eliminates the ability of utilities to increase generation by using additional electricity (i.e., electricity cannot be generated from electricity; it merely is necessary to run the boilers, etc.). The fossil-fuel nesting structure is unique to electricity generation and distinguishes it from other types of manufacturing. In electricity generation, the most important trade-off is between coal and natural gas, especially in developed countries, since many energy/environmental policies are likely to cause a shift between these two fuels. As shown in Figure 2-5, natural gas is combined with coal (σ_{cg}) with a relatively large degree of flexibility in fuel switching. Following that, the coal-gas composite is combined with oil (σ_{cgo}) using a lower substitution elasticity because oil generation is generally used for peaking generation, unlike coal and gas that provide more base-load generation.

In addition to conventional fossil generation and the non-fossil generation shown in Figure 2-7 below, ADAGE specifies two new advanced technology options for generating electricity that can enter if they become economically viable alternatives in a climate policy scenario (these are in addition to potential expansions in nuclear, hydroelectric, biomass, and wind/solar generation controlled by the structure in Figure 2-7).[24] The new technologies are integrated coal gasification combined cycle with carbon capture and storage (IGCC+CCS) and natural gas combined cycle with carbon capture and storage (CC+CCS).

Figure 2-6 illustrates the nested CES structure that is used to describe these new technology options (similar to the approach used in Paltsev et al. [2005], although this structure assumes a constant 90 percent removal of carbon, rather than a potentially increasing removal rate). An essential fixed factor (to approximate specialized engineering knowledge or other specialized inputs) at the top of the function controls the penetration of the new technology. Other inputs are then separated into generation and transmission components (no improvement in heat rates over the original specification of the engineering data are allowed – hence, the zero elasticity between fuel inputs, capital, and labor – σ_{kle}). Transmission and distribution costs are assumed a fixed share of the total cost of generation, excluding the value of the fixed factor.

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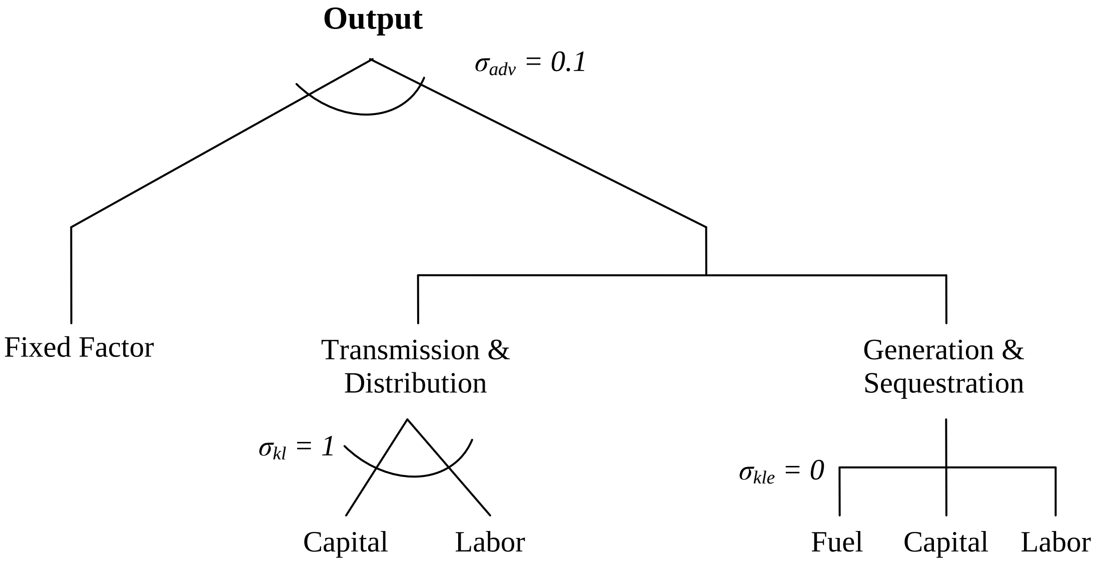
[24] For detailed discussions of how to introduce new technologies based on engineering cost data, see Bohringer and Rutherford (2006), McFarland et al. (2004), and Jacoby et al. (2006).

Figure 2-6. Advanced Fossil Generation (IGCC+CCS and CC+CCS)



Whether or not these new technologies will be cost effective in a particular climate policy investigation (without GHG allowance costs, they will never be cost effective) depends on input costs, fuel prices, and GHG allowance prices. It also depends on how much more expensive the new technologies are compared to conventional generation. This cost markup can be calculated by comparing the price-setting generation technology in the baseline forecasts to the estimated engineering costs for the new technologies.

Without a climate policy, the marginal generation of electricity (having the highest cost per MWh) would typically be a newly-constructed conventional combined cycle unit burning natural gas. Under a climate policy, the new advanced technologies will become this marginal cost provider, allowing calculation of a cost markup as the difference between the new and conventional technologies. The following data are needed to calculate average generation costs per MWh (data on overnight technology costs are estimated from the Assumptions to the Annual Energy Outlook 2009 Reference Case – shown below for 2020 in $2007). Illustrative fuel and electricity prices are shown – the CGE model endogenously calculates cost markups as a function of fuel, capital and labor costs during policy runs:

- Capital costs ($/kW) – CC of $857, CC+CCS of $1,651, IGCC+CCS of $3,076
- Fixed O&M costs ($/kW/yr) – CC of $11.70, CC+CCS of $19.90, IGCC+CCS of $46.12
- Variable O&M costs ($/MWh) – CC of $2.00, CC+CCS of $2.94, IGCC+CCS of $4.44
- Heat rates (btu/kWh) – CC of 6,333, CC+CCS of 7,493, IGCC+CCS of 8,307
- Capital charge rate – 13.1% (all types)
- Capacity factor – 85% (all types)
- Electricity price - $94.0/MWh
- Fuel costs – Coal of $1.92/MMBtu, Natural gas of $7.15/MMBtu
- Sequestration and costs – 90% removal, $55 per ton of CO_2 stored

These data give a cost markup of 32 percent for IGCC+CCS and of 33 percent for CC+CCS over conventional combined cycle units in 2020 (it is conservatively assumed that there is no additional learning-by-doing after the AEO forecasts end in 2030). Fuel shares can be calculated based on prices and heat rates as a function of total retail electricity prices. Following data from Paltsev et al. (2005), the remaining input shares are then set to sum up to 1.0, prior to the cost markup being applied in the model. Table 2-1 shows the results of these calculations.

Table 2-1. Cost Markups and Input Shares for Advanced Technologies

		Input Shares							
			Generation		T&D		Sequestration		
Technology	**Cost Markup**	**Fixed Factor**	**Capital**	**Labor**	**Capital**	**Labor**	**Capital**	**Labor**	**Fuel**
IGCC+CCS	32%	0.01	0.35	0.11	0.18	0.11	0.07	0.01	0.16
CC+CCS	33%	0.01	0.14	0.04	0.13	0.08	0.03	0.00	0.57

Figure 2-7 illustrates the process by which electricity generated from fossil fuels, advanced technologies, and nonfossil sources is combined.[25] The infinite elasticity of substitution in the second level of the diagram indicates that no distinction is made between electricity produced across advanced technologies, fossil fuels, nuclear, hydroelectric and biomass sources. Wind and solar is combined with other types of electricity using relatively low elasticities to capture the intermittent nature of the generation technologies. Nuclear, hydroelectric/geothermal, and biomass generation rely on a combination of resource inputs (uranium, dams, and biomass from land, respectively) and other types of inputs. Resource supply elasticities illustrate the crucial nature of these inputs and control any expansion in these types of generation.

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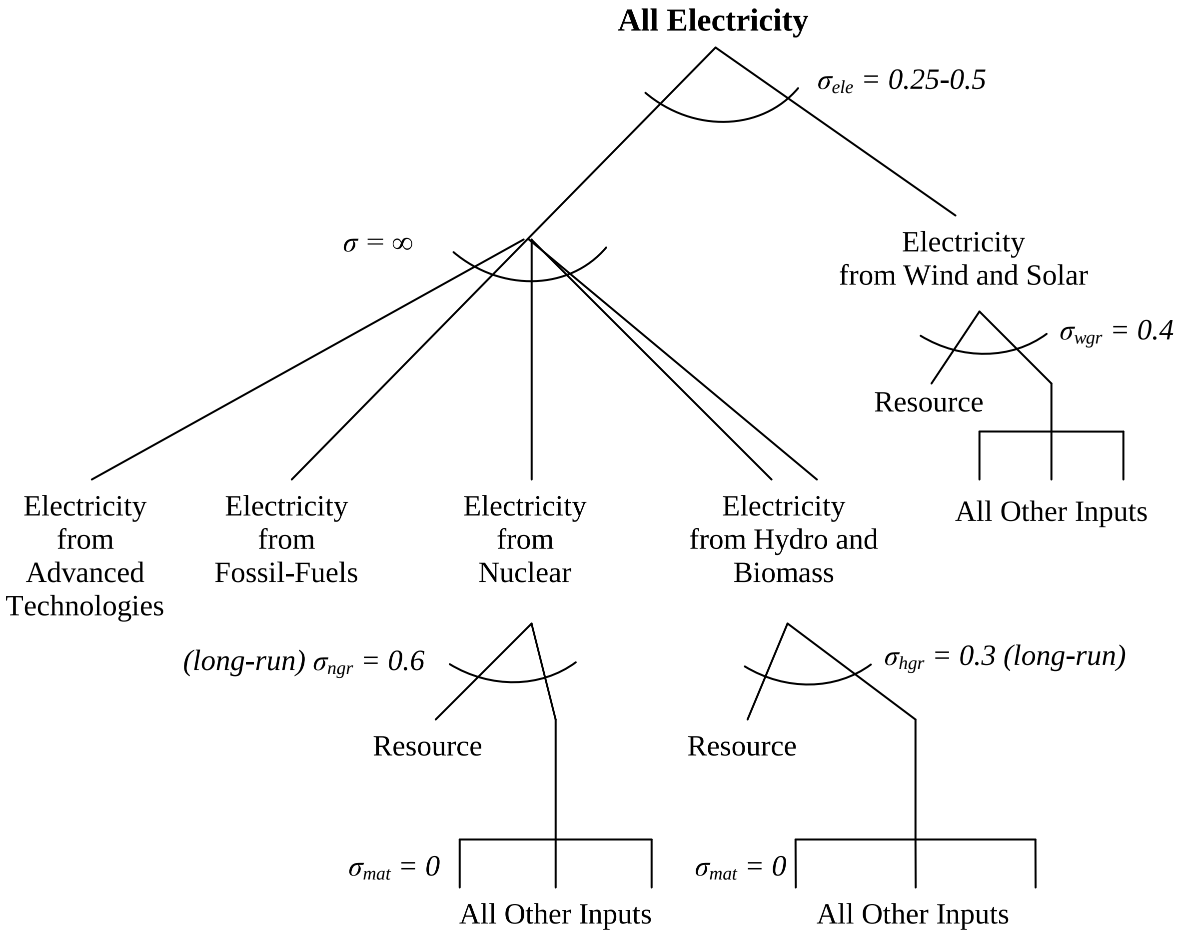
[25] Distinguishing different types of generation helps ADAGE track fuel use per unit of electricity (i.e., heat rates—Btus of energy input per kilowatt hour, kWh, of electricity output) to ensure it is consistent with theoretical limits on energy conversion and conventional technologies.

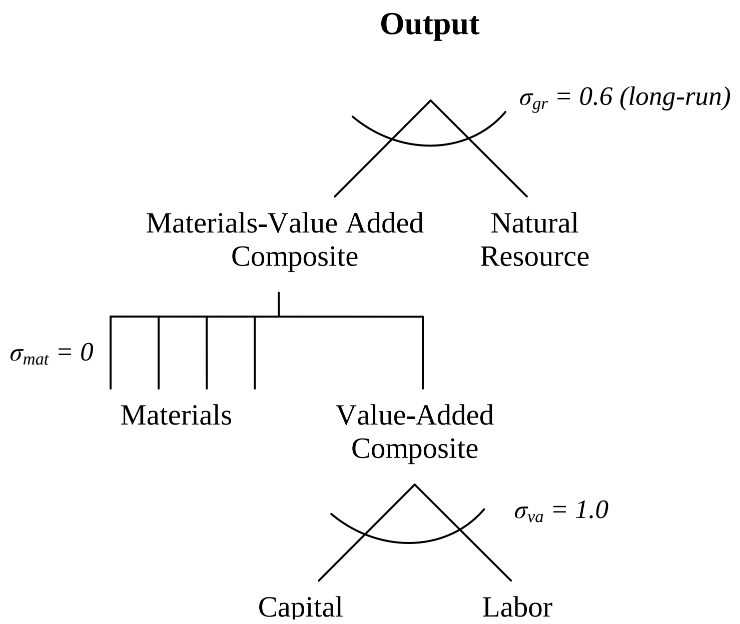
Figure 2-7. Total Electricity Generation



2.3.4 Fossil Fuels

Similar to agricultural goods, fossil-fuel supplies (coal, crude oil, and natural gas) are limited by the availability of a natural resource (the primary fuel reserves in the ground). Thus, a fixed factor in production is used to model resource constraints and give the production functions decreasing returns to scale across an economy. The formulation of the CES equations (Figure 2-8) captures the idea that, while it is possible to develop more efficient mining equipment or invest in discovering new resources, it is not possible to produce the natural resources themselves using only inputs like capital, labor, or materials. In the production nesting structure, the natural resource in the ground is combined with other productive inputs to extract it and make it available for use by other industries. Although some additional production is possible from using more factors or materials, these inputs must still be combined (elasticity σ_{gr}) with the fixed resource at the top of the CES nest.

Figure 2-8. Fossil Fuel Production (Coal, Crude Oil, and Natural Gas)



2.3.5 Petroleum Refining

Although petroleum refining is not a natural resource sector that relies on extraction of fossil fuels, its production is highly dependent on inputs of crude oil. The CES functions shown in Figure 2-9 capture this idea by allowing some substitution of factors (elasticity σ_{va}) but require that crude oil and materials enter the production structure in fixed proportions. This ensures that the model must use crude oil to produce petroleum products and cannot unrealistically increase output of refined petroleum by using other types of inputs.[26]

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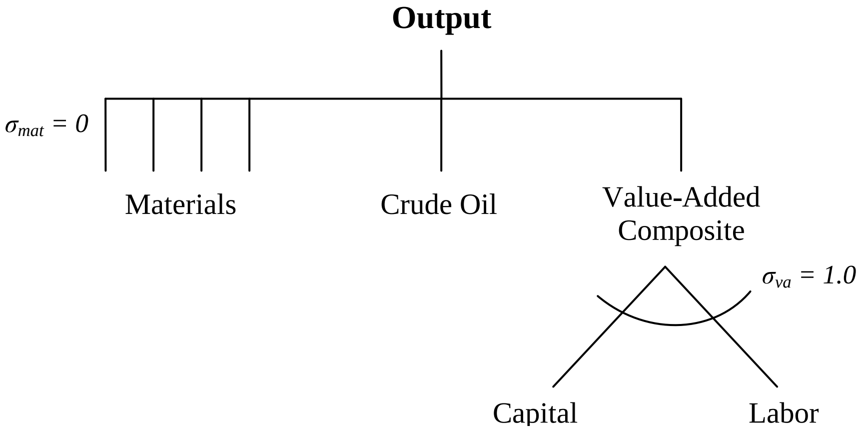
[26] Improvements in baseline refinery processing gains (as shown in the energy consumption forecasts) are handled through adjustments to the ratio of crude-oil inputs to petroleum output.

Figure 2-9. Refined Petroleum Production



2.4 Government

Government purchases of good and services are exogenous variables in ADAGE, which are maintained at their original levels and do not enter the optimization decisions of households and firms or adjust in response to policies. These purchase patterns are taken from the economic data sources used by ADAGE. Government expenditures are financed by taxes on output, personal income, consumption, capital, and imports/exports (see Section 4). Because the government is modeled as a separate agent in ADAGE, it is generally necessary to maintain its income during policy investigations to get meaningful welfare results for other agents (i.e., households) in the model. Unless a particular policy specifies an alternative approach, this is done through nondistortionary, lump-sum transfers between households and the government. Inclusion of a government sector and related revenue-generating taxes is important, however, because it allows ADAGE to consider how policies may interact with existing taxes, which can alter policy costs.

3. DYNAMICS, INVESTMENT, AND GROWTH

Economic growth in ADAGE comes from four sources: growth in the available labor supply from population growth and changes in labor productivity, capital accumulation through savings and investment, increases in stocks of natural resources, and technological change associated with improvements in manufacturing and energy efficiency. This section discusses these dynamic processes (data underlying actual growth paths in the model are discussed in Sections 4 and 5).

3.1 Labor Growth

At the beginning of the model horizon, households in each region in ADAGE are endowed with an initial supply of labor, the value of which is shown in the economic accounts used by the model. Similar to other CGE models, ADAGE then relies on exogenously specified rates of growth to determine how the value of labor endowments increases over time. Using the assumption of Harrod-neutral technical progress, the model tracks increases in effective units of labor available across the economy, encompassing both population growth and improvements in labor productivity. This approach facilitates incorporation of economic-growth forecasts from IEA and EIA, which also provide other forecasts used in ADAGE.

3.2 Investment, Capital Stocks, and Adjustment Dynamics

Decisions regarding savings by households and the associated capital formation control many of the behavioral responses estimated for policies. ADAGE 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.[27] By allowing agents to anticipate new policies, ADAGE can show how people will begin to prepare for policies that are announced today, but that may not begin until sometime in the future.

The savings motivated through these expectations about future needs for capital determine aggregate capital stocks in ADAGE. Both the GTAP and IMPLAN datasets provide details on the types of goods and services used to produce the investment goods underlying each economy's initial capital stocks. The model uses these data to specify an aggregate investment sector generating the capital needed by the economy. The data sources, however, do not contain a representation of actual capital stocks, so it is necessary to calibrate these stocks from the observed earnings generated by the unobserved capital stocks.[28] Typically, capital stock data, even if available, are not considered as reliable as capital earnings data, so this calibration approach may be used even if stock data are available.[29]

Dynamic processes controlling how capital stocks evolve over time will determine the transition path the economy takes from its initial baseline forecast to a new equilibrium in response to policies. ADAGE models these dynamics through a partial "putty-clay" approach (see Phelps [1963] and Lau et al. [2002]).[30] This methodology distinguishes between existing (or "clay") capital in place in industries today, which is assumed to produce output using technology represented

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[27] The theoretical basis for this approach comes from Ramsey (1928), Cass (1965), and Koopmans (1965).

[28] Capital earnings (K_e) are equal to the interest rate (r) plus the depreciation rate (δ) times the capital stock. This allows the initial stock of capital (K_s) to be calculated as $K_s = K_e / (r + \delta)$. The interest rate in ADAGE is assumed to equal 5 percent, based on the MIT EPPA model, and the overall depreciation rate is set at 7 percent, based on a weighted average rate across the capital assets shown in Table 4-7.

[29] See Babiker et al. (2001) for a discussion of the EPPA model's calibration of capital stocks.

[30] This approach represents a change from previous versions of ADAGE that assumed capital stocks were perfectly malleable across industries and used quadratic adjustment costs associated with installing new capital to control the model's dynamics.

Available capital stocks in time period t (K_t) are equal to new investment (I_t)plus depreciated capital left from the previous time period:

$$K_{t+1} = K_t(1-\delta) + I_t \,.$$

Thus, investment has to be sufficient to cover both economic growth (generating new capital demands) and depreciation of existing capital.

3.3 Fossil-Fuel Resources

Fossil-fuel resources (coal, crude oil, and natural gas), which are endowed to households in ADAGE, evolve over time through changes in quantities and prices. Expected future quantities and prices are matched to WEO and AEO forecasts from IEA and EIA (see Section 5); however, these forecasts do not provide information on the amount of resources available for extraction or the costs associated with extracting them. To address these limitations, ADAGE generates resource supply elasticities around forecasted production paths of the resources.

The supply elasticities reflect how production costs rise as more resources are extracted, along with effects of depleting the fossil-fuel resources. By selecting an elasticity of substitution between a resource and other production inputs in these industries (elasticity σ_{gr} in Figure 2-7), a given resource supply elasticity can be calibrated.[31] Fossil-fuel price paths from WEO and AEO forecasts are also matched by adjusting growth rates for the fixed-factor inputs to resource production so that prices in the baseline ADAGE solution are calibrated, as closely as is feasible, to desired forecasts.[32]

3.4 Energy Consumption

Energy consumption per unit of output tends to decrease over time through improvements in production technologies and energy conservation (although it is not necessarily true in developing countries as they move into more energy-intensive and less labor-intensive manufacturing processes). The energy mix in an industry may also shift as production techniques change. For example, natural gas use in electricity generation in the United States rose by almost 60 percent between 1990 and 2000, while coal use rose by less than 25 percent (EIA, *Annual Energy Review 2005*). When examining environmental policies, it is essential to include these technology shifts in the baseline forecasts of ADAGE.

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[31] ADAGE uses an approach to resource supply elasticities that is similar to the EPPA model. Algebraic calculations (Babiker et al., 2001) can demonstrate that the resource supply elasticity (η^s) is equal to the substitution elasticity (σ_{gr}), adjusted by the share of inputs of natural resources used to produce output from the resource industry (S_{nr}): $\eta^s = \sigma_{gr} * (1 - S_{nr}) / S_{nr}$.

[32] This emphasis is somewhat different than taken by MIT's EPPA model. There is not an explicit modeling of unextracted fossil-fuel resources in ADAGE, instead the focus is on matching WEO and AEO price paths, which are determined by these underlying resource stocks and using a supply elasticity to reflect how production quantities will change in response to price changes.

Similar to other CGE models, ADAGE captures these energy consumption changes through autonomous energy-efficiency improvement (AEEI) parameters. An AEEI index is specified in the model for each fuel type and each industry. These indices alter the physical amount of energy needed to produce a given quantity of output by accounting for improvements in energy efficiency, conservation, and switching among fuel types.[33] Rather than apply generic trends to these parameters based on overall energy-efficiency improvements from historical data, AEEIs are used in ADAGE to match expected trends in energy consumption from WEO and AEO forecasts.

4. ECONOMIC DATA IN ADAGE

This section discusses data requirements for ADAGE, methodologies for establishing a base year and baseline forecasts for the model, and sources for the international and U.S. economic data used in the model.

4.1 Data and Model Baseline Overview

Most CGE models rely on a SAM, an economy-wide dataset showing how goods and factors of production flow through the economy at a specific point in time (see, for example, Shoven and Whalley [1992] or Lofgren, Harris, and Robinson [2002] for more discussions of SAMs). The framework for a SAM comes from traditional I/O analyses (Leontief, 1936). An I/O table contains the values of economic transactions at a particular point in time. As such, it shows how firms combine intermediate inputs and productive factors to manufacture goods. This output is directed towards intermediate and final uses, where intermediate uses are the goods and services employed by other firms to make their products and final uses are the ultimate destination of goods purchased by households and government.

A SAM is an expanded version of traditional I/O tables. In addition to data normally in an I/O model, a SAM contains information on ownership of factors of production, allowing CGE models to estimate policy effects on the distribution of income. A SAM also includes data on direct taxes removed from income received by households and transferred to the government, and vice versa. I/O 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 base-year dataset in a dynamic CGE model.

ADAGE combines a variety of data sources to create a balanced SAM for each of its modules that characterizes a base year for the economy, accounting for all economic interactions

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[33] 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.

among agents. The starting point for the *International* module is the GTAP data, while the *US Regional* module is based on IMPLAN data. Each of these SAMs contains data on the value of output of each industry, payments for factors of production and intermediate input purchases by each industry, household income and consumption patterns, government purchases, taxes, investment, and trade flows. The GTAP data (Version 6) contain a balanced SAM with 87 regions and 57 sectors for the year 2001, and the IMPLAN data cover similar information for the 50 U.S. states (plus the District of Columbia) and 509 industries for the year 2004.

Starting from these data, a balanced SAM is generated for each module in ADAGE with an initial base year of 2010 that is consistent with desired sectoral and regional aggregations. This base year, which is different from the years of the GTAP and IMPLAN data, is selected to keep the databases of the different modules should be as consistent as is feasible so that results from one module can be used in another. Several historical and forecast data sources are used to expand the original GTAP and IMPLAN datasets to the 2010 base year (described in Sections 4 and 5). The process of achieving a balanced SAM for this base year is similar to the techniques used to incorporate energy data into the economic accounts and is discussed at the end of Section 5. In general, the process involves rebalancing trade flows to account for differential regional growth between the GTAP and IMPLAN data years and the base model year of 2010.

Before investigating policy scenarios, a baseline growth path must also be established for ADAGE that incorporates forecasts of future economic growth and technology changes. Beginning from the initial balanced SAM of economic accounts, a “steady-state” growth path is first specified for the economy to ensure that the model remains in equilibrium in future years, assuming all endowments and output grow at a constant rate.[34] Once the model is able to replicate a steady-state growth path, the assumption of a constant growth rate is replaced by actual forecasts from the WEO and AEO. After incorporating these forecasts, ADAGE is solved (in 5-year time intervals) to generate a baseline consistent with the forecasts through 2030. Beyond these forecast years, a combination of population growth, labor productivity improvements, and energy efficiency improvements are used to drive long-run baseline forecasts.

The baseline solution for ADAGE needs to reflect expected changes in the four sources of growth discussed in Section 3: growth in labor supplies, capital accumulation, increases in stocks of natural resources, and technological change associated with improvements in manufacturing and energy efficiency. Growth in labor endowments of households are adjusted to replicate forecasts of regional economic growth from the WEO and AEO. The

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[34] A steady-state growth path requires all variables in the model to grow at a constant rate over time, including labor, output, inputs to production, and consumption. If the model has been properly specified, the steady-state replication check will show that the economy remains in equilibrium in each year along this path.

capital accumulation needed to support these labor forces and consumption demands is determined endogenously by the model. The WEO and AEO forecasts are also used to establish target growth rates for natural resource quantities and associated prices.

Finally, a series of iterative model solutions are generated to find AEEI coefficients that replicate the energy consumption forecasts (see Section 5). Each model solve estimates the appropriate AEEI to match forecasts for energy use, and these findings are compared to desired results. Differences between model solution values and the desired forecasts are then used to adjust the AEEIs, and the model is resolved again until the baseline model solution is within a small percentage of the forecasts.[35] Once this baseline has been established, it is possible to run "counterfactual" policy experiments.

4.2 International Module

The *International* module relies primarily on GTAP data (Version 6). These economic data for the year 2001 contain balanced SAMs for 87 regions with 57 industries. Data on GDP in US dollars for the year 2007 from the World Factbook (CIA, 2008) are used to extend the economic data to 2007, after which forecasts from the *WEO 2008* and *AEO 2009* are used to extend the data to the base year in ADAGE of 2010. Additional information on international tax rates from Gurgel et al. (2006) is also used to supplement the GTAP data. Subsequent economic growth patterns are provided by IEA (2008) and EIA (2009).[36] After 2030, economic growth is assumed to be driven by a combination of population growth from the U.N. (2006) and labor productivity improvements (where productivity improvements are assumed to converge eventually at 1.8 percent per year across countries).

- **Economic data for 2001**—GTAP (2006). International economic data for production, consumption, income, taxes, and trade flows.
- **Economic growth rates for 2001–2007**—*The World Factbook* (CIA).
- **Economic growth rates for 2008–2030**—*World Energy Outlook 2008* (IEA), and *Annual Energy Outlook 2009 (March version)* (EIA).
- **Economic growth rates after 2030**—Population projections from UN (2006).

To improve the internal consistency of ADAGE, the state-level economic data described in Section 4.3 are used (at a national level) to represent the U.S. economy. While some differences exist between the GTAP definitions of industries and those in the U.S. state data, because there are over 500 industries in the U.S. data, it is generally feasible to define comparable economic sectors. Although this approach necessitates additional work to

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[35] Productive adjustments to capital and labor are occasionally needed in the *US Regional* module to match energy production forecasts for electricity and petroleum refining.

[36] The procedures developed by Babiker and Rutherford (1997) and described in Rutherford and Paltsev (2000), which are used to integrate economic and energy data, are also used to balance the economic data after these forecasts are included—see Section 5.3.

integrate the U.S. data with the GTAP international data, it improves the ability of ADAGE to apply results from the *International* module to regions/states within the United States.

4.3 *US Regional* Module

The state-level economic data used to develop a SAM for the *US Regional* module are provided by the Minnesota IMPLAN Group. The IMPLAN data show current manufacturing technologies and how goods are made from intermediate inputs and factors of production. These consistent state-level social accounts also show demand for goods and services by households and the government, along with how these expenditures are financed by households' sales of productive factors and by some types of government tax collections. The IMPLAN tax data are augmented with additional information on personal income, corporate, fuel, and sales taxes.

Each SAM from IMPLAN contains data on production and consumption of 509 different types of commodities for the year 2004, developed from a variety of government sources, including

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

Since computational constraints limit the total size of intertemporally optimizing CGE models, industry (and regional) aggregations of the IMPLAN databases are used in policy investigations. From among the 509 sectors in IMPLAN, aggregations are selected based on their relevance to the particular policy in question.[37]

These IMPLAN data provide a starting point for developing balanced state-level SAMs with an initial base year of 2010, consistent with desired sectoral and regional aggregations. The process of estimating economic activity in 2010 involves projecting IMPLAN data for the year 2004 to the year 2010 using the following data sources:

- **State-level gross state product (GSP)**—*Regional Economic Accounts*, U.S. Bureau of Economic Analysis (BEA) (2008). GSP by state and industry for 2004-2007.

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[37] These data are aggregated to desired product and regional levels using programs developed by Rutherford (2004).

- **Economic growth rates for 2006–2030**—*Annual Energy Outlook 2009* (EIA, 2009). Tables 33 and 126. Growth in industrial value of shipments and real income by Census region. These industrial and regional growth rates are used to provide business-as-usual forecasts for the *US Regional* module through 2030.
- **State-level population projections**—*State Population Projections Program*, U.S. Census Bureau. Also U.S. Census Bureau data on households by state.

GSP growth rates by industry are used to extend the IMPLAN data from 2004 to 2007. The resulting SAM is then rebalanced to ensure consistency, as discussed in Section 5.3. Data from the *AEO 2009* and U.S. Census Bureau population projections are then used to establish future growth rates in the economy.

Another issue with the IMPLAN data revolves around interstate trade flows, which can have important implications for regional impacts of policies. Although IMPLAN provides exports and imports of goods and services for each state, the data do not include information on bilateral interstate trade flows. To establish these trade patterns, a gravity model of trade is employed, which estimates trade flows as a function of income and distance (e.g., Bergstrand [1985 and 1989], Feenstra, Markusen, and Rose [1993], and Sanso, Cuairan, and Sanz [2001]). This approach generally exhibits a good correlation between empirical data and estimated trade flows (see Balistreri and Hillberry [2004] for a discussion of how these features can be calibrated in a CGE model). Once the economic data have been aggregated into the sectors used in ADAGE and trade flows have been established, the state-level data can be aggregated into the regions used in ADAGE.

Additional data are occasionally used in the *US Regional* module of ADAGE to report policy impacts in terms of costs per household or changes in employment. Sources for these information include the following:

- **State-level population projections**—*State Population Projections Program*, U.S. Census Bureau.
- **State-level housing units**—*Housing Units*, 2003, U.S. Census Bureau.
- **State-level employment**—*Income and Employment Tables*, U.S. Bureau of Economic Analysis (BEA). Tables SA05N, SA07N, SA25N, and SA27N—income and employment by industry.
- **National employment**—*Current Employment Statistics*, U.S. Bureau of Labor Statistics (BLS), Table B-12, employment by detailed components of the electric utility industry for 2005.
- **Trends in employment** —*Annual Energy Outlook 2009* (EIA, 2009), Table 126. Also *Occupational Outlook Handbook 2006* (BLS), Table 1.

State-level population growth trends through 2030 from the Census Bureau are combined with existing housing unit data to estimate growth in the number of households. Detailed data on industry employment from the BEA are combined with industry and regional employment trends from the AEO (Table 126) and BLS to estimate national employment trends by industry. Growth in regional employment in the model then depends on regional industry output as determined by ADAGE.

4.3.1 Taxes in the US Regional Module

Attention has been paid to taxes in ADAGE because of the crucial role that tax distortions can play in determining the costs of a policy. If existing taxes drive a wedge between the cost of producing a good and the price paid for it, producer and household behaviors will be distorted, giving rise to an excess burden greater than the amount of revenue raised by the tax. Theoretical and empirical literature have examined these "tax interactions" and found they can substantially alter policy costs.[38] Given these potential impacts, it is important for ADAGE to consider how tax distortions may interact with policies when estimating economic impacts.

While the GTAP data used by the *International* module contain tax information (especially regarding international trade), additional consideration has been given to tax rates in the *US Regional* module because it has subnational detail and also there is a greater availability of data on tax rates and their determinants for the United States than at the international level. In addition, there is more empirical literature regarding the expected effects of U.S. taxes on CGE model results to which the ADAGE results can be compared.

Similar to GTAP, the IMPLAN economic database includes some tax data, but they are not comprehensive and also do not necessarily contain the data needed to determine distortions associated with taxes. Consequently, several additional sources are used to provide data on U.S. federal and state tax rates by type:[39]

- **FICA taxes**—IMPLAN economic data. Average FICA tax rates by state.
- **Wage (and other forms of income) taxes**—*U.S. Federal and State Average Marginal Income Tax Rates*, NBER TAXSIM Model. Marginal wage, interest, dividend, and long-term capital gains tax rates by state for 2004 (including federal rates).
- **Corporate income taxes**—*State Corporate Income Tax Rates*, The Tax Foundation. Corporate (2008a) income tax rates by state for 2007. *Federal Corporate Income Tax Rates*, U.S. Internal Revenue Service (IRS) (2006), Publication 542 with rates for 2005.
- **Sales and indirect business taxes**—*State General Sales and Use Tax Rates*, The Tax Foundation, sales tax rates by state for 2007. Also IMPLAN economic data.

In the IMPLAN data, payments related to the Federal Insurance Contribution Act, or FICA, taxes (i.e., Social Security plus Medicare) appear as a direct claim on labor income by the U.S. government. However, IMPLAN follows National Income and Products Accounts (NIPA) conventions and reports factor payments at gross-of-tax values. Thus, the tax payments

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[38] See, for example, Goulder and Williams (2003), Goulder, Parry, and Burtraw (1997), Bovenberg and Goulder (1996), and Fullerton and Rogers (1993).

[39] Energy taxes are covered in Section 5.

and receipts associated with personal income taxes and corporate taxes are reported merely as transfers between households and the government, showing average tax rates but not the related marginal tax rates. Behavioral distortions caused by existing taxes, however, are a function of marginal rates, rather than average rates. Marginal rates affect business (and household) behavior when they are deciding whether to produce (or purchase) an additional unit of a good, the types of factors to use, and how much to invest. Since these decisions can significantly influence policy costs, additional data on average marginal income tax rates (the tax rate paid, on average, on the last unit of income earned) are collected from other sources and included in ADAGE.

The effective tax rate on labor is a function of FICA taxes and personal income taxes (PIT). The IMPLAN data on FICA taxes (covering both worker and employer contributions) is thus combined with state-level data on average marginal PIT tax rates. These rates are based on information from the TAXSIM model at the National Bureau of Economic Research (Feenberg and Coutts, 1993). TAXSIM is a microsimulation model of U.S. federal and state income tax systems that estimates average marginal tax rates for wage income, interest and dividend income, and capital-gains income.[40] The TAXSIM wage tax rate is applied to labor earnings in the *US Regional* module, along with FICA taxes. Following Ballard et al. (1985), ADAGE treats FICA as an *ad valorem* tax on labor and Social Security benefits as lump-sum transfers to households.[41] Combining FICA taxes from the IMPLAN data with TAXSIM's average marginal wage tax rate gives a total labor tax rate of approximately 41 percent.[42] This is similar to the 40 percent figure often cited in literature and used in CGE models (e.g., Williams [1999], Goulder et al. [1999], Browning [1987]).

4.3.2 Structure of Capital Taxes in the US Regional Module

This section discusses how data on corporate income-tax rates are combined with the TAXSIM income-tax data to calculate effective capital taxes. Characterization of the cost of capital in a CGE model can have significant impacts on estimated policy costs because capital taxes are relatively distortionary, influencing how households save and invest. This, in turn, affects the amount of capital available for future production, which controls economic growth. Capital costs depend on many factors such as interest rates, capital depreciation, personal income tax rates (because households pay taxes on capital earnings) and property taxes. Characterization of a marginal effective tax rate (METR) on capital earnings needs to account for how corporate tax rates affect the cost of capital, how PIT paid on capital earnings influences capital costs, how economic depreciation of capital assets (which depends on asset type) alters costs, how corporate structures in different industries

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[40] See NBER TAXSIM Model at <http://www.nber.org/~taxsim/> for these average marginal effective income tax rates by income type and state.

[41] Sales/excise taxes are also modeled as ad valorem taxes on output and purchases by households.

[42] Average FICA payments in the IMPLAN data represent an approximately 13 percent tax rate, which takes into account phasing out of employee contributions above certain income levels.

shape treatment of capital taxes, and how capital taxes vary across industries as a result of these interactions.

To incorporate these features, the *US Regional* module of ADAGE incorporates a user cost of capital structure based on the Fullerton and Rogers (1993) CGE model of tax policies (subsequently referred to as FR).[43] The approach allows explicit specification of the METR on capital as a function of its important components, most notably the relationship between PIT rates and the cost of capital. The FR documentation of how capital taxes were incorporated into their CGE model is relatively unique in its level of detail, both in terms of calculations and the associated data sources and parameter estimates. For these reasons, ADAGE uses a similar approach, although data used in the FR calculations have been updated where feasible.

The tables and equations below outline this approach, along with data sources, parameter estimates, and calculated METR by industry. Tables 4-1 and 4-2 define parameters used in the METR computations, followed by a discussion of the relevant equations as described by Fullerton and Rogers. Table 4-2 also presents some of the parameter values used and their sources. Other data sources and calculations are then described.

Table 4-1. Endogenous Variable Definitions

Parameter	Description
ρ_c^k	Corporate-sector gross-of-tax capital costs of type k
ρ_{nc}^k	Noncorporate sector gross-of-tax capital costs of type k
i	Nominal interest rate
r_c	Corporate sector discount rate (weighted average)
r_{nc}	Noncorporate sector discount rate (weighted average)
r_d	Discount rate on debt financing
r_{re}	Discount rate on retained earnings
r_{ns}	Discount rate on new shares
r_e	Discount rate on equity
w_k	Property tax rate on capital of type k
δ_k	Economic depreciation rate of capital of type k
z_c^k	Present value of depreciation allowance for corporate capital of type k
z_{nc}^k	Present value of depreciation allowance for noncorp capital of type k

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[43] The theoretical basis for this approach has a long history. See Jorgenson (1963) for development of theory related to capital costs and investment behavior. See Auerbach (1983) for a review of the literature on the cost of capital and CGE modeling work by Ballard et al. (1985) for additional information.

Table 4-2. Exogenous Variable Values

Variable	Description	Value	Source
r	Real interest rate	0.05	MIT EPPA model
π	Inflation rate	0.03	AEO 2009 (Table 20)
u_f	Statutory federal corporate tax rate	0.35	IRS Publication 542
u_s	Statutory state corporate tax rates	~0.06	The Tax Foundation
u	Statutory corporate tax rate (federal plus state)	~0.39	See Table 4-3 below
τ_{PIT}	Personal income tax rate	~0.29	NBER TAXSIM model
τ_d	Income tax rate on interest income (debt financing)	~0.28	NBER TAXSIM model
τ_{re}	Income tax rate on accrued capital gains (retained earnings)	~0.05	FR and NBER
τ_{ns}	Income tax rate on dividend income (new shares)	~0.28	NBER TAXSIM model
τ_{nc}	Income tax rate on noncorporate income (or PIT)	~0.29	NBER TAXSIM model
c_d	Proportion of corporate investment financed by debt	0.34	FR: Table 3-17
c_{re}	Proportion of corp. investment financed by retained earnings	0.33	FR: Table 3-17
c_{ns}	Proportion of corporate investment financed by new shares	0.33	FR: Table 3-17
n_d	Proportion of noncorporate investment financed by debt	0.34	FR: Table 3-17
n_e	Prop. of noncorp. investment financed by retained earnings	0.67	FR: Table 3-17

For corporations, the cost of financing is a function of interest payments on debt, costs of retained earnings, and costs of new shares.[44] As a weighted average across financial instruments, the overall corporate discount rate can thus be expressed as

$$r_c = c_d r_d + c_{re} r_{re} + c_{ns} r_{ns} \tag{4.1}$$

and the noncorporate discount rate can be expressed as

$$r_{nc} = n_d r_d + n_e r_e. \tag{4.2}$$

Arbitrage conditions among these rates of return will ensure that they are all equal on a net-of-tax basis, which implies that capital costs can be calculated from the net real return to holding debt [$r = i(1 - \tau_d) - \pi$] and leads to the following calculations. Because debt financing charges are deductible at the statutory corporate tax rate, firms pay the equivalent of the nominal interest rate excluding the statutory rate [$r_d = i(1 - u)$]. For

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[44] Following FR assumptions, ADAGE assumes that industries have fixed financial structures.

retained earnings, the nominal net return is the corporation's discount rate, which is a function of taxes paid on debt and the tax rate applied to retained earnings [$r_{re} = i(1 - \tau_d)/(1 - \tau_{re})$]. Similarly, the nominal net return for new shares is a function of taxes paid on debt and on dividend earnings [$r_{ns} = i(1 - \tau_d)/(1 - \tau_{ns})$]. Eq. (4.3) presents these three components of the corporate discount rate, weighted by the shares of each in overall corporate financing:

$$r_c = c_d\left[i(1-u)\right] + c_{re}\left[i(1-\tau_d)/(1-\tau_{re})\right] + c_{ns}\left[i(1-\tau_d)/(1-\tau_{ns})\right]. \tag{4.3}$$

For firms with a noncorporate structure, interest payments are deductible at the personal income rate applied to equity earnings. Equity returns must equal the return to holding debt because of arbitrage conditions. Eq. (4.4) gives these two components of the noncorporate discount rate, which are weighted by the shares of each in overall noncorporate financing:

$$r_{nc} = n_d\left[i(1-\tau_{nc})\right] + n_e\left[i(1-\tau_d)\right]. \tag{4.4}$$

Using the arbitrage condition to determine the real return to capital, *r*, and simplifying the FR equations by assuming that the PIT is applied to equity returns of noncorporate firms implies that Eqs. (4.3) and (4.4) can be expressed as[45]

$$r_c = c_d\left[((r+\pi)/(1-\tau_{PIT}))(1-u)\right] + c_{re}\left[(r+\pi)/(1-\tau_{re})\right] + c_{ns}\left[(r+\pi)/(1-\tau_{ns})\right] \tag{4.5}$$

$$r_{nc} = n_d\left[(r+\pi)(1-\tau_{PIT})/(1-\tau_d)\right] + \mathrm{n}_e\left[(r+\pi)\right]. \tag{4.6}$$

After these real returns to capital have been determined, they can be incorporated into an expression of a firm's profit-maximization decision to determine gross-of-tax costs of capital, following the methodology of Hall and Jorgenson (1967) as described in Fullerton and Lyon (1988) and Fullerton and Rogers (1993). Eqs. (4.7) and (4.8), adapted from FR,[46] illustrate these calculations for each type of capital asset, *k* (equipment, structures, inventories, land, and intangibles such as knowledge). The capital costs are expressed as functions of real returns, inflation, depreciation, PIT, the present value of depreciation allowances (*z*, which is equal to allowances divided by allowances plus real net returns), and property taxes:

$$\rho_c^k = \frac{r_c - \pi + \delta_k}{1-u}\left(1 - uz_c^k\right) + \omega_k - \delta_k \tag{4.7}$$

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[45] τ_{re} is assumed to be equal to one quarter of the long-term capital gains rate, following Fullerton and Rogers (1993). This reflects the fact that taxes on capital gains can be postponed by not realizing the gains until a future date, thereby lowering the effective tax rate.

[46] The original FR equations included discounts for investment tax credits (since phased out).

$$\rho_{nc}^{k} = \frac{r_{nc} - \pi + \delta_k}{1 - \tau_{PIT}} \left(1 - \tau_{PIT}\ z_{nc}^{k}\right) + \omega_k - \delta_k \tag{4.8}$$

METRs for capital can then be calculated for each asset class and corporate structure as the difference between the gross-of-tax capital cost (ρ) minus the net-of-tax cost (r) divided by the gross-of-tax cost. These METRs summarize the effects of all taxes applied to capital and characterize how changes in components of METRs will affect the cost of capital. Using these equations and the additional data sources discussed below, ADAGE develops a weighted average of the METR for each industry across all asset types and firm structures, based on the industry's share of corporate and noncorporate assets and associated types of capital.

Along with income tax data from the NBER TAXSIM model (for the variables τ_{PIT}, τ_{re}, τ_{d}, and τ_{ns}), information on corporate income taxes (u) and property taxes (w_k) is required in these equations. Data from the Tax Foundation on state-specific statutory corporate tax rates are combined with a federal statutory rate of 35 percent to determine region-specific corporate tax rates (see Table 4-3 for estimated rates at a regional level in ADAGE). Although the majority of states have only one tax bracket for corporations, some states have multiple brackets. The federal statutory tax rate also varies by income. In selecting the appropriate statutory rates, ADAGE is consistent with Fullerton (1987) and uses the top tax bracket in its calculations. In addition, it is necessary to assume that region-specific capital tax rates are applied to the capital earnings shown in the state-level IMPLAN data, given a lack of information on any differences between the location of earnings and the actual assessment of corporate taxes.

Table 4-3. Regional Income and Corporate Tax Rates

Region	PIT	Average State Corporate[a]	Combined State and Federal Corporate[b]
Northeast	31.4%	8.6%	40.6%
South	27.8%	6.0%	38.9%
Midwest	29.5%	6.2%	39.0%
Plains	26.8%	2.5%	36.6%
West	30.5%	6.9%	39.5%

[a] In these examples, the capital earnings in each state from the IMPLAN data are used to weight the corporate tax rates across states within these regions.

[b] The total statutory corporate tax rate, based on combined state plus federal corporate tax rates, is calculated according to the method used in Fullerton (1987) as federal (35 percent) + state * (1 – federal).

Calculations of average effective property tax rates are based on calculations from King and Fullerton (1984) and updated using NIPA data (U.S. BEA, 2004c) on state and local property tax receipts. These data are available as a total figure covering personal and business property taxes (equal to $254 billion). Information from King and Fullerton (1984) on the relative shares of business property taxes in total property taxes, separated into land and structures versus equipment and inventories, is used to apportion this total. Multiplying the shares by total property taxes and then dividing the resulting figure by total capital assets of each type (see Table 4-7) gives the property tax rates shown in Table 4-4 (along with depreciation data from Fullerton and Rogers, 1993).

Table 4-4. Property Taxes and Depreciation by Asset Type

Asset Type	Property Tax Rates	Economic Depreciation	Depreciation Allowance
Equipment	0.00574	0.1300	0.3400
Structures	0.00865	0.0300	0.1350
Inventories	0.00574	0.0000	0.0000
Land	0.00865	0.0000	0.0000
Intangibles	0.00000	0.2100	1.0000

Sources: Property tax rates—authors' calculations (see text). Depreciation rates and allowances—Fullerton and Rogers (1993).

In addition to updating tax rates, recent data sources are used to calculate existing capital assets by industry. The user cost-of-capital equations require data on five types of assets (equipment, structures, inventory, land, and intangibles) owned by two different types of firms (corporate and noncorporate). Data on equipment and structures owned by industries are available from the U.S. Bureau of Economic Analysis (BEA, 2004b). However, these data do not distinguish asset values by corporate and noncorporate organizations. Thus, BEA data that separate out legal organization forms by broad industry category are employed (see Table 4-5).

Data on inventories and land assets come from two sources. The U.S. Census Bureau publishes asset data for inventory and land for selected mining and manufacturing industries in the *Quarterly Manufacturing Reports* (U.S. Census Bureau, 2001). Similarly, the U.S. Department of Agriculture estimates land assets in the agricultural sector in the *Agricultural Economics and Land Ownership Survey* (USDA, 2000). For most of the mining and manufacturing data, asset values are distinguished by corporate and noncorporate sectors using the Federal Reserve Board's *Flow of Funds Accounts* (see Table 4-6). In cases where updated information could not be identified, data from Fullerton and Rogers (1993) were used to estimate asset distributions.

Table 4-5. Corporate and Noncorporate Equipment and Structures Assets

Asset Type	Corporate	Noncorporate
Farms		
Equipment and software	11%	89%
Structures	7%	93%
Manufacturing		
Equipment and software	98%	2%
Structures	98%	2%
Nonfarm nonmanufacturing		
Equipment and software	86%	14%
Structures	69%	31%

Source: U.S. Bureau of Economic Analysis (BEA). 2004b. "Current-Cost Net Stock of Nonresidential Fixed Assets by Industry Group and Legal Form of Organization, Table 4-1." <http://www.bea.doc.gov/bea/dn/faweb/AllFATables.asp>.

Table 4-6. Corporate and Noncorporate Inventory and Land Assets

Asset Type	Corporate	Noncorporate
Inventories	75%	25%
Land	70%	30%

Source: Federal Reserve Board. 2004. *Flow of Funds Accounts of the United States*, Coded Tables for Z.1 Release. Tables B.102 and B.103. <http://www.federalreserve.gov/releases/Z1/20040115/Coded/coded.pdf>.

For the final type of assets, intangibles, values are estimated using the methodology described in Fullerton and Lyon (1988). Development of intangible capital (i.e., knowledge or information) requires investment by firms, but these assets are treated differently than other types of assets (in part because there is no tangible asset to measure). The kinds of investments used to generate intangible capital include advertising expenditures, research and development (R&D), and expenses related to training and customer relations. Unlike other assets, these investments are usually deducted from business income immediately, instead of being depreciated over time. This preferential tax treatment has implications for capital tax rates that are accounted for by the FR user cost-of-capital approach.

Following Fullerton and Lyon (1988), intangible capital stocks are assumed to comprise the depreciated present values of advertising and R&D expenditures. The U.S. Internal Revenue Service publishes flows of advertising deductions by industry (U.S. IRS, 1995–2001). Implied capital stocks associated with these flows are computed using data for the period 1994 through 2000, based on an annual depreciation rate of 33 percent. Asset values connected to R&D expenditures are taken from the National Science Foundation's (NSF's)

Industrial Research and Development Information System. Data by industry from 1980 to 2000 (NSF, 2001a and 2001b) are employed to estimate capital stock values using an annual depreciation rate of 15 percent. In the absence of other data, Fullerton and Lyon (1988) data are used to distribute these stocks between corporate and noncorporate sectors.

The combination of the tax rates and asset data above, along with general ADAGE assumptions about real interest rates (set at 5 percent, following the MIT EPPA model), are sufficient to allow calculation of the marginal effective tax rates on capital, based on Eqs. (4.1) to (4.8). Table 4-7 presents the results of the estimates of capital assets by industry and associated marginal tax rates for 30 industries (generally following NAICS industry classifications). The *US Regional* module of ADAGE then uses weighted averages of these rates across the relevant industries in a particular policy run, where the METR enters the model as a tax on capital earnings by industry. These estimated rates range from around 25 percent in industries such as computers that depend heavily on R&D assets (which can be deducted from business profits immediately) to more than 40 percent in sectors such as primary metals where assets mainly comprise equipment and structures that receive less favorable tax treatment. Most industries have METRs of around 40 percent, which is similar to what is typically assumed in CGE modeling of tax distortions (e.g., Goulder et al. [1999]).[47]

4.4 Labor Supply Decisions of Households and Interactions with Tax Distortions

As discussed above, economic literature has found that interactions between the distortions caused by an existing tax structure and a new economic policy can substantially alter estimated policy costs, implying that these distortions need to be carefully considered in a CGE model. The extent of the distortions associated with taxes are a function of both the marginal tax rates in the model and the labor-supply decisions of households. Thus, similar to CGE models focused on interactions between tax and environmental policies (e.g., Bovenberg and Goulder [1996], Goulder and Williams [2003]), an important feature of ADAGE is its inclusion of a labor-leisure choice—how people decide between supplying labor to businesses and leisure time.

Labor-supply elasticities related to this choice determine, to a large extent, how distortionary taxes are in a CGE model. If households are very willing to switch between leisure and work in response to changes in wages, existing labor taxes will have significantly distorted economic behavior from what would have occurred in the absence of the taxes, implying a large excess burden for labor taxes, and the reverse if households are not willing

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[47] As noted in Fullerton (1987), METR tend to show less variation across industries than average tax rates. Thus, use of METR will imply lower overall distortions from capital taxes in a CGE model than average rates.

Table 4-7. U.S. Capital Stocks and Average Marginal Effective Tax Rates

Industry Group	Specific Industries	Percent of Total Capital Stock					Total Capital Stock in 2000 ($million)	Marginal Effective Tax Rate
		Equipment	Structures	Inventories	Land	Intangibles		
Non-Manufacturing	Agriculture	19.0%	25.0%	6.0%	49.9%	0.1%	$991,706	35.6%
	Construction	19.0%	8.9%	47.7%	22.6%	1.8%	$515,704	45.8%
	Mining	31.1%	55.3%	1.1%	11.5%	1.0%	$73,585	41.0%
	Services	29.6%	51.9%	3.3%	8.6%	6.5%	$7,253,948	38.9%
	Transportation Services	32.5%	39.8%	2.3%	24.7%	0.8%	$988,119	40.1%
Manufacturing	Food	33.3%	27.2%	16.6%	2.0%	20.9%	$255,506	37.7%
	Beverages and Tobacco	25.8%	21.1%	12.8%	1.6%	38.7%	$75,608	32.0%
	Textile Mills	41.9%	38.4%	12.8%	0.5%	6.3%	$25,574	42.1%
	Textile Product Mills	41.9%	38.4%	12.8%	0.5%	6.3%	$13,529	42.1%
	Apparel	38.1%	34.9%	11.6%	0.5%	14.9%	$32,771	39.6%
	Leather	24.1%	41.2%	13.1%	0.5%	21.2%	$4,641	38.0%
	Lumber and Wood	34.6%	35.4%	16.5%	10.1%	3.5%	$48,957	43.5%
	Paper	53.0%	19.9%	11.4%	8.4%	7.4%	$150,607	42.0%
	Printing and Publishing	44.6%	32.8%	10.8%	2.6%	9.3%	$94,167	41.3%
	Chemicals	30.0%	20.9%	12.1%	1.7%	35.4%	$481,973	34.0%
	Rubber and Plastic	45.1%	24.8%	15.9%	1.4%	12.8%	$102,290	40.5%
	Nonmetallic Minerals	44.5%	28.6%	12.7%	7.8%	6.4%	$82,916	42.4%
	Primary Metals	49.9%	29.6%	13.6%	3.6%	3.2%	$171,545	43.2%
	Fabricated Metal	46.2%	24.9%	16.3%	1.3%	11.3%	$133,914	40.9%
	Machinery	27.9%	20.7%	15.4%	1.1%	34.9%	$136,837	34.3%
	Computer and Elec Equipment	16.1%	12.0%	8.9%	0.6%	62.4%	$383,811	26.3%
	Electronic Equipment	36.0%	26.7%	26.7%	1.5%	9.0%	$277,762	42.0%
	Transportation Equipment	23.8%	15.7%	20.4%	1.0%	39.1%	$427,302	33.7%
	Furniture	25.1%	33.2%	23.8%	2.0%	15.9%	$28,633	39.9%
	Miscellaneous	8.3%	8.5%	26.1%	1.5%	55.6%	$96,769	28.9%
Energy	Coal	32.4%	52.2%	1.2%	13.1%	1.0%	$54,431	41.2%
	Crude Oil	12.7%	80.1%	0.6%	6.2%	0.5%	$508,043	40.3%
	Electricity	20.8%	50.2%	2.2%	26.6%	0.3%	$1,096,476	40.0%
	Natural Gas	11.3%	58.2%	2.1%	28.0%	0.4%	$363,872	39.7%
	Petroleum Refining	26.8%	35.9%	10.4%	16.6%	10.3%	$156,400	43.2%

to substitute leisure time for work (and hence consumption goods). Existing taxes on labor income have two effects on labor supply: a *substitution effect*—a reduction in the amount of labor available for production because they lower income received by households providing the labor and an *income effect*—an increase in work effort because taxes have lowered overall income levels. The interaction of these two effects is an empirical question.

Russek (1996) reviews the relevant empirical literature, which cites estimates for total labor supply elasticities (covering women and men) ranging between –0.1 and 2.3. Fuchs, Krueger, and Poterba (1998) also review estimated elasticities with similar findings. Following these findings, the values for labor-supply elasticities most commonly used in CGE models are in the mid-point of this range—typically around 0.4 for compensated elasticities and 0.15 for uncompensated elasticities (e.g., Parry and Bento [2000], Williams [1999], Goulder, Parry, and Burtraw [1997], Bovenberg and Goulder [1996]).

The selection of labor-supply elasticities must also take into consideration their implications for measurements of the distortions caused by the existing tax structure in the CGE model. These distortions are typically measured in two ways: marginal cost of funds (MCF) and marginal excess burden (MEB) (see Bovenberg, Goulder, and Gurney [2003]). MCF is the cost of raising an additional dollar of government revenue in terms of household income, where government-supplied public goods are separable from household utility. MEB is the same cost assuming that the tax revenue is returned to households in a lump-sum fashion, rather than being spent on public goods. Both measures attempt to quantify efficiency costs associated with taxes (i.e., how taxes have caused households to alter their behavior in ways that reduce household welfare).

Ground-breaking CGE modeling by Bovenberg and Goulder (1996) on interactions between environmental policies and existing tax structures estimates MCF for PIT as ranging between 1.24 and 1.29. This implies it costs around $1.25 in welfare terms (as measured by Hicksian equivalent variation) to raise an additional dollar of government income through the PIT. Distortions associated with corporate taxes are typically higher, but an accepted empirical range is less well established and most literature focuses on income taxes. MEB estimates presented in the CGE literature are generally around 0.3 (measured as the incremental cost of raising taxes and then returning the revenue to households).[48]

Labor supply elasticities have been chosen for ADAGE such that measurements of MCF and MEB in the *US Regional* module are similar to these estimates (for consistency and due to a lack of estimates for international regions, the same elasticities are applied to all regions in the ADAGE model). To estimate MEB and MCF in ADAGE, equal-yield constraints on government income have been included in the model. These equations allow the model to replace an existing tax instrument with an alternative approach that raises the same amount of revenue—or maintains a given level of utility. Following Ballard et al. (1985), the equal-yield constraints in ADAGE are modeled as ensuring equal purchasing power for the government at the new prices prevailing under the alternative tax policy.[49]

Based on these calculations and the elasticity estimates from the other CGE models mentioned above, in ADAGE the compensated labor-supply elasticity (η_c) is set at 0.40 and the uncompensated labor-supply elasticity (η_{uc}) is set at 0.15. These choices imply that the elasticity between consumption goods and leisure (σ_{cl} in Figure 2-1) is approximately 0.95 (see Ballard [1999]). The MEB associated with these choices is 0.31. The various MCF for different types of taxes include across all taxes of 1.23, personal income taxes of 1.25, and corporate income taxes of 1.31.[50]

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[48] See, for example, Goulder et al. (1999), Goulder, Parry, and Burtraw (1997), Browning (1987), and Ballard et al. (1985).

[49] This avoids the need to specify a utility function for the government and limits the number of utility-maximizing agents in the model (which simplifies results interpretation).

[50] These results are based on all interactions among economic data, tax rates, CES production functions, and production and consumption elasticities, measured at the baseline solution in ADAGE. As noted in Bovenberg and Goulder (1996), the appropriate equilibrium at which to measure MCF is a post-policy equilibrium, so the MCF will also depend on the policy in question.

5. ENERGY DATA IN ADAGE

When investigating environmental and climate-change mitigation policies, the GTAP and IMPLAN economic data in ADAGE are supplemented with additional information on energy consumption and production for two reasons. First, when the policies under consideration focus on energy markets, it is essential to include the best possible characterization of these markets in the model, and the GTAP and IMPLAN economic data do not always agree with energy information collected by IEA and EIA. And second, physical quantities of energy consumption are required for ADAGE to accurately estimate GHG emissions. IEA and EIA report physical quantities, while the economic databases do not.

This section discusses the relevant energy data sources needed to develop balanced energy markets for ADAGE (in physical units and value terms) and how these data are integrated with the economic data in the model. Note that, as with the economic data, all energy data used in the United States' region of the *International* module in ADAGE come from discussions pertaining to the *US Regional* module (see Section 5.2), rather than the international data sources. This may introduce some inconsistencies between the energy forecasts used for the United States and those for other nations—to the extent that the WEO forecasts for the United States differ from the AEO forecasts. However, the approach maintains internal consistency within ADAGE and allows results from the *International* module to be applied to regions/states within the United States, which has been deemed the preferable option since a single forecast covering both U.S. states and international countries is not available.

5.1 *International* Module

The first step in balanced markets for the energy goods in ADAGE (coal, crude oil, electricity, natural gas, and refined petroleum) is to collect historical data on production, consumption, and trade. IEA provides these data for the year 2004 in physical units for a wide range of countries. This information is then combined with other IEA data on energy prices and associated taxes[51] to convert the physical units into value terms for the SAM used by the CGE model. International bilateral trade flows needed to balance world energy markets are also estimated, based on IEA historical data on trade patterns.

The necessary energy data for this process have been collected from the following publications:

- **Energy Production and Consumption**: *Energy Balances of OECD Countries 2006,* and *Energy Balances of Non-OECD Countries 2006*, IEA (2006c, 2006d). National energy production, exports, imports, and consumption by sector and fuel type.

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[51] These tax rates are maintained at existing rates in the future in ADAGE, unless they are specifically designated to be phased out.

- **Energy Prices**[52]
  - *Energy Prices and Taxes*, IEA (2006e): Energy prices and tax rates by fuel and consumer. Also energy price indices by country and consumer and fuel import/export prices.
  - *International Fuel Prices 2003/2005* (Metschies, 2003/2005): International prices for diesel fuel and gasoline. (Tax rates from *International Fuel Prices 2003*).
  - *Beijing Energy Efficiency Center*: Data on China's coal and gasoline prices.
  - *Developing China's Natural Gas Markets* (IEA): China natural gas prices.
  - *Asian Development Bank Country Tables* (ADB): Supplemental price data.
  - *International Energy Annual 2005*, EIA: Additional price information.
- **Energy Trade**: *Coal Information 2006*, *Electricity Information 2006*, *Natural Gas Information 2006*, and *Oil Information 2006*, IEA (2006a, 2006b, 2006f, 2006g). Bilateral energy trade flows from IEA online data service.

Once historical data have been collected (energy quantities are generally for 2004 and prices for 2005), forecasts from the WEO are used to advance the representation of the energy markets to the base year in ADAGE of 2010, as necessary (these forecasts are subsequently used to provide business-as-usual growth paths for energy production, consumption and prices in the model):

- **Energy Consumption and Electricity Production**: *World Energy Outlook 2008*, IEA (2008). National energy consumption by economic sector and electricity generation by type.
- **Nonelectricity Energy Production**: National forecasts from IEA (online data service and the *WEO 2008*).
- **Energy Prices**: *World Energy Outlook 2008*, IEA (2008). World crude oil prices, and U.S. domestic prices, from *Annual Energy Outlook 2009* (EIA, 2009).

In addition to replacing U.S. energy data from IEA with information from the data sources described in Section 5.2, price forecasts for crude oil in all ADAGE modules are taken from the *Annual Energy Outlook* to improve consistency across model components. *WEO 2008* shows crude oil prices of $100 and $100 per barrel in 2010 and 2015, respectively. *AEO 2009 (March version)* has prices of $78 and $110 per barrel in 2010 and 2015. By 2030, the *AEO 2009* crude oil price is $130 per barrel, compared with approximately $122 in *WEO 2008*.

5.2 *US Regional* Module

Data on current and future state-level production and consumption of energy, and associated prices, are developed from a variety of EIA publications, as discussed below. In general, the process involves building up data on energy markets from state-level historical data and projecting this information along regional forecasts from the AEO.

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[52] See Dimaranan (2006) and Malcolm and Babiker (1998) for discussions of most of these data sources and their use in developing the GTAP-E database.

5.2.1 U.S. Energy Production Data

This section discusses energy production data for the five types of energy in the model.

Coal Production. Coal production data are developed from historical state-level production data, while trends in production and prices come from AEO. Data sources include the following:

- **State-Level Coal Production**: *Annual Coal Report 2007* (EIA, 2008c), Table 6. Production by state and coal rank.
- **Trends in Production and Prices**: *Annual Energy Outlook 2009* (EIA, 2009), Tables 121 and 122.
- **Coal Energy Content***: Assumptions to AEO 2009* (EIA, 2009b), Table 12.5. Heat content per ton of coal by coal rank.

Following the historical data from the *Annual Coal Report*, trends for production and prices for each state are based on projections from the *Annual Energy Outlook*. In establishing these trends, each state is assigned to the most closely related coal-production region in the AEO forecasts according to the following scheme:[53]

- Northern Appalachia—MD, OH, PA
- Central Appalachia—KY, VA, WV
- Southern Appalachia—AL, TN
- Eastern Interior—IN, IL
- Western Interior—AR, KS, MO, OK
- Gulf Lignite—LA, MS, TX
- Dakota Lignite—ND
- Power and Green River Basins—MT,[54] WY
- Rocky Mountain—CO, UT
- Southwest—AZ, NM
- Northwest—AK, WA

These trends are applied at a coal-rank level before being aggregated to a single type of coal in each producing state prior to entering ADAGE. Regional minemouth prices from AEO are used to establish the value of coal output in each state because many of the state-level minemouth prices in the *Annual Coal Report* are withheld. Federal excise taxes on coal production from the Tax Foundation of between $0.55 and $1.10 per ton are then added to these prices. Units are converted from tons of coal to heat content (Btu) prior to entering the model.

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[53] States not shown do not produce coal.

[54] Trends in Montana lignite production and prices are based on the Dakota region of EIA's *Coal Market Module*.

Crude Oil and Natural Gas Production. Unlike the methodology used for coal, crude oil and natural gas production data are developed from AEO regional data to improve the fit with AEO forecasts (historical state-level production data are used to allocate state's shares of regional production), while trends in production and prices come from AEO. Data sources include the following:

- **State-Level Crude Oil Production**: *Petroleum Supply Annual 2007* (EIA, 2008d), Table 13. Production by state in 2007 (barrels).
- **Regional Crude Oil Production***:* *Annual Energy Outlook 2009* (EIA, 2009), Table 113. Lower 48 states' production in EIA's *Oil and Gas Supply Model* regions.
- **State-Level Natural Gas Production***:* *Natural Gas Annual 2007* (EIA, 2008e), Natural Gas Dry Production by state in 2006 (MMCF).
- **Regional Natural Gas Production**: *Annual Energy Outlook 2009* (EIA, 2009), Table 114. Lower 48 states' production by EIA Oil and Gas Supply Model regions.
- **Trends in Production and Prices**: *Annual Energy Outlook 2009* (EIA, 2009), Tables 1, 113, and 114.
- **Crude Oil and Natural Gas Energy Content**: *Annual Outlook 2009* (EIA, 2009), Appendix G1. Conversion factors for production.

In establishing state-level production and prices, each state is assigned to the most closely related Oil and Gas Supply Model (OGSM) region in the AEO forecasts according to the following scheme:[55]

- Northeast—IL, IN, KY, MD, MI, NY, OH, PA, TN, VA, WV
- Gulf and Southwest—AL, FL, LA, MS, NM, TX
- Mid-continent—AR, KS, MO, NE, OK
- Rockies—AZ, CO, MT, ND, NV, SD, UT, WY
- West coast—CA, OR
- Alaska—AK[56]
- Offshore (lower 48 states)

To ensure that total U.S. production corresponds with AEO forecasts, state-level production is used to share out AEO regional production. AEO's regional wellhead prices for natural gas are used to determine marketed values of states' natural gas production, while AEO's world crude oil price forecast is used to determine the value of crude oil production (this assumption reflects the ADAGE model assumption of a uniform world crude oil price). When determining trends, the Southwest and Gulf regions in OGSM are combined because they divide Texas, one of the most important producing regions, in half. In the *US Regional* module, federal offshore production in the lower 48 states, which represents around 20 percent of natural gas production and 35 to 50 percent of crude oil production from the

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[55] States not shown do not produce crude oil or natural gas.

[56] Data for Alaska are not shared out from regional AEO data.

lower 48 states, is modeled as a separate region controlled by the federal government.[57] Prior to determining retail natural gas values, distribution costs are added into these wholesale values.

Electricity Generation. Electricity data are developed from historical state-level data, while trends in production, fuel use, and prices come from AEO. Data sources include the following:

- **Electricity Generation**: *Electric Power Annual 2007* (EIA, 2008f), historical spreadsheet. Generation by state, type of producer, and energy source. 1990–2007.
- **Electricity Fuel Consumption and Costs**: *Electric Power Annual 2007* (EIA, 2008f), historical spreadsheet. Fossil-fuel consumption and prices by state and type of producer (coal, natural gas, and oil).[58]
- **Electricity Prices**: *Electric Power Annual 2007* (EIA, 2008f), historical spreadsheet. Average electricity prices by state.
- **Renewable Generation**: *Renewable Energy Annual 2006* (EIA, 2008g), Table 15. Renewable generation by state and type (geothermal, hydroelectric, municipal solid waste, biomass, solar, wind, and wood).
- **Trends in Generation, Fuel Use, and Prices**: *Annual Energy Outlook 2009* (EIA, 2008), Tables 72–101.

At the state level, generation and fossil-fuel consumption and fuel prices for the electricity industry are determined from historical data in the *Electricity Power Annual*. In ADAGE, this industry covers electric utilities, independent power producers (IPPs), and combined heat and power (CHP) intended for electric power.[59] Average state-level electricity prices are combined with total state-level generation to determine revenues associated with the electricity industry in each state.[60]

Following the historical data from the *Electricity Power Annual* and *Renewable Energy Annual*, trends for generation, fuel use, and prices for each state are based on projections from the *Annual Energy Outlook*. In establishing these trends, each state is assigned to the most closely related NERC region in the AEO forecasts according to the following scheme:[61]

- ECAR—IN, KY, MI, OH, WV
- ERCOT—TX
- MAAC—DC, DE, MD, NJ, PA

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[57] Although economic data typically combined crude oil and natural gas extraction since they are, to a certain extent, joint products, ADAGE separates them into separate industries to prevent the model from allowing imports of crude oil to be reclassified as natural gas.

[58] Coal use in short tons, natural gas use in million cubic feet, and oil use in barrels are converted to Btus with conversion factors from AEO 2009, Appendix G, for electric utilities.

[59] CHP for commercial and industrial power, and its fuel use, is captured by industry-specific data in the model.

[60] As such, these revenues cover generation, transmission, and distribution costs to be consistent with the definition of the NAICS 2211 electric utility industry that is used in ADAGE.

[61] AK and HI trends are assumed to follow average U.S. growth paths.

- MAIN—IA, IL, MO, WI
- MAPP—MN, ND, NE, SD
- NY—NY
- NE—CT, MA, ME, NH, RI, VT
- FRCC—FL
- SERC—AL, AR, GA, LA, MS, NC, SC, TN, VA
- SPP—KS, OK
- NPPA—ID, MT, NV, OR, UT, WA, WY
- RMPA—AZ, CO, NM
- CA—CA

Trends for each state are based on projections for these associated NERC regions. Future growth in renewable generation shown in the AEO for these NERC regions (with the exceptions of ERCOT, NY, FRCC, and CA that encompass a single state) is shared out across states within regions according to the state's historical shares of each generation type.

Refined Petroleum Production. In general, petroleum refining is tracked at the PADD level (Petroleum Administration for Defense Districts), rather than state level, which necessitates a difference methodology for determining state-level production quantities and values. Data sources include the following:

- **Refinery Capacity (historical)**: *Refinery Capacity Report 2007* (EIA, 2008h), Table 1. Capacity by state (barrels per calendar day).
- **Imports and Exports of Refined Petroleum Products**: *PSA 2007*, Tables 23 and 29. Imports and exports (barrels).
- **Output Quantities and Prices, Trends, and Capacity Additions/Utilization**: *Annual Energy Outlook 2009* (EIA, 2009), Tables 1, 2, 3, and 102–114.

In determining state-level refinery capacity, PADD regions are used, which are defined along the following state lines:

- PADD I—CT, DC, DE, FL, GA, MA, MD, ME, NC, NH, NJ, NY, PA, RI, SC, VA, VT, WV
- PADD II—IA, IL, IN, KS, KY, MI, MN, MO, ND, NE, OH, OK, SD, TN, WI
- PADD III—AL, AR, LA, MS, NM, TX
- PADD IV—CO, ID, MT, UT, WY
- PADD V—AK, AZ, CA, HI, NV, OR, WA

Historical state-level refinery capacity data from the *PSA 2005* are combined with PADD-level capacity additions forecasts from the AEO. These capacity additions are assumed to be distributed across states within each PADD according to historical capacity shares. State-level refinery capacity forecasts are then combined with AEO forecasts for PADD-level capacity utilization rates to determine an "effective" capacity in each state over the 2010 through 2030 time horizon.

National output of refined petroleum by type of product, measured in either barrels or energy content (Btus), can be determined from data in the AEO forecasts. This is accomplished by using the equation: output equals total consumption (AEO, Table 2) plus exports minus imports (AEO, Table 1), where trade in specific types of petroleum is estimated by combining overall imports and exports from the AEO with data on current petroleum trade by product from *PSA 2007*, Tables 23 and 29. However, the wholesale value of production is more difficult to measure from AEO data because energy prices in AEO Table 3 are delivered prices that include taxes and distribution costs. Also, wholesale prices for different types of petroleum vary across grades because some, such as motor gasoline, command higher prices than other grades of petroleum. Consequently, to determine state-level wholesale values of petroleum products, it is first assumed that the mix of petroleum products refined from each barrel of crude oil is uniform across parts of the country. This allows national production quantities by type of oil to be shared out across states using the "effective" capacity forecasts discussed above (consumption of crude oil by refineries—AEO Table 1—is assigned to states using the same process). After this step, regional wholesale prices from AEO Tables 102 through 112 can be used to establish an overall wholesale value of petroleum production in each state, excluding taxes and distribution costs. When determining retail petroleum values, distribution costs and taxes (AEO Tables 102 through 112 and Tax Foundation, 2008c) are added back into wholesale values.

5.2.2 U.S. Energy Consumption Data

This section discusses energy consumption data for the five types of energy goods in the model. In general, EIA provides consumption information on four classes of energy consumers—residential, commercial, industrial, and transportation—which are adjusted as necessary to match sectors in ADAGE. The residential sector gives household energy use but only includes energy consumption for household appliances, heating, etc., and, thus, has to be combined with other EIA consumption data related to private transportation to match ADAGE. The commercial sector contains energy data on service-providing facilities and equipment, which corresponds to service industries (with the exception that government buildings are included in the commercial sector). The industrial sector covers energy use by manufacturing facilities and provides some industry-specific data. The transportation sector covers all energy use by vehicles whose primary purpose is moving people and goods (household and military fuel use in this sector is assigned to the appropriate sectors in ADAGE).

Household Consumption. Household energy consumption data are developed by combining historical state-level consumption data with national forecasts from AEO. Data sources include the following:

- **State-Level Energy Consumption**: *State Energy Consumption, Price, and Expenditure Estimates 2006* (EIA, 2008i). Residential energy consumption in physical units, energy content, expenditures, and prices for the year 2006.

- **Electricity Demand**: *Electricity Power Annual 2007* (EIA, 2008f), historical spreadsheet. Demand by state and type of consumer, 1990–2007.
- **Population Growth**: *Decennial Census and Population Surveys 2004* (Census Bureau), population estimates through 2030.
- **Trends in Consumption and Prices**: *Annual Energy Outlook 2009* (EIA). Tables 2, 3, 46, 72–85, 103–112, 117, and 118.
- **Trends in Energy Consumption after 2030:** After 2030, it is assumed that heat rates in electricity generation improve at 0.1% per year and overall energy efficiency per dollar of GDP improves at around 1.5% per year, based on AEO 2009 trends.

The process for estimating state-level electricity demand by households follows a process similar to establishing state-level electricity generation. Historical data from the *Electricity Power Annual* on sales in each state to different types of customer are combined with AEO's NERC-level forecasts for demand growth and prices (Tables 72 through 85) to get future demand for and the value of electricity purchases by households.

In determining state-level consumption of natural gas by households (and by other sectors discussed in the following sections), AEO data from Tables 117 and 118 are used, which contain gas consumption and delivered price estimates by sector. These data are provided at a Census region level, defined along the following state lines:

- New England—CT, ME, MA, NH, RI, VT
- Middle Atlantic—NJ, NY, PA
- East North Central—IL, IN, MI, OH, WI
- West North Central—IA, KS, MN, MO, NE, ND, SD
- South Atlantic—DC, DE, FL, GA, MD, NC, SC, VA, WV
- East South Central—AL, KY, MS, TN
- West South Central—AR, LA, OK, TX
- Mountain—AZ, CO, ID, MT, NM, NV, UT, WY
- Pacific—AK, CA, HI, OR, WA

To estimate natural gas consumption by households in each state, current consumption by households from the *State Energy Data Reports* is combined with each state's expected population growth from the Census Bureau. The combination of these data is used to share out AEO's residential gas consumption data (Table 117), available at a Census-region level, to account for the existing distribution of consumption and any future changes across states as the result of population growth. This energy consumption is multiplied by estimated delivered prices from AEO Table 118 to determine the value of household gas purchases.

For the other types of energy used by households (coal and refined petroleum), the AEO mainly provides national estimates of consumption and prices, rather than Census or NERC region estimates. A similar process is used to determine state-level consumption of these types of energy, based on historical data from the State Energy Data reports and AEO forecasts. Coal use by households is relatively minor. Any coal consumption in the AEO data (Table 2) is shared out across states according to the historical data and price trends that come from the AEO forecasts (Table 3). National petroleum use by households includes both residential use of heating oil (AEO Table 2) and use of motor gasoline (AEO Table 46—light-duty, noncommercial use of motor gasoline). The process for sharing out this petroleum use to states depends on historical state-level data for both residential and transportation use of oil, weighted by expected population growth, and scaled to match national totals. State-level price differences are maintained by extending each state's historical petroleum prices along national forecast paths from the AEO. Similarly, state motor gasoline tax rates (Tax Foundation, 2006c) are extended along AEO's Census region forecasts for state tax rates (Tables 90 through 99). Diesel and jet-fuel tax rates for the transportation services sector also come from AEO Tables 103 through 112.

Manufacturing. Energy consumption by manufacturing industries is included in the industrial sector in EIA's historical data. At the national level, the AEO provides consumption by specific industries. Developing an estimate of energy consumption by different types of manufacturers involves the following data sources:

- **State-Level Energy Consumption**: *State Energy Consumption, Price, and Expenditure Estimates 2006* (EIA). Industrial-sector energy consumption in physical units, energy content, expenditures, and prices ($/MMBtu) for the year 2006.
- **Industry-Specific Energy Consumption**: *Manufacturing Energy Consumption Survey 2002*, or MECS (EIA), and *Annual Energy Outlook 2009* (EIA), Tables 34–44.
- **Trends in Consumption and Prices**: *Annual Energy Outlook 2009* (EIA). Tables 2, 3, 34–44, 72–85, 117, and 118.

AEO forecasts provide energy consumption data for the following manufacturing sectors of the economy at the national level (Tables 34 through 44):

- food
- paper
- chemicals
- glass cement
- iron and steel
- aluminum
- petroleum refining
- agriculture
- construction
- mining
- metal-based durables (fabricated, machinery, computers, transportation equipment)
- other manufacturing (wood products, plastics, other)

With the exceptions of mining, metal-based durables, and other manufacturing that cover multiple industries, the energy consumption data for these sectors is maintained in ADAGE. The mining sector covers coal, crude oil, natural gas extraction, and other types of mining. IMPLAN data on output of these sectors are used to share out energy consumption data, implying identical energy consumption per unit of output for these four industries. Historical MECS data on energy consumption industry and type of fuel are used to share out the metal-based durables and other manufacturing energy data to specific industries not covered in AEO forecasts.

To estimate state-level energy consumption by different industries, historical data from the *State Energy Data Reports* on industrial energy consumption (the industrial category in EIA data covers all manufacturing) are combined with energy consumption per unit of output from AEO forecasts and IMPLAN data on state-level output in the year 2004 (for energy industries, excluding electricity, the calculated energy production discussed above is used). First, the AEO energy consumption per unit of output data is applied to the IMPLAN data on output. These results are then scaled to match historical energy consumption by the industrial sector in each state to maintain differences in energy efficiency across the United States. Finally, for consistency with AEO forecasts, these state-level estimates are scaled to match AEO total energy consumption for the industries discussed above. Energy prices for manufacturing sectors are established by extending historical industrial prices along the AEO forecasts.

Service Sector and Transportation Services. Energy consumption by service and transportation industries is included in the commercial and transportation sectors in EIA's historical and forecast data (excluding government consumption as discussed in the following subsection). Developing an estimate of energy consumption involves the following data sources:

- **State-Level Energy Consumption**: *State Energy Consumption, Price, and Expenditure Estimates 2006* (EIA). Commercial-sector energy consumption in physical units, energy content, expenditures, and prices ($/MMBtu) for the year 2006.
- **Trends in Consumption and Prices**: *Annual Energy Outlook 2009* (EIA). Tables 2, 3, 46, 72–85, 117, and 118.

The process for estimating state-level electricity demand by the services and transportation industries follows a process similar to establishing state-level electricity generation. Historical data from the *Electricity Power Annual* on sales in each state to different types of customers is used to share out AEO's NERC-level forecasts for demand in kilowatt hours and values (Tables 72 through 85).

To estimate natural gas consumption by the service and transportation industries in each state, current consumption from the *State Energy Data Reports* is combined with each state's expected population growth from the Census Bureau. The combination of these data is used to share out AEO's commercial and transportation gas consumption data, available at a Census-region level, to account for the existing distribution of consumption and any future changes across states as the result of population growth. This energy consumption is multiplied by estimated delivered prices from AEO Table 118 to determine the value of these natural gas purchases.

For coal and refined petroleum used by the service and transportation industries, the AEO provides national estimates of consumption and prices, rather than Census or NERC region estimates. A similar process is used to determine state-level consumption of these types of energy, based on historical data from the *State Energy Data Reports* and AEO forecasts. Coal use by these industries is relatively minor. Any coal consumption in the AEO data for these industries (Table 2) is shared out across states according to the historical data, and price trends come from the AEO forecasts (Table 3). National petroleum use by these industries comes from AEO Tables 2 and 46 (excluding household use of motor gasoline). The process for sharing out petroleum use to states depends on historical state-level data for commercial and transportation use of oil, weighted by expected population growth and scaled to match national totals. State-level price differences are maintained by extending each state's historical petroleum prices along national forecast paths from the AEO.

Government. Government energy consumption is included in the commercial sector in EIA's historical and forecast data and must be separated from energy use by service industries. Developing an estimate of government consumption involves the following data sources:

- **State-Level Energy Consumption**: *State Energy Consumption, Price, and Expenditure Estimates 2006* (EIA). Commercial-sector energy consumption in physical units, energy content, expenditures, and prices ($/MMBtu) for the year 2000.
- **Government Building Energy Demand**: *Commercial Buildings Energy Consumption Survey*, or CBECS, (EIA), Table 1. Energy use by government and nongovernment buildings.
- **Military Fuel Use and Trends in Consumption and Prices**: *Annual Energy Outlook 2009* (EIA). Tables 2, 3, 46, 72–85, 117, and 118.

The CBECS data are used to separate AEO's commercial energy use (Table 2) into government and service-sector energy use. This is combined with delivered energy prices to the commercial sector (AEO Table 3) and military fuel consumption (AEO Tables 3 and 46) to determine national governmental energy use and expected trends. Historical data on state-level commercial-sector energy consumption are then used to determine state shares of the national total energy use. Similar to the process for other sectors, for electricity and natural gas consumption, the AEO NERC-region and Census-region data are used to establish prices and consumption trends.

5.2.3 U.S. Energy Trade

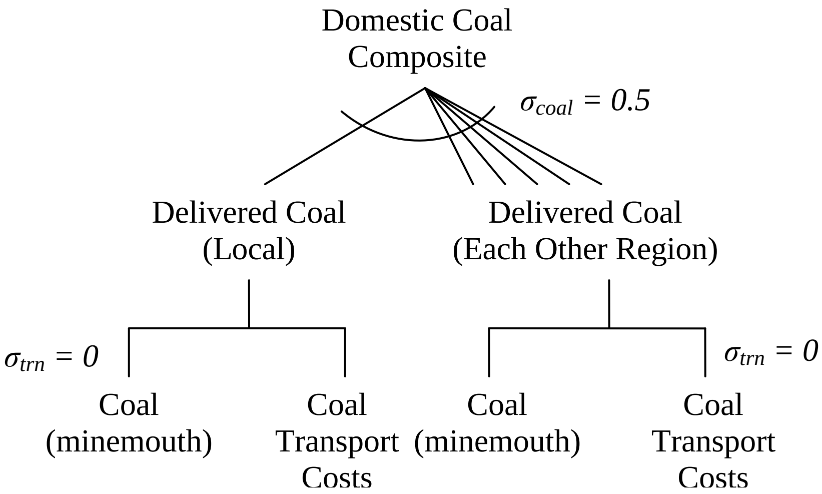
State-level energy trade patterns are developed from historical data, while quantities, values, and trends come from the AEO. Data sources include the following:

- **Coal Trade**: *Coal Distribution 2004* (EIA). State-to-state coal trade flows (thousand short tons). *Coal Transportation: Rates and Trends in the United States, 1979-2001* (EIA, 2004). Data on transportation costs. *Assumptions to AEO 2009* (EIA), changes in transportation costs over time.
- **Electricity Trade**: *State Energy Consumption, Price, and Expenditure Estimates 2006* (EIA) data on international imports and exports by states, along with net domestic trade flows into each state. *Annual Energy Outlook 2009* (EIA), Tables 72–85, with international and interregional trade in electricity across NERC regions. *Integrated Planning Model* (EPA), Table 3.4, with data on electricity transmission constraints among regions.
- **Natural Gas Trade**: *Natural Gas Annual 2007* (EIA), Table 12. State-to-state gas flows and states' foreign trade (MMCF). Also *Natural Gas Transportation 2001* (EIA), Table 1. Regional gas flows (average flows among regions).
- **Crude Oil and Refined Petroleum Trade**: *Petroleum Supply Annual 2007* (EIA), Volume 1, Table 32. Movements of oil among PADDs.
- **Quantities and Trends**: *Annual Energy Outlook 2009* (EIA), Tables 1, 3, 16, 72–85.

The *Annual Coal Report* (ACR) provides origin and destination information on state-to-state and foreign coal trade flows. Foreign trade quantities are used to share out foreign coal trade from the AEO (Tables 3 and 16) in quantity and value terms. The values of exports from coal-producing states to other states are estimated by assuming that export shares, both to other states and of total production within a state, remain constant between the ACR data (year 2004) and the base year of ADAGE (year 2010). This allows determination of export values without transportation costs.

The *US Regional* module distinguishes among types of coal by origin to account for differences in sulfur and heat content. As shown in Figure 5-1, this is done by using the Armington assumption of differentiated commodities. Coal mined in each region, combined with transport costs, produces a different type of delivered coal, which is an imperfect substitute for delivered coal from other regions (σ_{coal}).

Figure 5-1. U.S. Interregional Coal Trade



Following EIA (*Assumptions for the AEO 2006*), it is assumed that transportation costs for coal are the difference between minemouth prices and delivered prices in each region. Combining the export data with distances among state capitals (see Section 4.3) then allows estimation of the amount of transportation services (typically railroads) that have been used to supply coal from each producing state to each consuming state.[62] Future changes in transportation costs come from the *Assumptions for the AEO 2009*, which allows establishment of future trading links among states not currently trading coal. On average, this process estimates delivery costs equal to around 40 percent of the delivered value of coal, consistent with EIA data on coal transportation costs (EIA, *Coal Transportation Information*).

For the other types of energy in the model, less data are available on net interstate trade flows, which necessitates different estimation procedures. For electricity, the *State Energy Data Reports* provide state-level estimates of international trade in electricity. These data are used to share out AEO data on NERC-level international trade flows (Tables 72 through 85). Within each NERC region, total exports are assumed to be based on electricity generation, and total imports are assumed to be based on electricity consumption, in the absence of other data. Feasible state-to-state electricity transmission capabilities are established using data on transmission links from EPA's Integrated Planning Model (EPA, 2006).

These IPM data show transmission capabilities, in maximum sustainable one-directional flows of power, among regions in the model. They have been developed from NERC estimates of First Contingency Total Transfer Capability (FCTTC) links among parts of the

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[62] It is assumed for coal and other energy goods that these transportation services are provided by the producing state.

country, adjusted to account for "sustainable" flows. This information is combined with data from the *State Energy Data Reports* on net interstate exports of electricity to provide estimates of state-to-state trade in electricity when balancing the energy data (discussed in Section 5.3).[63] The net interstate flows needed to balance electricity markets in each state are then estimated based on the relative sizes of transmission links among regions.

For natural gas, the *Natural Gas Annual* (NGA) provides foreign trade flows for gas in 2007, which are used to share out AEO data from Tables 1 and 3 (in physical quantities and values). However, interstate flows in NGA are gross of total movements of gas across state borders. Consequently, the *Natural Gas Transportation* report is used to provide regional net exports and imports of gas, which are shared out to states within these regions based on their production and consumption, respectively.[64] Similar to the procedure for estimating petroleum production, it is assumed that crude oil and petroleum imports are based on state-level "effective" refining capacity. As with regional gas flows, export and import flows of crude oil and petroleum among states are based on regional PADD-level data from the PSA 2005, shared out to states within regions based on their production and consumption, respectively.

5.3 Energy Data Balancing and Integration in the SAM

Once energy data have been collected, the energy markets must be balanced and then integrated with the economic data to give a balanced SAM for the base year in the model. Because the initial year in ADAGE is 2010, which is different than the historical economic data, applying region- and commodity-specific growth rates to the original data will result in an unbalanced SAM, as will the integration of new energy data. These imbalances must be corrected before data enter the model.

In this process, physical flows of energy goods are first balanced across all regions in each module. Energy prices (and taxes) are then applied, and the resulting value flows of energy goods are rebalanced by adjusting the values of trade flows as necessary. Prior to integrating these energy markets with the economic data, nonenergy intermediate inputs to energy production must be established. These inputs have been based on the value shares shown in the GTAP and IMPLAN databases, except for the values of extracted natural resources used in the coal, crude oil, and natural gas industries where value shares are

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[63] These two data sources are also helpful when examining ADAGE model results regarding electricity trade in policy simulations because they provide a reference point for feasible changes in electricity flows among states and regions of the United States.

[64] Similar to coal, natural-gas distribution costs are modeled as the difference between wellhead prices and delivered prices. Modeling these costs separately allows a better match between the natural gas industry and methane emissions associated with the production and transmission of natural gas.

based on MIT data from the EPPA model (Babiker et al., 2001). In addition, relative cost shares for nonfossil electricity generation are based on EIA data.[65]

Subsequently, the two types of data (energy and economic) must be integrated. Procedures developed by Babiker and Rutherford (1997) and described in Rutherford and Paltsev (2000) are used to integrate relevant economic and energy data (this approach was originally applied to energy data gathered by GTAP). The methodology relies on standard optimization techniques to maintain calculated energy statistics, while minimizing the changes needed in the economic data to rebalance the SAM. Once the data are integrated, a balanced SAM is generated that incorporates forecasts for economic and energy growth between the initial year of the data and the base year of 2010.

6. GHG EMISSIONS IN ADAGE

This section discusses the estimates of GHG emissions in ADAGE and the techniques for modeling their abatement costs. The model is designed to consider a variety of approaches to limiting emissions through cap-and-trade programs: national caps, regional caps, sector-specific caps, and/or caps that exclude some emission sources (i.e., household emissions).

6.1 Carbon Dioxide

The ADAGE model tracks fuel consumption in physical units (Btu) using information from the WEO and AEO forecasts. Because CO_2 emissions from fuel use are tied directly to combustion of given quantities of fossil fuels, ADAGE is able to determine emissions levels in terms of millions of metric tons of carbon dioxide (equivalent), or $MMTCO_2e$—see Section 7 for baseline emissions estimates. Substitution options for replacing energy inputs to production are controlled by the model's CES nesting structure and substitution elasticities. Households also have the ability to switch fuels, lower overall consumption, and improve their energy efficiency. Costs of these CO_2 emissions reductions are determined by the elasticities of substitution shown in Section 2.

6.2 Other Greenhouse Gases

ADAGE has endogenized emissions abatement costs associated with five non-CO_2 gases using the innovative approach developed in Hyman et al. (2002) and used in recent work by MIT's EPPA model (referred to hereafter as the MIT approach). Their work (and modeling efforts coordinated by the Stanford Energy Modeling Forum—EMF 21—see Yatchew, 2006) finds that these non-CO_2 gases are a critical part of cost-effective GHG reduction policies and, because of these gases' high global warming potentials (GWP), they could contribute significantly to short-term efforts to lower atmospheric GHG concentrations. This section

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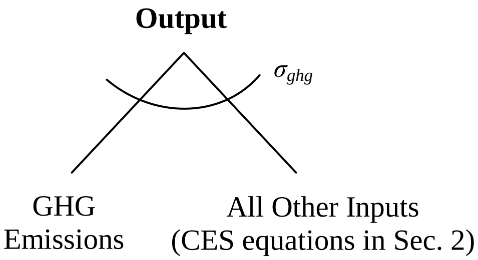
[65] Table 8.2 in EIA's *Assumptions to the Annual Energy Outlook 2009*.

summarizes the MIT approach and the marginal abatement costs of emissions reductions (please see their paper for additional details).

Non-CO_2 GHGs come from a variety of sources: methane (CH_4) from fuel production and transport, landfills, and agriculture; nitrous oxide (N_2O) from agricultural and industrial activities and fuel combustion; hydrofluorocarbons (HFCs) from various industrial processes, perfluorocarbons (PFCs) from manufacturing aluminum, semiconductors, and solvents; and sulfur hexafluoride (SF_6) from electricity switchgear and transmission/distribution, along with magnesium production. However, because these gases are not emitted in fixed proportions to energy consumption in the same manner as CO_2, the modeling of abatement costs is more problematic.

Rather than relying on exogenous marginal abatement cost functions, which ignore important interactions among economic sectors, the MIT approach models emissions of non-CO_2 gases directly as an input to production (see Figure 6-1). This methodology allows specification of industry-specific abatement cost curves through selection of an elasticity of substitution (σ_{ghg}) between each GHG and all other inputs to production. Although the formulation rules out "no regrets" options and assumes a low initial GHG permit price ($1/MMTCE), the modeler is able to select a σ_{ghg} parameter that approximates abatement costs from "bottom-up" engineering studies. Emissions reductions can then be achieved at these costs in the CGE model by increasing the use of other productive inputs.

Figure 6-1. GHG Emissions Abatement Modeling



ADAGE uses σ_{ghg} elasticities of substitution based on abatement cost data developed by the EPA (2006c) – these elasticities are shown in Table 6-1 below. In general, these elasticities imply that most sources of CH_4, HFCs, PFCs, and SF_6 emissions can be reduced significantly at relatively low cost; CH_4 emissions from manufacturing and energy-related sources can be reduced moderately at a moderate cost; and reduction opportunities for CH_4 and N_2O emissions from agriculture are more limited (with some variation across countries, depending on their crop mix).

Table 6-1. Emissions Sources and Elasticities

Gas	Source	General ADAGE Sector *	Elasticity of Substitution**
CH_4	Coal mines	Coal	0.40
	Pipelines	Natural gas	0.13
	Petroleum refining	Petroleum	0.10
	Enteric fermentation Manure management Rice cultivation Other agriculture	Agriculture	0.05[1]
	Chemicals Iron and Steel	Energy-intensive manufacturing	0.11
	Other industrial	Manufacturing	0.11
	Landfills Wastewater treatment	Households	0.21
	Stationary and mobile combustion, biomass combustion	Households, General Industry[2]	0
N_2O	Adipic and nitric acid production	Energy-intensive manufacturing	0.70
	Agricultural soils Manure management Other agriculture/biomass	Agriculture	0.07[3]
	Stationary and mobile combustion, municipal solid waste combustion, wastewater treatment, other	Households, General Industry[2]	0
HFCs	Aerosols Fire Extinguisher Foams HFC production Refrigeration	Manufacturing	0.40
PFCs	Aluminum production Solvents and other	Energy-intensive manufacturing	0.12
	Semiconductor production	Manufacturing	0.14
SF_6	Magnesium production	Energy-intensive manufacturing	0.60
	Electricity distribution	Electricity	0.16

* If more disaggregated sectors are used in a policy analysis (e.g., rice, aluminum, etc.), the elasticities are applied to the appropriate subsector.

** Numbers presented are for the year 2020 and beyond. In a limited number of cases, abatement opportunities and hence elasticities are lower for the years 2010 and 2015.

[1] CH4 elasticity for the U.S., they vary from 0.02 to 0.05 for other countries.

[2] Stationary and mobile combustion emissions are related to several activities, however, no abatement opportunities are assumed for these emissions (σ_{ghg}.=0) and any emissions are tracked separately.

[3] N2O elasticity for the U.S., they vary from 0.03 to 0.09 for other countries.

International emissions and projected trends of non-CO_2 gases by source are taken from the U.S. EPA (EPA, 2006b) data on multigas abatement. For cases where two sets of emissions trends are provided, ADAGE uses the projection based on technology adoption, which is lower than if new technologies are not adopted (this also implies few opportunities to reduce emissions below this baseline path). Data for U.S. emissions are from U.S. EPA *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2006*. Regional shares of EPA's U.S. emissions are assigned to states based on output and consumption from the IMPLAN and EIA data according to the logic below.

Methane emissions from U.S. coal mines in the EMF data are apportioned to underground and surface mines using EPA (2008) data (*Inventory of U.S. Greenhouse Gas Emissions and Sinks*). Net emissions, accounting for methane recovery, from these mines are assigned to states based on state-level coal production (with underground mines in the eastern states and surface mines in the west). Methane emissions associated with natural gas transmission are assigned based on states' shares of national gas transmission, while emissions from petroleum products are determined by states' oil consumption. State-level agricultural emissions of methane from enteric fermentation, animal waste, rice cultivation, and crop residue burning are estimated based on state's shares of national agricultural production of the relevant commodities as shown in the IMPLAN data. Growth in each state's agricultural emissions depends on agriculture production growth within ADAGE as a share of national production. Similar logic is applied to emissions from the iron and steel and chemical manufacturing industries. Methane emissions from landfills are assumed to be a function of each state's population as a share of national population.

Emissions of N_2O from fuel combustion are based on the ADAGE state-level estimates of energy consumption. As with some types of methane sources, other N_2O emissions from agriculture and manufacturing depend on the IMPLAN production data and regional growth rates determined within the model. Similar logic is also applied to all HFC and PFC emissions and to SF_6 emissions related to magnesium production. SF_6 emissions from the electricity industry are based on the state-level estimates of electricity generation in ADAGE (in kWh).

7. BASELINE ECONOMIC AND ENERGY DATA IN ADAGE

This section presents tables with results from the baseline solution for ADAGE, covering general economic and industrial growth as well as energy production, consumption, and prices. Results from the *US Regional* module for the United States and five regions are presented in Tables 7-1 to 7-12. Baseline results for other countries in the International module are shown in Tables 7-13 to 7-24. Note that these baseline findings depend on all model parameters and will change if assumptions are altered (all dollar figures in these tables are in U.S. $2005).

Table 7-1. United States (total) – Macroeconomic

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Macroeconomic									
Population (millions)	308.9	322.4	335.8	349.4	363.6	373.8	383.1	391.6	399.6
GDP (billion 2005$)	$13,246	$15,420	$17,430	$19,767	$22,618	$25,537	$28,595	$31,867	$35,377
% Change in GDP	--	--	--	--	--	--	--	--	--
Consumption (bill 2005$)	$10,005	$11,575	$13,168	$14,911	$17,079	$19,307	$21,655	$24,124	$26,752
% Change in Consump	--	--	--	--	--	--	--	--	--
Allowance Price - $/tCO2e	--	--	--	--	--	--	--	--	--
Energy Prices - delivered (with allowance price)									
Coal ($ per MMBtu)	$1.80	$1.87	$1.84	$1.87	$1.94	$1.96	$1.96	$1.97	$1.98
Electricity ($ per kWh)	$0.085	$0.085	$0.089	$0.094	$0.099	$0.101	$0.103	$0.104	$0.106
Natural Gas ($ per MMBtu)	$7.94	$8.14	$8.51	$8.87	$9.66	$9.76	$9.86	$9.95	$10.04
Petroleum ($ per MMBtu)	$17.71	$23.32	$23.82	$24.60	$25.96	$26.54	$27.21	$27.84	$28.47
% Change in Coal	--	--	--	--	--	--	--	--	--
% Change in Electricity	--	--	--	--	--	--	--	--	--
% Change in Natural Gas	--	--	--	--	--	--	--	--	--
% Change In Petroleum	--	--	--	--	--	--	--	--	--
GHG Emissions - mmt CO2e									
CO2	5,995.8	6,088.5	6,108.3	6,213.3	6,480.9	6,676.7	6,859.0	7,026.7	7,191.6
CH4	559.0	562.6	575.9	574.1	576.5	572.5	569.2	559.9	551.1
N2O	372.6	381.3	391.9	400.6	409.6	400.9	392.5	375.0	358.4
HFC	169.4	230.2	295.1	286.7	279.1	270.1	261.9	260.3	258.7
PFC	6.1	5.4	5.1	5.3	5.5	5.7	5.9	6.0	6.0
SF6	15.0	13.8	13.5	13.5	13.4	13.2	13.0	13.0	12.9
Total	**7,118**	**7,282**	**7,390**	**7,494**	**7,765**	**7,939**	**8,101**	**8,241**	**8,379**
% Change	--	--	--	--	--	--	--	--	--
Primary Energy Use - Quadrillion Btu									
Coal	22.8	23.4	23.6	23.9	25.8	26.8	28.1	29.2	30.5
Natural Gas	23.2	23.7	24.2	25.4	25.3	26.0	26.5	27.0	27.6
Petroleum	38.2	38.2	37.7	37.7	39.2	40.0	40.5	40.9	41.1
Nuclear	8.4	8.6	9.0	9.0	9.4	9.4	9.4	9.4	9.4
Hydro	3.0	3.2	3.3	3.3	3.3	3.3	3.3	3.3	3.3
Renewable Elec.	1.1	1.5	2.2	2.6	2.8	2.9	3.0	3.1	3.2
Total *	**96.6**	**98.7**	**99.9**	**102.0**	**105.8**	**108.5**	**110.8**	**113.0**	**115.0**
	--	--	--	--	--	--	--	--	--
Energy Intensity - total *									
1000 btu per $ of GDP	7.29	6.40	5.73	5.16	4.68	4.25	3.88	3.54	3.25
Electricity Generation - billion kWh									
Fossil fuels w/o CCS	2,814	2,912	3,034	3,222	3,407	3,663	3,890	4,117	4,352
Nuclear	809	831	862	867	905	905	905	905	905
Hydro / Geothermal	286	314	316	317	320	320	320	320	320
Biomass / MSW	28	55	116	134	141	147	153	159	165
Wind / Solar	82	88	96	116	131	135	138	142	145
IGCC + CCS	0	0	0	0	0	0	0	0	0
CC + CCS	0	0	0	0	0	0	0	0	0
Total	**4,019**	**4,201**	**4,424**	**4,656**	**4,904**	**5,169**	**5,405**	**5,642**	**5,888**
% Change	--	--	--	--	--	--	--	--	--

* Note: only renewable energy used in electricity generation is included.

Table 7-2. United States (total) – Output and Energy Consumption

Industry	2010	2015	2020	2025	2030	2035	2040	2045	2050
Coal	$36,062	$38,268	$38,303	$39,164	$43,610	$45,761	$48,488	$50,805	$52,976
Crude Oil	$92,996	$125,016	$128,739	$132,205	$139,781	$142,478	$146,020	$148,842	$151,329
Electricity	$328,627	$346,781	$381,558	$420,781	$471,243	$505,050	$535,955	$568,592	$602,867
Natural Gas	$112,041	$117,996	$132,082	$149,521	$170,873	$177,990	$184,187	$190,252	$196,677
Petroleum	$492,849	$661,697	$676,552	$700,007	$771,343	$809,277	$842,683	$871,022	$895,819
Agriculture	$378,537	$488,973	$584,392	$651,625	$747,788	$839,394	$926,327	$1,010,023	$1,092,664
Energy-Intensive Manufacturing	$2,636,556	$3,047,074	$3,357,422	$3,579,242	$3,949,859	$4,308,650	$4,652,799	$4,988,232	$5,321,376
Other Manufacturing	$4,304,769	$5,534,441	$6,084,559	$6,858,950	$8,340,629	$9,780,500	$10,972,430	$12,167,216	$13,336,786
Services	$17,677,354	$20,503,446	$23,298,783	$26,555,181	$30,316,735	$34,226,318	$38,448,896	$42,990,597	$47,884,883
Transportation	$800,662	$936,875	$1,030,001	$1,143,953	$1,286,099	$1,421,064	$1,569,847	$1,726,830	$1,893,174

Sector	Fuel	2010	2015	2020	2025	2030	2035	2040	2045	2050
Residential	Electricity	4.81	4.85	5.11	5.39	5.68	5.87	6.01	6.12	6.20
	Natural Gas	4.80	4.88	4.96	4.99	4.93	4.77	4.58	4.37	4.15
	Oil - Heat	1.29	1.20	1.16	1.13	1.10	1.05	1.01	0.95	0.90
	Oil - Motor gas	16.24	15.67	15.08	14.36	14.31	13.99	13.59	13.13	12.64
	Total	**27.14**	**26.60**	**26.31**	**25.86**	**26.02**	**25.69**	**25.19**	**24.57**	**23.89**
Electricity	Coal	21.00	21.51	21.84	22.17	24.04	25.10	26.39	27.65	28.94
	Natural Gas	6.45	6.30	6.66	7.57	7.24	7.90	8.38	8.85	9.34
	Oil	0.49	0.50	0.50	0.50	0.51	0.56	0.60	0.63	0.66
	Total	**27.94**	**28.30**	**29.00**	**30.24**	**31.79**	**33.57**	**35.37**	**37.13**	**38.94**
Petroleum Refining	Crude Oil	30.38	30.37	30.48	30.43	31.31	32.09	32.61	32.97	33.21
	Electricity	0.16	0.17	0.17	0.17	0.17	0.18	0.19	0.20	0.21
	Natural Gas	1.10	1.37	1.41	1.40	1.41	1.42	1.45	1.51	1.61
	Oil	2.22	2.06	2.03	2.02	2.09	2.15	2.20	2.26	2.31
	Total	**33.85**	**33.96**	**34.09**	**34.02**	**34.99**	**35.84**	**36.46**	**36.95**	**37.34**
Agriculture	Coal	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Electricity	0.15	0.16	0.16	0.16	0.17	0.15	0.16	0.17	0.18
	Natural Gas	0.09	0.09	0.10	0.10	0.10	0.10	0.11	0.11	0.11
	Oil	0.78	0.79	0.78	0.78	0.81	0.82	0.84	0.84	0.84
	Total	**1.03**	**1.04**	**1.03**	**1.04**	**1.08**	**1.08**	**1.10**	**1.12**	**1.13**
Energy-Intensive Manufacturing	Coal	1.63	1.63	1.56	1.53	1.53	1.49	1.42	1.35	1.27
	Electricity	1.87	1.94	1.92	1.95	2.02	1.78	1.82	1.87	1.92
	Natural Gas	4.40	4.50	4.30	4.33	4.36	4.35	4.32	4.27	4.21
	Oil	3.67	2.80	2.43	2.40	2.40	2.40	2.37	2.35	2.32
	Total	**11.56**	**10.86**	**10.21**	**10.21**	**10.31**	**10.01**	**9.94**	**9.83**	**9.72**
Other Manufacturing	Coal	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.04	0.04
	Electricity	1.08	1.16	1.14	1.16	1.20	1.45	1.53	1.61	1.69
	Natural Gas	1.01	1.10	1.07	1.14	1.25	1.32	1.35	1.37	1.38
	Oil	1.48	1.91	1.80	1.80	1.91	1.99	2.01	2.02	2.03
	Total	**3.61**	**4.21**	**4.05**	**4.12**	**4.39**	**4.80**	**4.93**	**5.04**	**5.13**
Services	Coal	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.04
	Electricity	3.53	3.83	4.14	4.42	4.68	5.18	5.53	5.91	6.31
	Natural Gas	2.31	2.40	2.46	2.54	2.60	2.66	2.71	2.76	2.81
	Oil	0.41	0.41	0.41	0.41	0.41	0.42	0.42	0.43	0.43
	Total	**6.30**	**6.69**	**7.06**	**7.42**	**7.75**	**8.30**	**8.71**	**9.14**	**9.60**
Transportation	Coal	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Electricity	0.02	0.02	0.03	0.03	0.04	0.03	0.03	0.04	0.04
	Natural Gas	0.03	0.05	0.07	0.08	0.09	0.10	0.10	0.11	0.11
	Oil	10.02	11.32	11.87	12.66	13.88	14.86	15.67	16.39	17.01
	Total	**10.07**	**11.40**	**11.96**	**12.77**	**14.01**	**14.99**	**15.81**	**16.54**	**17.16**
Total	Coal	22.78	23.38	23.63	23.94	25.81	26.83	28.06	29.25	30.46
	Electricity	13.24	13.87	14.55	15.28	16.08	16.91	17.69	18.49	19.31
	Natural Gas	23.15	23.67	24.15	25.45	25.32	26.03	26.53	27.04	27.61
	Oil	38.15	38.25	37.71	37.74	39.15	40.02	40.53	40.87	41.06
	Total *	**97.33**	**99.17**	**100.03**	**102.40**	**106.37**	**109.79**	**112.81**	**115.64**	**118.45**

Table 7-3. Northeast U.S. – Macroeconomic

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Macroeconomic									
Population *(millions)*	63.1	64.2	65.1	65.7	66.1	65.8	65.1	64.3	63.3
GDP *(billion 2005$)*	$3,132	$3,611	$4,045	$4,557	$5,169	$5,763	$6,337	$6,924	$7,519
% Change in GDP	--	--	--	--	--	--	--	--	--
Consumption *(bill 2005$)*	$2,289	$2,621	$2,940	$3,283	$3,704	$4,107	$4,492	$4,873	$5,252
% Change in Consump	--	--	--	--	--	--	--	--	--
Allowance Price - \$/tCO_2e	--	--	--	--	--	--	--	--	--
Energy Prices - delivered (with allowance price)									
Coal *($ per MMBtu)*	$2.14	$2.21	$2.15	$2.19	$2.25	$2.26	$2.27	$2.29	$2.30
Electricity *($ per kWh)*	$0.110	$0.117	$0.121	$0.127	$0.134	$0.136	$0.138	$0.140	$0.143
Natural Gas *($ per MMBtu)*	$9.63	$9.85	$10.21	$10.57	$11.50	$11.64	$11.73	$11.84	$11.95
Petroleum *($ per MMBtu)*	$18.26	$23.76	$24.16	$24.89	$26.20	$26.79	$27.37	$27.96	$28.56
% Change in Coal	--	--	--	--	--	--	--	--	--
% Change in Electricity	--	--	--	--	--	--	--	--	--
% Change in Natural Gas	--	--	--	--	--	--	--	--	--
% Change In Petroleum	--	--	--	--	--	--	--	--	--
GHG Emissions - mmt CO_2e									
CO_2	844.7	838.2	829.8	828.3	846.2	870.0	874.2	877.7	881.1
CH_4	58.2	56.9	56.0	53.6	52.0	51.0	49.8	48.8	47.9
N_2O	33.5	32.6	31.8	30.6	28.4	26.8	25.7	24.3	23.1
HFC	27.4	36.6	46.2	44.2	42.4	40.5	39.0	38.6	38.2
PFC	1.2	1.1	1.0	1.0	1.1	1.1	1.1	1.1	1.1
SF_6	3.0	2.8	2.7	2.7	1.6	1.6	1.5	1.5	1.5
Total	**968**	**968**	**968**	**960**	**972**	**991**	**991**	**992**	**993**
% Change	--	--	--	--	--	--	--	--	--
Primary Energy Use - Quadrillion Btu									
Coal	2.0	2.0	2.0	2.0	2.3	2.5	2.6	2.7	2.8
Natural Gas	3.5	3.5	3.5	3.7	3.6	3.7	3.7	3.7	3.7
Petroleum	7.0	6.9	6.6	6.5	6.5	6.4	6.3	6.2	6.1
Nuclear	2.1	2.1	2.1	2.1	2.2	2.2	2.2	2.2	2.2
Hydro	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Renewable Elec.	0.3	0.5	0.8	0.8	0.9	0.9	1.0	1.0	1.0
Total *	**15.2**	**15.3**	**15.5**	**15.6**	**15.9**	**16.2**	**16.2**	**16.2**	**16.3**
							--	--	--
Energy Intensity - total *									
1000 btu per $ of GDP	4.86	4.24	3.84	3.42	3.07	2.80	2.56	2.35	2.16
		-2.67%	-1.98%	-2.29%	-2.16%	-1.77%	-1.83%	-1.71%	-1.60%
Electricity Generation - billion kWh									
Fossil fuels w/o CCS	328	318	309	329	341	389	411	432	455
Nuclear	202	204	206	206	214	214	214	214	214
Hydro / Geothermal	32	34	34	34	34	34	34	34	34
Biomass / MSW	19	32	65	71	74	77	80	83	87
Wind / Solar	11	14	14	12	14	14	14	15	15
IGCC + CCS	0	0	0	0	0	0	0	0	0
CC + CCS	0	0	0	0	0	0	0	0	0
Total	**592**	**604**	**628**	**652**	**677**	**729**	**754**	**779**	**805**
% Change	--	--	--	--	--	--	--	--	--

* Note: only renewable energy used in electricity generation is included.

Table 7-4. Southern U.S. – Macroeconomic

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Macroeconomic									
Population *(millions)*	71.9	76.4	81.0	86.0	91.3	95.7	99.9	104.0	107.9
GDP *(billion 2005$)*	$2,810	$3,313	$3,793	$4,339	$5,020	$5,745	$6,502	$7,331	$8,242
% Change in GDP	--	--	--	--	--	--	--	--	--
Consumption *(bill 2005$)*	$2,206	$2,585	$2,978	$3,412	$3,957	$4,541	$5,171	$5,857	$6,608
% Change in Consump	--	--	--	--	--	--	--	--	--
Allowance Price - $\$/\text{tCO}_2\text{e}$	--	--	--	--	--	--	--	--	--
Energy Prices - delivered (with allowance price)									
Coal *($ per MMBtu)*	$2.39	$2.48	$2.45	$2.50	$2.59	$2.61	$2.62	$2.63	$2.64
Electricity *($ per kWh)*	$0.078	$0.079	$0.081	$0.085	$0.090	$0.092	$0.093	$0.095	$0.096
Natural Gas *($ per MMBtu)*	$7.56	$7.90	$8.31	$8.74	$9.52	$9.66	$9.75	$9.84	$9.92
Petroleum *($ per MMBtu)*	$17.38	$22.85	$23.41	$24.20	$25.56	$26.18	$26.79	$27.39	$28.00
% Change in Coal	--	--	--	--	--	--	--	--	--
% Change in Electricity	--	--	--	--	--	--	--	--	--
% Change in Natural Gas	--	--	--	--	--	--	--	--	--
% Change In Petroleum	--	--	--	--	--	--	--	--	--
GHG Emissions - mmt CO_2e									
CO_2	1,352.1	1,373.1	1,395.4	1,427.7	1,512.1	1,614.8	1,680.0	1,743.1	1,804.8
CH_4	107.2	103.7	100.5	94.5	90.0	87.2	85.1	83.1	81.5
N_2O	69.9	66.0	62.3	58.2	53.2	48.9	46.1	42.8	40.2
HFC	31.3	43.5	57.5	57.6	57.9	57.3	56.4	56.7	56.8
PFC	0.9	0.8	0.8	0.8	0.9	0.9	1.0	1.0	1.0
SF_6	3.4	3.1	3.1	3.1	1.8	1.8	1.7	1.8	1.8
Total	**1,565**	**1,590**	**1,619**	**1,642**	**1,716**	**1,811**	**1,870**	**1,928**	**1,986**
% Change	--	--	--	--	--	--	--	--	--
Primary Energy Use - Quadrillion Btu									
Coal	5.3	5.4	5.5	5.6	6.2	6.8	7.3	7.7	8.1
Natural Gas	4.5	4.5	4.6	4.9	4.8	5.1	5.2	5.4	5.6
Petroleum	9.1	9.2	9.2	9.4	9.9	10.3	10.5	10.7	10.9
Nuclear	3.1	3.2	3.5	3.5	3.9	3.9	3.9	3.9	3.9
Hydro	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Renewable Elec.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total *	**22.3**	**22.8**	**23.3**	**23.8**	**25.2**	**26.5**	**27.4**	**28.1**	**28.9**
							--	--	--
Energy Intensity - total *									
1000 btu per $ of GDP	7.93	6.87	6.14	5.50	5.03	4.62	4.21	3.84	3.51
		-2.82%	-2.25%	-2.17%	-1.78%	-1.68%	-1.85%	-1.82%	-1.79%
Electricity Generation - billion kWh									
Fossil fuels w/o CCS	742	785	836	907	947	1,068	1,148	1,231	1,316
Nuclear	293	309	334	339	377	377	377	377	377
Hydro / Geothermal	36	39	39	39	39	39	39	39	39
Biomass / MSW	3	3	3	3	4	4	4	4	4
Wind / Solar	0	0	0	0	0	0	0	0	0
IGCC + CCS	0	0	0	0	0	0	0	0	0
CC + CCS	0	0	0	0	0	0	0	0	0
Total	**1,075**	**1,136**	**1,213**	**1,288**	**1,367**	**1,488**	**1,568**	**1,651**	**1,736**
% Change	--	--	--	--	--	--	--	--	--

* Note: only renewable energy used in electricity generation is included.

Table 7-5. Midwest U.S. – Macroeconomic

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Macroeconomic									
Population *(millions)*	62.1	63.0	63.7	64.0	64.3	63.8	63.0	62.0	60.9
GDP *(billion 2005$)*	$2,394	$2,768	$3,071	$3,412	$3,837	$4,254	$4,636	$5,027	$5,425
% Change in GDP	--	--	--	--	--	--	--	--	--
Consumption *(bill 2005$)*	$1,928	$2,200	$2,459	$2,730	$3,063	$3,382	$3,685	$3,984	$4,281
% Change in Consump	--	--	--	--	--	--	--	--	--
Allowance Price - \$/tCO$_2$e	--	--	--	--	--	--	--	--	--
Energy Prices - delivered (with allowance price)									
Coal *($ per MMBtu)*	$1.67	$1.74	$1.71	$1.74	$1.80	$1.81	$1.81	$1.81	$1.81
Electricity *($ per kWh)*	$0.074	$0.075	$0.079	$0.083	$0.088	$0.090	$0.091	$0.092	$0.094
Natural Gas *($ per MMBtu)*	$9.00	$9.10	$9.43	$9.62	$10.42	$10.50	$10.52	$10.59	$10.68
Petroleum *($ per MMBtu)*	$17.93	$23.53	$23.97	$24.67	$25.93	$26.47	$27.02	$27.59	$28.18
% Change in Coal	--	--	--	--	--	--	--	--	--
% Change in Electricity	--	--	--	--	--	--	--	--	--
% Change in Natural Gas	--	--	--	--	--	--	--	--	--
% Change In Petroleum	--	--	--	--	--	--	--	--	--
GHG Emissions - mmt CO$_2$e									
CO$_2$	1,542.2	1,559.0	1,532.9	1,521.8	1,548.6	1,487.8	1,494.6	1,501.6	1,509.7
CH$_4$	112.3	106.7	106.0	103.0	100.6	94.1	90.5	87.0	83.9
N$_2$O	81.1	81.0	80.4	77.8	72.6	66.8	62.7	58.0	54.2
HFC	58.9	79.5	100.1	95.4	90.8	86.5	83.0	81.8	80.8
PFC	1.4	1.3	1.2	1.1	1.1	1.1	1.1	1.1	1.0
SF$_6$	3.7	3.3	3.2	3.2	2.3	2.2	2.2	2.1	2.1
Total	**1,800**	**1,831**	**1,824**	**1,802**	**1,816**	**1,738**	**1,734**	**1,731**	**1,732**
% Change	--	--	--	--	--	--	--	--	--
Primary Energy Use - Quadrillion Btu									
Coal	8.6	8.8	8.7	8.6	8.8	8.2	8.3	8.5	8.6
Natural Gas	4.2	4.2	4.2	4.3	4.3	4.2	4.1	4.0	3.9
Petroleum	7.2	7.1	6.9	6.8	6.9	7.0	7.0	6.9	6.9
Nuclear	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7
Hydro	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Renewable Elec.	0.3	0.4	0.6	0.9	1.0	1.0	1.1	1.1	1.1
Total *	**22.0**	**22.4**	**22.2**	**22.4**	**22.8**	**22.2**	**22.2**	**22.3**	**22.3**
							--	--	--
Energy Intensity - total *									
1000 btu per $ of GDP	9.21	8.08	7.24	6.58	5.94	5.21	4.79	4.43	4.12
		-2.59%	-2.15%	-1.91%	-2.01%	-2.60%	-1.66%	-1.56%	-1.46%
Electricity Generation - billion kWh									
Fossil fuels w/o CCS	827	855	877	897	950	923	953	984	1,018
Nuclear	166	166	167	167	160	160	160	160	160
Hydro / Geothermal	6	6	8	8	9	9	9	9	9
Biomass / MSW	2	12	28	32	36	37	39	40	42
Wind / Solar	25	28	35	58	63	64	66	68	69
IGCC + CCS	0	0	0	0	0	0	0	0	0
CC + CCS	0	0	0	0	0	0	0	0	0
Total	**1,026**	**1,068**	**1,114**	**1,163**	**1,217**	**1,193**	**1,226**	**1,261**	**1,298**
% Change	--	--	--	--	--	--	--	--	--

* Note: only renewable energy used in electricity generation is included.

Table 7-6. Plains U.S. – Macroeconomic

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Macroeconomic									
Population *(millions)*	39.7	42.0	44.4	46.9	49.7	52.0	54.2	56.3	58.3
GDP *(billion 2005$)*	$1,726	$2,011	$2,290	$2,609	$3,011	$3,447	$3,889	$4,383	$4,935
% Change in GDP	--	--	--	--	--	--	--	--	--
Consumption *(bill 2005$)*	$1,287	$1,492	$1,706	$1,941	$2,236	$2,553	$2,898	$3,274	$3,686
% Change in Consump	--	--	--	--	--	--	--	--	--
Allowance Price - $/t$CO_2$e	--	--	--	--	--	--	--	--	--
Energy Prices - delivered (with allowance price)									
Coal *($ per MMBtu)*	$1.34	$1.41	$1.41	$1.43	$1.48	$1.49	$1.48	$1.48	$1.49
Electricity *($ per kWh)*	$0.079	$0.081	$0.088	$0.092	$0.099	$0.100	$0.102	$0.103	$0.105
Natural Gas *($ per MMBtu)*	$6.34	$6.56	$6.90	$7.22	$7.90	$7.98	$8.04	$8.12	$8.21
Petroleum *($ per MMBtu)*	$16.46	$22.32	$22.82	$23.63	$25.08	$25.71	$26.36	$27.00	$27.66
% Change in Coal	--	--	--	--	--	--	--	--	--
% Change in Electricity	--	--	--	--	--	--	--	--	--
% Change in Natural Gas	--	--	--	--	--	--	--	--	--
% Change In Petroleum	--	--	--	--	--	--	--	--	--
GHG Emissions - mmt CO_2e									
CO_2	1,170.7	1,195.0	1,208.1	1,247.3	1,303.3	1,364.3	1,405.0	1,445.8	1,488.8
CH_4	137.9	147.5	156.2	160.3	169.5	175.3	178.4	177.1	174.8
N_2O	86.2	100.7	118.7	139.6	163.8	173.8	178.4	176.2	172.0
HFC	28.7	38.8	49.3	47.5	45.6	43.8	42.2	41.7	41.3
PFC	0.9	0.7	0.7	0.8	0.8	0.9	0.9	0.9	0.9
SF_6	2.1	2.0	1.9	1.9	3.0	2.9	2.9	2.9	2.9
Total	**1,426**	**1,485**	**1,535**	**1,597**	**1,686**	**1,761**	**1,808**	**1,845**	**1,881**
% Change	--	--	--	--	--	--	--	--	--
Primary Energy Use - Quadrillion Btu									
Coal	4.2	4.3	4.5	4.8	5.2	5.6	5.8	6.1	6.4
Natural Gas	5.5	5.7	5.8	5.9	5.9	6.1	6.3	6.4	6.6
Petroleum	7.1	7.0	6.9	6.9	7.2	7.4	7.5	7.6	7.7
Nuclear	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Hydro	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Renewable Elec.	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.3
Total *	**17.9**	**18.2**	**18.4**	**18.8**	**19.5**	**20.3**	**20.8**	**21.3**	**21.9**
							--	--	--
Energy Intensity - total *									
1000 btu per $ of GDP	10.38	9.08	8.02	7.21	6.48	5.89	5.35	4.87	4.44
		-2.65%	-2.45%	-2.10%	-2.11%	-1.89%	-1.90%	-1.88%	-1.84%
Electricity Generation - billion kWh									
Fossil fuels w/o CCS	498	526	556	594	629	677	715	754	796
Nuclear	72	73	75	75	74	74	74	74	74
Hydro / Geothermal	14	15	15	15	15	15	15	15	15
Biomass / MSW	1	1	1	1	1	1	1	1	1
Wind / Solar	26	25	24	21	22	22	23	23	24
IGCC + CCS	0	0	0	0	0	0	0	0	0
CC + CCS	0	0	0	0	0	0	0	0	0
Total	**610**	**639**	**669**	**704**	**740**	**789**	**827**	**867**	**910**
% Change	--	--	--	--	--	--	--	--	--

* Note: only renewable energy used in electricity generation is included.

Table 7-7. Western U.S. – Macroeconomic

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Macroeconomic									
Population *(millions)*	72.2	76.8	81.6	86.8	92.1	96.6	100.9	105.0	109.1
GDP *(billion 2005$)*	$3,184	$3,718	$4,231	$4,851	$5,581	$6,329	$7,231	$8,202	$9,257
% Change in GDP	--	--	--	--	--	--	--	--	--
Consumption *(bill 2005$)*	$2,295	$2,677	$3,086	$3,546	$4,120	$4,725	$5,409	$6,136	$6,925
% Change in Consump	--	--	--	--	--	--	--	--	--
Allowance Price - $/t$CO_2$e	--	--	--	--	--	--	--	--	--
Energy Prices - delivered (with allowance price)									
Coal *($ per MMBtu)*	$1.49	$1.54	$1.51	$1.54	$1.62	$1.62	$1.62	$1.63	$1.64
Electricity *($ per kWh)*	$0.093	$0.088	$0.092	$0.095	$0.101	$0.102	$0.104	$0.107	$0.109
Natural Gas *($ per MMBtu)*	$7.96	$8.14	$8.56	$8.97	$9.85	$9.95	$10.16	$10.32	$10.45
Petroleum *($ per MMBtu)*	$18.53	$24.18	$24.72	$25.57	$27.00	$27.53	$28.41	$29.15	$29.83
% Change in Coal	--	--	--	--	--	--	--	--	--
% Change in Electricity	--	--	--	--	--	--	--	--	--
% Change in Natural Gas	--	--	--	--	--	--	--	--	--
% Change In Petroleum	--	--	--	--	--	--	--	--	--
GHG Emissions - mmt CO_2e									
CO_2	1,086.0	1,123.2	1,142.3	1,188.2	1,270.8	1,339.8	1,405.2	1,458.6	1,507.2
CH_4	143.3	147.9	157.2	162.8	164.4	164.9	165.4	164.0	163.1
N_2O	101.8	100.9	98.6	94.5	91.6	84.6	79.6	73.8	69.0
HFC	23.1	31.9	42.1	42.1	42.4	42.0	41.3	41.5	41.6
PFC	1.7	1.5	1.4	1.5	1.7	1.8	1.9	1.9	1.9
SF_6	2.8	2.6	2.6	2.6	4.8	4.7	4.7	4.7	4.7
Total	**1,359**	**1,408**	**1,444**	**1,492**	**1,576**	**1,638**	**1,698**	**1,744**	**1,787**
% Change	--	--	--	--	--	--	--	--	--
Primary Energy Use - Quadrillion Btu									
Coal	2.8	2.8	2.8	2.8	3.3	3.7	4.0	4.3	4.6
Natural Gas	5.5	5.7	6.1	6.6	6.6	6.9	7.2	7.5	7.8
Petroleum	7.8	8.1	8.1	8.2	8.7	8.9	9.2	9.4	9.5
Nuclear	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Hydro	2.1	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3
Renewable Elec.	0.2	0.3	0.4	0.5	0.6	0.6	0.7	0.7	0.7
Total *	**19.1**	**20.0**	**20.5**	**21.3**	**22.4**	**23.3**	**24.2**	**25.0**	**25.7**
							--	--	--
Energy Intensity - total *									
1000 btu per $ of GDP	6.01	5.37	4.84	4.39	4.01	3.69	3.35	3.04	2.77
		-2.21%	-2.06%	-1.93%	-1.78%	-1.68%	-1.90%	-1.90%	-1.87%
Electricity Generation - billion kWh									
Fossil fuels w/o CCS	419	428	457	496	540	606	663	716	768
Nuclear	76	80	79	79	79	79	79	79	79
Hydro / Geothermal	198	219	220	222	223	223	223	223	223
Biomass / MSW	3	6	20	27	27	28	29	30	32
Wind / Solar	20	21	24	24	33	34	35	36	37
IGCC + CCS	0	0	0	0	0	0	0	0	0
CC + CCS	0	0	0	0	0	0	0	0	0
Total	**716**	**754**	**800**	**848**	**902**	**970**	**1,030**	**1,084**	**1,139**
% Change	--	--	--	--	--	--	--	--	--

* Note: only renewable energy used in electricity generation is included.

Table 7-8. Europe – Macroeconomic

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Macroeconomic									
Population *(millions)*	542.4	547.5	550.7	552.5	553.0	552.2	550.4	547.6	543.9
GDP *(billion 2005$)*	$16,161	$17,977	$19,886	$21,883	$23,969	$26,254	$28,754	$31,466	$34,402
% Change in GDP	--	--	--	--	--	--	--	--	--
Consumption *(bill 2005$)*	$10,946	$12,250	$13,590	$14,979	$16,423	$17,983	$19,671	$21,467	$23,375
% Change in Consump	--	--	--	--	--	--	--	--	--
Allowance Price - \$/tCO_2e	--	--	--	--	--	--	--	--	--
Energy Prices - delivered (with allowance price)									
Coal *($ per MMBtu)*	$5.89	$5.74	$5.57	$5.41	$5.25	$5.19	$5.15	$5.13	$5.11
Electricity *($ per kWh)*	$0.170	$0.172	$0.182	$0.188	$0.194	$0.196	$0.197	$0.199	$0.201
Natural Gas *($ per MMBtu)*	$17.98	$18.05	$18.79	$19.09	$19.33	$19.25	$19.20	$19.19	$19.21
Petroleum *($ per MMBtu)*	$19.75	$21.99	$22.06	$22.22	$22.64	$22.65	$22.69	$22.10	$21.42
% Change in Coal	--	--	--	--	--	--	--	--	--
% Change in Electricity	--	--	--	--	--	--	--	--	--
% Change in Natural Gas	--	--	--	--	--	--	--	--	--
% Change In Petroleum	--	--	--	--	--	--	--	--	--
GHG Emissions - mmt CO_2e									
CO_2	4,544.9	4,609.7	4,559.4	4,472.4	4,353.0	4,262.8	4,236.3	4,225.9	4,247.8
CH_4	461.5	459.7	460.7	459.3	460.7	452.5	444.8	440.0	435.5
N_2O	457.8	459.7	470.4	488.0	508.2	506.6	505.3	496.6	488.4
HFC	69.2	99.5	103.4	100.1	97.4	93.3	89.4	88.5	87.6
PFC	10.1	8.7	8.6	8.8	8.9	9.1	9.2	9.2	9.2
SF_6	2.3	1.9	1.7	1.7	1.7	1.6	1.6	1.6	1.6
Total	**5,546**	**5,639**	**5,604**	**5,530**	**5,430**	**5,326**	**5,287**	**5,262**	**5,270**
% Change	--	--	--	--	--	--	--	--	--
Primary Energy Use - Quadrillion Btu									
Coal	15.3	15.6	15.1	14.4	13.2	12.6	12.4	12.2	12.2
Natural Gas	21.4	22.7	23.4	24.0	24.9	24.4	24.3	24.3	24.4
Petroleum	29.9	29.3	28.5	27.8	26.8	26.7	26.7	26.8	27.1
Nuclear	9.3	8.8	7.9	7.3	6.6	6.4	6.3	6.2	6.2
Hydro	5.6	6.2	6.7	7.0	7.2	7.4	7.6	7.8	8.0
Renewable Elec.	2.6	4.6	6.0	7.2	8.5	9.6	10.0	10.5	11.0
Total *	**84.2**	**87.2**	**87.6**	**87.6**	**87.1**	**87.1**	**87.3**	**87.8**	**88.8**
							--	--	--
Energy Intensity - total *									
1000 btu per $ of GDP	5.21	4.85	4.40	4.00	3.64	3.32	3.04	2.79	2.58
		-1.42%	-1.91%	-1.89%	-1.91%	-1.81%	-1.76%	-1.68%	-1.55%
Electricity Generation - billion kWh									
Fossil fuels w/o CCS	1,814	1,886	1,959	2,008	2,061	1,942	1,906	1,882	1,872
Nuclear	893	846	760	703	632	613	607	601	595
Hydro / Geothermal	545	602	646	677	697	718	735	753	771
Biomass / MSW	116	148	175	203	220	234	250	266	284
Wind / Solar	140	296	405	495	605	702	727	754	782
IGCC + CCS	0	0	0	0	0	0	0	0	0
CC + CCS	0	0	0	0	0	0	0	0	0
Total	**3,508**	**3,778**	**3,943**	**4,087**	**4,215**	**4,210**	**4,225**	**4,256**	**4,305**
% Change	--	--	--	--	--	--	--	--	--

* Note: only renewable energy used in electricity generation is included.

Table 7-9. Canada – Macroeconomic

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Macroeconomic									
Population *(millions)*	33.8	35.2	36.6	37.9	39.1	40.1	41.1	41.9	42.8
GDP *(billion 2005$)*	$1,314	$1,492	$1,686	$1,903	$2,144	$2,390	$2,659	$2,954	$3,280
% Change in GDP	--	--	--	--	--	--	--	--	--
Consumption *(bill 2005$)*	$807	$920	$1,051	$1,195	$1,355	$1,533	$1,726	$1,936	$2,168
% Change in Consump	--	--	--	--	--	--	--	--	--
Allowance Price - $/tCO$_2$e	--	--	--	--	--	--	--	--	--
Energy Prices - delivered (with allowance price)									
Coal *($ per MMBtu)*	$2.12	$2.13	$2.12	$2.08	$2.05	$2.06	$2.08	$2.10	$2.12
Electricity *($ per kWh)*	$0.098	$0.100	$0.105	$0.108	$0.111	$0.112	$0.113	$0.114	$0.115
Natural Gas *($ per MMBtu)*	$14.16	$14.52	$15.34	$15.78	$16.26	$16.46	$16.67	$16.87	$17.08
Petroleum *($ per MMBtu)*	$17.04	$19.07	$19.23	$19.52	$20.04	$20.23	$20.44	$20.66	$20.89
% Change in Coal	--	--	--	--	--	--	--	--	--
% Change in Electricity	--	--	--	--	--	--	--	--	--
% Change in Natural Gas	--	--	--	--	--	--	--	--	--
% Change In Petroleum	--	--	--	--	--	--	--	--	--
GHG Emissions - mmt CO$_2$e									
CO$_2$	612.7	667.3	708.1	716.5	722.2	739.7	775.1	815.3	861.5
CH$_4$	108.0	116.3	124.2	123.6	123.4	123.0	122.6	122.3	122.1
N$_2$O	62.4	68.0	73.8	77.4	81.3	81.1	80.9	79.4	78.1
HFC	9.4	13.0	16.7	16.1	15.4	14.9	14.3	14.2	14.2
PFC	2.8	2.9	3.6	3.6	3.6	3.7	3.7	3.7	3.7
SF$_6$	1.9	1.9	1.9	1.8	1.8	1.8	1.7	1.7	1.7
Total	**797**	**869**	**928**	**939**	**948**	**964**	**998**	**1,037**	**1,081**
% Change	--	--	--	--	--	--	--	--	--
Primary Energy Use - Quadrillion Btu									
Coal	1.4	1.6	1.7	1.6	1.4	1.4	1.5	1.7	1.9
Natural Gas	3.6	4.0	4.4	4.7	5.2	5.3	5.5	5.8	6.1
Petroleum	4.2	4.4	4.6	4.7	4.7	4.8	4.9	5.1	5.3
Nuclear	0.9	0.9	0.9	1.0	1.0	1.0	1.0	0.9	0.9
Hydro	3.2	3.3	3.4	3.4	3.5	3.6	3.6	3.7	3.7
Renewable Elec.	0.2	0.4	0.6	0.8	1.0	1.2	1.1	1.1	1.1
Total *	**13.5**	**14.5**	**15.5**	**16.2**	**16.8**	**17.3**	**17.8**	**18.3**	**19.0**
							--	--	--
Energy Intensity - total *									
1000 btu per $ of GDP	10.26	9.73	9.22	8.51	7.83	7.22	6.68	6.20	5.79
		-1.04%	-1.07%	-1.59%	-1.67%	-1.59%	-1.56%	-1.46%	-1.37%
Electricity Generation - billion kWh									
Fossil fuels w/o CCS	186	229	247	276	298	304	334	367	404
Nuclear	85	83	91	99	99	96	94	91	89
Hydro / Geothermal	311	318	325	332	339	345	350	355	359
Biomass / MSW	10	11	13	16	19	20	21	22	22
Wind / Solar	7	24	42	60	81	96	90	85	80
IGCC + CCS	0	0	0	0	0	0	0	0	0
CC + CCS	0	0	0	0	0	0	0	0	0
Total	**599**	**665**	**718**	**783**	**836**	**861**	**888**	**919**	**955**
% Change	--	--	--	--	--	--	--	--	--

* Note: only renewable energy used in electricity generation is included.

Table 7-10. Pacific (Japan/Australia/New Zealand) – Macroeconomic

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Macroeconomic									
Population *(millions)*	153.4	153.5	152.5	150.8	148.4	145.6	142.5	139.2	135.8
GDP *(billion 2005$)*	$4,962	$5,419	$5,899	$6,414	$6,955	$7,521	$8,114	$8,734	$9,396
% Change in GDP	--	--	--	--	--	--	--	--	--
Consumption *(bill 2005$)*	$3,428	$3,755	$4,083	$4,429	$4,795	$5,175	$5,568	$5,971	$6,389
% Change in Consump	--	--	--	--	--	--	--	--	--
Allowance Price - $/t$CO_2$e	--	--	--	--	--	--	--	--	--
Energy Prices - delivered (with allowance price)									
Coal *($ per MMBtu)*	$4.18	$4.14	$4.04	$3.94	$3.85	$3.82	$3.80	$3.78	$3.77
Electricity *($ per kWh)*	$0.215	$0.218	$0.229	$0.236	$0.242	$0.244	$0.246	$0.248	$0.251
Natural Gas *($ per MMBtu)*	$20.20	$20.18	$20.79	$20.90	$20.94	$20.71	$20.55	$20.43	$20.35
Petroleum *($ per MMBtu)*	$16.34	$18.32	$18.48	$18.02	$17.72	$17.45	$17.24	$17.09	$16.96
% Change in Coal	--	--	--	--	--	--	--	--	--
% Change in Electricity	--	--	--	--	--	--	--	--	--
% Change in Natural Gas	--	--	--	--	--	--	--	--	--
% Change In Petroleum	--	--	--	--	--	--	--	--	--
GHG Emissions - mmt CO_2e									
CO_2	1,738.7	1,759.0	1,755.9	1,722.3	1,656.5	1,607.2	1,579.3	1,556.9	1,541.3
CH_4	185.6	192.8	199.9	195.4	191.5	187.5	183.8	182.4	181.1
N_2O	89.3	91.5	97.3	101.7	107.2	106.0	105.1	102.5	100.2
HFC	42.7	52.6	60.7	58.1	55.6	53.4	51.4	51.1	50.8
PFC	7.7	7.2	7.3	7.5	7.8	8.0	8.2	8.3	8.3
SF_6	1.2	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Total	**2,065**	**2,104**	**2,122**	**2,086**	**2,020**	**1,963**	**1,929**	**1,902**	**1,883**
% Change	--	--	--	--	--	--	--	--	--
Primary Energy Use - Quadrillion Btu									
Coal	7.4	7.7	7.8	7.6	7.3	7.0	6.9	6.8	6.7
Natural Gas	4.8	5.2	5.8	6.2	6.4	6.1	6.0	5.9	5.9
Petroleum	11.2	10.8	10.2	9.6	9.0	8.9	8.8	8.7	8.6
Nuclear	3.3	3.6	3.8	4.1	4.0	4.1	4.1	4.0	4.0
Hydro	1.4	1.5	1.5	1.6	1.6	1.6	1.6	1.6	1.7
Renewable Elec.	0.3	0.4	0.5	0.6	0.7	0.8	0.8	0.8	0.8
Total *	**28.4**	**29.2**	**29.6**	**29.8**	**29.0**	**28.6**	**28.2**	**27.9**	**27.7**
							--	--	--
Energy Intensity - total *									
1000 btu per $ of GDP	5.72	5.38	5.02	4.64	4.17	3.80	3.48	3.19	2.95
		-1.21%	-1.41%	-1.54%	-2.11%	-1.85%	-1.77%	-1.67%	-1.59%
Electricity Generation - billion kWh									
Fossil fuels w/o CCS	861	894	916	932	958	914	897	883	874
Nuclear	314	346	363	393	383	394	391	389	389
Hydro / Geothermal	139	146	149	154	157	158	158	159	160
Biomass / MSW	24	27	31	35	39	43	45	47	49
Wind / Solar	4	10	17	24	31	36	35	34	33
IGCC + CCS	0	0	0	0	0	0	0	0	0
CC + CCS	0	0	0	0	0	0	0	0	0
Total	**1,342**	**1,423**	**1,476**	**1,539**	**1,567**	**1,545**	**1,526**	**1,512**	**1,505**
% Change	--	--	--	--	--	--	--	--	--

* Note: only renewable energy used in electricity generation is included.

Table 7-11. China – Macroeconomic

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Macroeconomic									
Population *(millions)*	1,351.5	1,388.6	1,421.3	1,445.8	1,458.4	1,469.8	1,479.9	1,488.7	1,496.1
GDP *(billion 2005$)*	$3,507	$4,660	$6,164	$7,926	$9,976	$12,039	$14,075	$16,209	$18,401
% Change in GDP	--	--	--	--	--	--	--	--	--
Consumption *(bill 2005$)*	$1,700	$2,422	$3,308	$4,352	$5,590	$6,849	$8,093	$9,394	$10,724
% Change in Consump	--	--	--	--	--	--	--	--	--
Allowance Price - $/tCO$_2$e	--	--	--	--	--	--	--	--	--
Energy Prices - delivered (with allowance price)									
Coal *($ per MMBtu)*	$3.74	$3.72	$3.66	$3.60	$3.54	$3.56	$3.57	$3.58	$3.59
Electricity *($ per kWh)*	$0.058	$0.059	$0.062	$0.064	$0.066	$0.066	$0.067	$0.067	$0.068
Natural Gas *($ per MMBtu)*	$1.78	$1.86	$1.97	$2.03	$2.09	$2.11	$2.12	$2.13	$2.13
Petroleum *($ per MMBtu)*	$17.77	$20.33	$20.61	$21.05	$21.79	$22.07	$22.31	$22.50	$22.67
% Change in Coal	--	--	--	--	--	--	--	--	--
% Change in Electricity	--	--	--	--	--	--	--	--	--
% Change in Natural Gas	--	--	--	--	--	--	--	--	--
% Change In Petroleum	--	--	--	--	--	--	--	--	--
GHG Emissions - mmt CO$_2$e									
CO$_2$	6,638.2	8,200.2	9,116.0	9,898.5	10,485.0	11,423.3	12,223.0	12,926.4	13,520.5
CH$_4$	876.1	943.6	1,009.0	1,044.9	1,086.4	1,081.0	1,077.0	1,066.6	1,056.7
N$_2$O	719.3	761.9	806.8	834.6	863.9	869.1	874.7	867.6	860.9
HFC	55.6	102.1	116.6	113.7	111.9	112.6	114.4	115.0	115.7
PFC	18.5	15.6	14.0	14.7	15.5	16.2	16.9	17.0	17.1
SF$_6$	10.6	14.2	18.7	20.8	23.2	24.7	26.2	26.3	26.4
Total	**8,318**	**10,038**	**11,081**	**11,927**	**12,586**	**13,527**	**14,332**	**15,019**	**15,597**
% Change	--	--	--	--	--	--	--	--	--
Primary Energy Use - Quadrillion Btu									
Coal	58.7	71.7	79.0	84.5	87.7	95.2	101.7	107.4	112.0
Natural Gas	3.3	4.7	5.7	6.8	7.8	8.6	9.3	9.9	10.4
Petroleum	16.2	19.9	22.3	25.1	28.1	31.1	33.5	35.7	37.7
Nuclear	1.1	2.0	2.5	2.9	3.5	4.3	4.7	5.2	5.7
Hydro	4.8	6.3	7.3	8.2	9.0	10.4	11.7	13.3	15.0
Renewable Elec.	0.2	0.3	0.5	1.1	3.4	4.5	4.8	5.1	5.5
Total *	**84.3**	**105.0**	**117.2**	**128.5**	**139.4**	**154.0**	**165.7**	**176.5**	**186.4**
							--	--	--
Energy Intensity - total *									
1000 btu per $ of GDP	24.03	22.54	19.02	16.22	13.98	12.80	11.77	10.89	10.13
		-1.28%	-3.34%	-3.14%	-2.93%	-1.75%	-1.65%	-1.55%	-1.44%
Electricity Generation - billion kWh									
Fossil fuels w/o CCS	2,721	3,734	4,452	5,057	5,393	5,818	6,210	6,536	6,787
Nuclear	103	197	236	281	333	414	453	497	544
Hydro / Geothermal	462	609	703	789	868	1,003	1,135	1,285	1,454
Biomass / MSW	8	21	33	71	130	163	182	203	226
Wind / Solar	10	13	18	34	202	271	283	296	309
IGCC + CCS	0	0	0	0	0	0	0	0	0
CC + CCS	0	0	0	0	0	0	0	0	0
Total	**3,304**	**4,572**	**5,441**	**6,232**	**6,926**	**7,669**	**8,264**	**8,816**	**9,321**
% Change	--	--	--	--	--	--	--	--	--

* Note: only renewable energy used in electricity generation is included.

Table 7-12. Rest of World – Macroeconomic

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Macroeconomic									
Population *(millions)*	4,510.8	4,841.4	5,163.5	5,468.6	5,752.6	6,014.3	6,255.3	6,471.4	6,657.6
GDP *(billion 2005$)*	$11,416	$13,788	$16,517	$19,646	$23,237	$27,108	$31,199	$35,569	$40,216
% Change in GDP	--	--	--	--	--	--	--	--	--
Consumption *(bill 2005$)*	$6,879	$8,603	$10,601	$12,877	$15,498	$18,334	$21,363	$24,620	$28,071
% Change in Consump	--	--	--	--	--	--	--	--	--
Allowance Price - $/tCO$_2$e	--	--	--	--	--	--	--	--	--
Energy Prices - delivered (with allowance price)									
Coal *($ per MMBtu)*	$2.82	$2.82	$2.80	$2.76	$2.74	$2.75	$2.76	$2.77	$2.78
Electricity *($ per kWh)*	$0.098	$0.099	$0.105	$0.109	$0.112	$0.113	$0.114	$0.115	$0.116
Natural Gas *($ per MMBtu)*	$6.93	$7.05	$7.42	$7.64	$7.87	$7.97	$8.07	$8.17	$8.26
Petroleum *($ per MMBtu)*	$12.68	$14.21	$14.38	$14.66	$14.88	$14.71	$14.66	$14.75	$14.80
% Change in Coal	--	--	--	--	--	--	--	--	--
% Change in Electricity	--	--	--	--	--	--	--	--	--
% Change in Natural Gas	--	--	--	--	--	--	--	--	--
% Change In Petroleum	--	--	--	--	--	--	--	--	--
GHG Emissions - mmt CO$_2$e									
CO$_2$	10,717.2	12,045.3	13,160.4	14,444.8	15,722.3	16,575.2	17,527.9	18,426.1	19,266.4
CH$_4$	4,519.7	4,907.5	5,348.9	5,569.8	5,816.0	5,957.1	6,110.6	6,101.5	6,093.9
N$_2$O	1,773.1	1,959.7	2,173.7	2,238.1	2,306.1	2,323.4	2,341.2	2,329.9	2,319.2
HFC	110.5	150.8	191.5	199.8	208.8	222.1	236.5	239.4	242.4
PFC	32.8	32.8	33.5	35.2	37.0	38.6	40.3	40.5	40.8
SF$_6$	20.1	22.8	25.9	29.4	33.2	35.4	37.8	37.9	38.1
Total	**17,173**	**19,119**	**20,934**	**22,517**	**24,123**	**25,152**	**26,294**	**27,175**	**28,001**
% Change	--	--	--	--	--	--	--	--	--
Primary Energy Use - Quadrillion Btu									
Coal	35.2	40.1	44.6	50.0	54.9	56.8	59.8	62.5	65.0
Natural Gas	61.2	69.1	75.9	84.3	93.8	98.3	103.9	109.3	114.3
Petroleum	63.4	70.1	75.0	79.9	84.4	90.8	96.6	102.0	107.3
Nuclear	5.5	7.0	7.8	8.8	9.6	11.8	13.1	14.6	16.4
Hydro	12.0	13.4	15.0	16.6	18.4	20.5	22.0	23.7	25.5
Renewable Elec.	0.8	1.8	2.8	3.9	6.8	8.9	9.7	10.7	11.9
Total *	**178.3**	**201.5**	**221.1**	**243.6**	**267.8**	**287.1**	**305.1**	**322.9**	**340.3**
							--	--	--
Energy Intensity - total *									
1000 btu per $ of GDP	15.62	14.61	13.38	12.40	11.53	10.59	9.78	9.08	8.46
		-1.32%	-1.74%	-1.51%	-1.45%	-1.68%	-1.58%	-1.48%	-1.39%
Electricity Generation - billion kWh									
Fossil fuels w/o CCS	4,246	5,036	5,736	6,529	7,369	7,538	7,914	8,245	8,518
Nuclear	534	668	750	849	924	1,130	1,260	1,408	1,579
Hydro / Geothermal	1,164	1,297	1,447	1,609	1,776	1,981	2,131	2,294	2,471
Biomass / MSW	47	84	131	176	244	307	353	405	465
Wind / Solar	34	89	141	205	414	555	595	639	688
IGCC + CCS	0	0	0	0	0	0	0	0	0
CC + CCS	0	0	0	0	0	0	0	0	0
Total	**6,025**	**7,175**	**8,205**	**9,368**	**10,729**	**11,512**	**12,252**	**12,991**	**13,721**
% Change	--	--	--	--	--	--	--	--	--

* Note: only renewable energy used in electricity generation is included.

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REFERENCES

Andriamananjara, S., E.J. Balistreri, and M.T. Ross. 2006. "State-Level Equity and the Demise of the Agreement on Textiles and Clothing." *North American Journal of Economics and Finance* 17(1):17-33.

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

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

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

Asian Development Bank. 2005. *Country Tables*. <http://www.adb.org/Documents/Books/Key_Indicators/2004/default.asp>.

Auerbach, A.J. 1983. "Corporate Taxation in the United States." *Brookings Papers on Economic Activity* 2:451-505.

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. Cambridge, MA. <http://web.mit.edu/globalchange/www/MITJPSPGC_Rpt71.pdf>.

Balistreri, E.J., and R.H. Hillberry. 2004. "Estibration: An Illustration of Structural Estimation As Calibration." Available at <http://www.mines.edu/~ebalistr/Papers/estib4aer.pdf>.

Balistreri, E.J., and T.F. Rutherford. 2004. "Assessing the State-level Burden of Carbon Emissions Abatement." Available at <http://www.mines.edu/~ebalistr/Papers/CO2004.pdf>.

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.

Ballard, C.L. 1999. "How Many Hours Are in a Simulated Day? The Effects of Time Endowment on the Results of Tax-Policy Simulation Models." Mimeo: Department of Economics, Michigan State University.

Beijing Energy Efficiency Center. "Energy Prices." <http://www.beconchina.org/energy_price.htm>.

Bergstrand, J.H. 1985. “The Gravity Equation in International Trade: Some Microeconomic Foundations and Empirical Evidence.” *The Review of Economics and Statistics* 67(3):474-481.

Bergstrand, J.H. 1989. “The Generalized Gravity Equation, Monopolistic Competition, and the Factor-Proportions Theory in International Trade.” *The Review of Economics and Statistics* 71(1):143-153.

Bohringer, C. and T.F. Rutherford. 2006. “Combining Top-Down and Bottom-Up in Energy Policy Analysis: A Decomposition Approach.” ZEW Discussion Paper No. 06-007. <ftp://ftp.zew.de/pub/zew-docs/dp/dp06007.pdf>.

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, L.A., and L.H. Goulder. 2000. “Neutralizing the Adverse Industry Impacts of CO_2 Abatement Policies: What Does It Cost?” In *Behavioral and Distributional Impacts of Environmental Policies*, C. Carraro and G. Metcalf (eds.). Chicago, IL: University of Chicago Press.

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>.

Brooke, A., D. Kendrick, A. Meeraus, and R. Raman. 1998. *GAMS: A User’s Guide*. GAMS Development Corporation. <http://www.gams.com>.

Browning, E.K. 1987. “On the Marginal Welfare Cost of Taxation.” *American Economic Review* 77:11-23.

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

Central Intelligence Agency (CIA). 2006. *The World Factbook.* <https://www.cia.gov/library/publications/the-world-factbook/>.

Dimaranan, B.V., (Editor). 2006. *Global Trade, Assistance, and Production: The GTAP 6 Data Base*. Center for Global Trade Analysis, Purdue University. <https://www.gtap.agecon.purdue.edu/databases/v6/default.asp>.

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

European Commission, Directorate-General for Energy and Transportat. 2006. European Energy and Transport: Trends to 2030 – Update 2005. Luxembourg: Office for Official Publications of the European Communities. <http://ec.europa.eu/dgs/energy_transport/figures/trends_2030_update_2005/index_en.htm>.

Federal Reserve Board. 2004. *Flow of Funds Accounts of the United States*, Coded Tables for Z.1 Release. Tables B.102 and B.103. <http://www.federalreserve.gov/releases/Z1/20040115/Coded/coded.pdf>.

Feenberg, D., and E. Coutts. 1993. “An Introduction to the TAXSIM Model.” *Journal of Policy Analysis and Management* 12(1):189-194. <http://www.nber.org/~taxsim/>.

Feenstra, R.C., J.R. Markusen, and A.K. Rose. 2001. "Using the Gravity Equation to Differentiate among Alternative Theories of Trade." *The Canadian Journal of Economics* 34(2):430-477.

Fuchs, V.R., A.B. Krueger, and J.M. Poterba. 1998. "Economists' Views about Parameters, Values, and Policies: Survey Results in Labor and Public Economics." *Journal of Economic Literature* 36:1387-1425.

Fullerton, D. 1987. "The Indexation of Interest, Depreciation, and Capital Gains and Tax Reform in the United States." *Journal of Public Economics* 32:25-51.

Fullerton, D., and A. Lyon. 1988. "Tax Neutrality and Intangible Capital." In *Tax Policy and the Economy*, vol. 2, Lawrence Summers (ed.), p. 63-88. Cambridge, MA: MIT Press.

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

Goulder, L.H., and R.C. Williams. 2003. "The Substantial Bias from Ignoring General Equilibrium Effects in Estimating Excess Burden, and a Practical Solution." *Journal of Political Economy* 111:898-927.

Goulder, L.H., Ian W.H. Parry, R.C. Williams, and D. Burtraw. 1999. "The Cost-Effectiveness of Alternative Instruments for Environmental Protection in a Second-Best Setting." *Journal of Public Economics* 72:329-360.

Goulder, L.H., Ian W.H. 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.

Gurgel, A., G. Metcalf, and J. Reilly. 2006. "Comparing Tax Rates using OECD and GTAP6 Data." MIT Technical Note No. 7. <http://web.mit.edu/globalchange/www/MITJPSPGC_TechNote7.pdf>.

Hall, R.E., and D.W. Jorgenson. 1967. "Tax Policy and Investment Behavior." *American Economic Review* 57:391-414.

Hyman, R.C., J.M. Reilly, M.H. Babiker, A. De Masin, and H.D. Jacoby. 2002. "Modeling Non-CO_2 Greenhouse Gas Abatement." MIT Joint Program on the Science and Policy of Global Change, Report No. 94. Cambridge, MA. <http://web.mit.edu/globalchange/www/MITJPSPGC_Rpt94.pdf>.

International Energy Agency (IEA). 2002. *Developing China's Natural Gas Markets: The Energy Policy Challenges*. <http://www.iea.org/dbtw-wpd/Textbase/nppdf/free/2000/chinagas2002.pdf>.

International Energy Agency (IEA). 2006a. *Coal Information 2006*. ISBN 92-64-10742-8 <http://www.iea.org/bookshop/add.aspx?id=35>. Also see additional online data at <http://data.iea.org/ieastore/statslisting.asp>.

International Energy Agency (IEA). 2006b. *Electricity Information 2006*. ISBN 92-64-10750-9 <http://www.iea.org/bookshop/add.aspx?id=34>. Also see additional online data at <http://data.iea.org/ieastore/statslisting.asp>.

International Energy Agency (IEA). 2006c. *Energy Balances of Non-OECD Countries 2006*. ISBN 92-64-10765-7 <http://www.iea.org/bookshop/add.aspx?id=31>. Also see additional online data at <http://data.iea.org/ieastore/statslisting.asp>.

International Energy Agency (IEA). 2006d. *Energy Balances of OECD Countries 2006*. ISBN 92-64-10760-6 <http://www.iea.org/bookshop/add.aspx?id=29>. Also see additional online data at <http://data.iea.org/ieastore/statslisting.asp>.

International Energy Agency (IEA). 2006e. *Energy Prices and Taxes 2006 - Annual*. ISBN 0256-2332. <http://www.iea.org/bookshop/add.aspx?id=37>. Also see additional online data at <http://data.iea.org/ieastore/statslisting.asp>.

International Energy Agency (IEA). 2006f. *Natural Gas Information 2006*. ISBN 92-64-10746-0. <http://www.iea.org/bookshop/add.aspx?id=33>. Also see additional online data at <http://data.iea.org/ieastore/statslisting.asp>.

International Energy Agency (IEA). 2006g. *Oil Information 2006*. ISBN 92-64-10734-7. <http://www.iea.org/bookshop/add.aspx?id=32>. Also see additional online data at <http://data.iea.org/ieastore/statslisting.asp>.

International Energy Agency (IEA). 2008. *World Energy Outlook 2008*. ISBN 978-92-64-02730-5. <http://www.worldenergyoutlook.org/>

Jacoby, H.D., J.M. Reilly, J.R. McFarland, and S. Paltsev. 2006. "Technology and Technical Change in the MIT EPPA Model." *Energy Economics* 28:610-631.

Jorgenson, D.W. 1963. "Capital Theory and Investment Behavior." *American Economic Review* 53(2):247-259.

King, M.A., and D. Fullerton. 1984. *The Taxation of Income from Capital*. Chicago, IL: University of Chicago Press.

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

Lau, M., A. Pahlke, and T. Rutherford. 2002. "Approximating Infinite-Horizon Models in a Complementarity Format: A Primer in Dynamic General Equilibrium Analysis." *Journal of Economic Dynamics and Control* 26(4):577-609.

Leontief, W.W. 1936. "Quantitative Input-Output Relations in the Economic System of the United States." *The Review of Economics and Statistics* 18:105-25.

Lofgren, H., R. Harris, and S. Robinson. 2002. *A Standard Computable General Equilibrium (CGE) Model*. International Food Policy Research Institute, Microcomputers in Policy Research 5 working paper. <http://www.ifpri.org/pubs/microcom/5/mc5.pdf>.

Malcolm, G., and M. Babiker. 1998. "Documentation for Energy Price/Tax Database." Center for Global Trade Analysis. <http://www.gtap.agecon.purdue.edu/resources/download/94.pdf>.

McFarland, J.R., J.M. Reilly, and H.J. Herzog. 2004. "Representing energy technologies in top-down economic models using bottom-up information." *Energy Economics* 26:685-707.

McFarland, J.R., and H.J. Herzog. 2006. "Incorporating carbon capture and storage technologies in integrated assessment models." *Energy Economics* 28:632-652.

Metschies, G. 2003/2005. *International Fuel Prices*. <http://www.zietlow.com/docs/Fuel-Prices-2003.pdf>.

Minnesota IMPLAN Group. 2005. State-Level Data for 2005 and IMPLAN Professional, Version 2.0 (ed. 2), Social Accounting & Impact Analysis Software. Stillwater, MN. <http://www.implan.com>.

National Science Foundation (NSF). 2001a. "Company and Other (Except Federal) Funds for Industrial R&D Performance, by Industry and by Size of Company: 1953–98." Table H-25. <http://www.nsf.gov/sbe/srs/iris/start.htm>. Last updated September 2001.

National Science Foundation (NSF). 2001b. "Company and Other Non-Federal Funds for Industrial R&D Performance in the U.S., by Industry and Size of Company: 1997–2000." Table A-7. <http://www.nsf.gov/sbe/srs/iris/start.htm>. Last updated September 2001.

Paltsev, S., J.M. Reilly, H.D. Jacoby, R.S. Eckaus, J. McFarland, M. Sarofim, M. Asadoorian, and M. Babiker. 2005. "The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Version 4." MIT Joint Program on the Science and Policy of Global Change, Report No. 125. Cambridge, MA. <http://web.mit.edu/globalchange/www/eppa.html>.

Parry, Ian W.H., and A.M. Bento. 2000. "Tax Deductions, Environmental Policy, and the 'Double Dividend' Hypothesis." *Journal of Environmental Economics and Management* 39:67-96.

Phelps, E. S. 1963. "Substitution, Fixed Proportions, Growth and Distribution." *International Economic Review* 4:265-288.

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

Rodrıguez, A.G. 1994. "A Computable General Equilibrium Model for Natural Resource Policy Analysis in Costa Rica." Ph.D. Dissertation, Agricultural Economics, Pennsylvania State University.

Ross, M.T., R.H. Beach, B.M. Depro, and B.C. Murray. 2005. "EMPAX-CGE Model Documentation." <http://www.epa.gov/ttn/ecas/econmodels.html>.

Russek, F.S. 1996. "Labor Supply and Taxes." Congressional Budget Office working paper. <http://www.cbo.gov/ftpdocs/33xx/doc3372/labormkts.pdf>.

Rutherford, T.F. 1999. "Applied General Equilibrium Modeling with MPSGE as a GAMS Subsystem: An Overview of the Modeling Framework and Syntax." *Computational Economics 1*4(1):1-46.

Rutherford, T.F. 2004. "Tools for Building National Economic Models Using State-Level IMPLAN Social Accounts." University of Colorado Web site <http://debreu.colorado.edu/implan98.htm>.

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.

Sanso, M., R. Cuairan, and F. Sanz. 1993. "Bilateral Trade Flows, The Gravity Equation, and Functional Form." *The Review of Economics and Statistics* 75(2): 266-275.

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

The Tax Foundation. 2008a. *State General Sales and Use Tax Rates*. <http://www.taxfoundation.org/taxdata>. As of December 31, 2007.

The Tax Foundation. 2008b. *State Corporate Income Tax Rates*. <http://www.taxfoundation.org/taxdata>. As of December 31, 2007.

The Tax Foundation. 2008c. *State Gasoline Tax Rates*. <http://www.taxfoundation.org/taxdata>. As of December 31, 2007.

United Nations (UN). 2006. *World Population Prospects: The 2006 Revision Population Database.* <http://esa.un.org/unpp/>.

UU.S. Bureau of Economic Analysis (BEA). 2004a. "Current-Cost Net Stock of Nonresidential Fixed Assets by Industry Group and Legal Form of Organization, Table 4-1." <http://www.bea.doc.gov/bea/dn/faweb/AllFATables.asp>.

U.S. Bureau of Economic Analysis (BEA). 2004b. "Detailed Estimates for Private Nonresidential Fixed Assets by Detailed Industry and by Detailed Asset Type, Current Cost Net Stocks: 1947-2001." <http://www.bea.doc.gov/bea/dn/faweb/Details/Index.html>.

U.S. Bureau of Economic Analysis (BEA). 2004c. "State and Local Government Current Receipts and Expenditures, Table 3-3." <http://www.bea.doc.gov/bea/dn/nipaweb/Index.asp>.

U.S. Bureau of Economic Analysis (BEA). 2008. "Regional Economic Accounts—Gross State Product." <http://www.bea.doc.gov/bea/regional/gsp/>.

U.S. Bureau of Labor Statistics (BLS). 2004. *Consumer Expenditure Survey*. <http://www.bls.gov/cex/home.htm>.

U.S. Department of Labor, Bureau of Labor Statistics (BLS). *Occupational Outlook Handbook for 2014*. <http://www.bls.gov/news.release/ooh.toc.htm>.

U.S. Census Bureau. 2001. "Quarterly Financial Report for Manufacturing, Mining, and Trade Corporations." Third Quarter 2001, Series QFR/01-Q3. Washington, DC: U.S. Government Printing Office.

U.S. Census Bureau. 2005a. *Decennial Census and Population Surveys: State Interim Population Projections by Age and Sex: 2004 - 2030*. <http://www.census.gov/population/www/projections/projectionsagesex.html>.

U.S. Census Bureau. 2005b. "Housing Unit Estimates." <http://www.census.gov/popest/housing/>.

U.S. Department of Agriculture (USDA). 2000. "1999 Agriculture Economics and Land Ownership Survey, Table 72." <http://www.nass.usda.gov/census/census97/aelos/aelos.htm>.

U.S. Department of Labor, Bureau of Labor Statistics (BLS). *Current Employment Statistics*. <http://www.bls.gov/ces/home.htm#ee>. Table B-12.

U.S. Department of Labor, Bureau of Labor Statistics (BLS). *Occupational Outlook Handbook*. <http:// http://www.bls.gov/emp/>. Table 1.

U.S. Energy Information Administration (EIA) at Department of Energy (DOE). *Commercial Buildings Energy Consumption Survey*. <http://www.eia.doe.gov/emeu/cbecs/ce951b.html>.

U.S. Energy Information Administration (EIA) at Department of Energy (DOE). *International Energy Annual 2005*. <http://www.eia.doe.gov/iea/>.

U.S. Energy Information Administration (EIA) at Department of Energy (DOE). *International Energy Price Information*. <http://www.eia.doe.gov/emeu/international/prices.html>.

U.S. Energy Information Administration (EIA) at Department of Energy (DOE). *Manufacturing Energy Consumption Survey 2002*. <http://www.eia.doe.gov/emeu/mecs/contents.html>.

U.S. Energy Information Administration (EIA) at Department of Energy (DOE). 2001. *Natural Gas Transportation: Infrastructure Issues and Operations Trends.* <http://www.eia.doe.gov/pub/oil_gas/natural_gas/analysis_publications/natural_gas_infrastructure_issue/pdf/nginfrais.pdf>.

U.S. Energy Information Administration (EIA) at Department of Energy (DOE). 2004. *Coal Transportation: Rates and Trends in the United States, 1979-2001*. <http://www.eia.doe.gov/cneaf/coal/page/trans/ratesntrends.html>.

U.S. Energy Information Administration (EIA) at Department of Energy (DOE). 2005a. *Coal Distribution Report 2004*. <http://www.eia.doe.gov/cneaf/coal/page/coaldistrib/coal_distributions.html>.

U.S. Energy Information Administration (EIA) at Department of Energy (DOE). 2005b. *Annual Energy Review 2005*. DOE/EIA-0384. <http://www.eia.doe.gov/emeu/aer/contents.html>.

U.S. Energy Information Administration (EIA) at Department of Energy (DOE). 2005c. *International Energy Outlook 2004*. DOE/EIA-0484. <http://www.eia.doe.gov/oiaf/ieo/index.html>.

U.S. Energy Information Administration (EIA) at Department of Energy (DOE). 2009. *Annual Energy Outlook 2009*. DOE/EIA-0383. <http://www.eia.doe.gov/oiaf/aeo/index.html>.

U.S. Energy Information Administration (EIA) at Department of Energy (DOE). 2009b. *Assumptions to the Annual Energy Outlook 2009*. DOE/EIA-0445. <http://www.eia.doe.gov/oiaf/aeo/assumption/index.html>.

U.S. Energy Information Administration (EIA) at Department of Energy (DOE). 2008c. *Annual Coal Report 2007*. DOE/EIA-0584. <http://www.eia.doe.gov/cneaf/coal/page/acr/acr_sum.html>.

U.S. Energy Information Administration (EIA) at Department of Energy (DOE). 2008d. *Petroleum Supply Annual 2007, Volume 1*. DOE/EIA-0340/1. <http://www.eia.doe.gov/oil_gas/petroleum/data_publications/petroleum_supply_annual/psa_volume1/psa_volume1.html>.

U.S. Energy Information Administration (EIA) at Department of Energy (DOE). 2008e. *Natural Gas Annual 2007.* DOE/EIA-0131. <http://www.eia.doe.gov/oil_gas/natural_gas/data_publications/natural_gas_annual/nga.html>.

U.S. Energy Information Administration (EIA) at Department of Energy (DOE). 2008f. *Electric Power Annual 2007*. DOE/EIA-0348. <http://www.eia.doe.gov/cneaf/electricity/epa/epa_sum.html>.

U.S. Energy Information Administration (EIA) at Department of Energy (DOE). 2008g. *Renewable Energy Annual 2006*. DOE/EIA-0603. <http://www.eia.doe.gov/cneaf/solar.renewables/page/rea_data/rea_sum.html>.

U.S. Energy Information Administration (EIA) at Department of Energy (DOE). 2008h. *Refinery Capacity Report 2007*. <http://www.eia.doe.gov/oil_gas/petroleum/data_publications/refinery_capacity_data/refcapacity.html>.

U.S. Energy Information Administration (EIA) at Department of Energy (DOE). 2008i. *State Energy Consumption, Price, and Expenditure Estimates 2006*. <http://www.eia.doe.gov/emeu/states/_seds.html>.

U.S. Environmental Protection Agency (EPA), Science Advisory Board. 2004. "Review of the Revised Analytical Plan for EPA's Second Prospective Analysis—Benefits and Costs of the Clean Air Act 1990-2020: An Advisory by a Special Panel of the Advisory Council on Clean Compliance Analysis." EPA-SAB-COUNCIL-ADV-04-004. <http://www.epa.gov/sab/pdf/secondprospcaad.pdf>.

U.S. Environmental Protection Agency (EPA). 2006a. "Documentation of the IPM Model" <http://www.epa.gov/airmarkets/progsregs/epa-ipm/index.html>.

U.S. Environmental Protection Agency (EPA). 2006b. "Non-CO2 Gases Economic Analysis and Inventory." <http://www.epa.gov/nonco2/econ-inv/international.html#global_anthropogenic>.

U.S. Environmental Protection Agency (EPA). 2008. *US Emissions Inventory—Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2006*. <http://www.epa.gov/climatechange/emissions/usinventoryreport.html>.

U.S Internal Revenue Service (IRS). 1995-2001. *Corporation Tax Returns by Industry*. <http://www.irs.gov/taxstats/article/0,,id=96388,00.html>.

U.S. Internal Revenue Service (IRS). 2004. *Publication 542: Corporations 2003 Returns.* <http://www.irs.gov/pub/irs-pdf/p542.pdf>.

Yatchew, A. (editor). 2006. "Multi-Greenhouse Gas Mitigation and Climate Policy." *Energy Journal,* Special Issue.

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.