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

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List of ABBREVIATIONS

|  |  |
| --- | --- |
| ADAGE | Applied Dynamic Analysis of the Global Economy |
| AEEI | Autonomous Energy-Efficiency Improvement |
| AEZ | Agro-ecological Zones |
| AFR | Africa |
| AFV | Alternative Fuel Vehicle |
| AIRP | Airline Transportation (passenger) |
| ARSE | Biofuel from Agricultural Residue |
| ATB | Annual Technology Baseline |
| BEA | Bureau of Economic Analysis |
| BEV | Electric Battery Vehicle |
| BIO | Bioelectricity |
| BRA | Brazil |
| BTS | Bureau of Transportation Statistics |
| Btu | British Thermal Unit |
| CC | Combined Cycle |
| CCS | Carbon Capture and Storage |
| CES | Constant Elasticity of Substitution |
| CET | Constant Elasticity of Transformation |
| CETH | Corn Ethanol |
| CGE | Computable General Equilibrium |
| CHN | China |
| COBD | Corn Oil Biodiesel |
| COL | Coal |
| CONV | Conventional Electricity Generation |
| CRU | Crude Oil |
| DDGS | Distillers’ Grains with Solubles |
| DOE | Department of Energy |
| EDGAR | Emissions Database for Global Atmospheric Research |
| EIA | U.S. Energy Information Administration |
| EIM | Energy Intensive Manufacturing |
| ELE | Electricity |
| EPA | U.S. Environmental Protection Agency |
| EPPA | Emissions Prediction and Policy Analysis |
| ERS | Economic Research Service |
| EUR | European Union 27 |
| FAO | Food and Agriculture Organization |
| FCEV | Hydrogen Fuel Cell Vehicle |
| FCTO | Fuel Cell Technologies Office |
| FRED | Federal Reserve Bank of St. Louis |
| FRS | Forestry |
| FRSE | Biofuel from Forest Residue |
| FRWE | Biofuel from Forest Pulpwood |
| GAMS | General Algebraic Modeling System |
| GAS | Natural Gas |
| GasV | Natural Gas Vehicle |
| GCAM | Global Change Assessment Model |
| GDP | Gross Domestic Product |
| GEO | Geothermal |
| GHG | Greenhouse Gas |
| GRON | Rest of Cereal Grains |
| GTAP | Global Trade Analysis Project |
| HDV | Heavy Duty Vehicle |
| HEV | Oil Electric Hybrid Vehicle |
| HFC | Hydrofluorocarbon |
| HYD | Hydropower |
| I/O | Input-Output |
| IEA | International Energy Agency |
| IGEM | Intertemporal General Equilibrium Model |
| IMF | International Monetary Fund |
| IMPLAN | Economic Impact Analysis for Planning |
| LDV | Light-Duty Vehicle |
| LIV | Livestock |
| MAN | Other Manufacturing |
| MEA | Meat |
| MSCE | Ethanol from Miscanthus |
| MSRP | Manufacturer’s Suggested Retail Price |
| NREL | National Renewable Energy Lab |
| NUC | Nuclear |
| OCR | Rest of Crops |
| OECD | Organisation for Economic Co-operation and Development |
| OEV | Traditional Gasoline-Biofuel “Original Equipment Vehicle” |
| OFD | Other Food Products |
| OIL | Refined Oil |
| OLS | Ordinary Least Squares |
| OMEL | Vegetable Oil Meal |
| OSDN | Rest of Oilseeds |
| OTRN | Off Road and Pipeline |
| PFC | Perfluorocarbon |
| PLBD | Palm-Kernel Biodiesel |
| PMT | Passenger-Mile Traveled |
| PNNL | Pacific Northwest National Laboratory |
| RalF | Rail Freight |
| RalP | Rail Passenger |
| RodF | Road Freight (truck) |
| RodP | Road Passenger (bus) |
| ROW | Rest of World |
| RPBD | Rape-mustard Biodiesel |
| SAB | EPA’s Science Advisory Board |
| SAM | Social Accounting Matrix |
| SBET | Sugar beet ethanol |
| SCET | Sugarcane Ethanol |
| SOL | Solar |
| SOYB | Soybeans |
| SRBT | Sugar Beet |
| SRCN | Sugarcane |
| SRV | Services |
| SWGE | Ethanol from Switchgrass |
| SYBD | Soy Biodiesel |
| TEM | Terrestrial Ecosystem Model |
| TMT | Ton-Mile Traveled |
| USA | United States |
| USDA | U.S. Department of Agriculture |
| VOL | Vegetable Oils |
| VTO | Vehicle Technologies Office |
| WETH | Wheat Ethanol |
| WHT | Wheat |
| WND | Wind |
| WTRT | Marine Transportation (freight) |
| XAS | Rest of Asia |
| XLM | Rest of South America |
|  |  |

# Introduction

The Applied Dynamic Analysis of the Global Economy (ADAGE) model, developed by RTI International, is a multiregion, multisector computable general equilibrium (CGE) model. ADAGE follows the classical Arrow-Debreu general equilibrium framework (Arrow and Debreu, 1954) covering the whole economy including production, consumption, trade, and investment. Households earn income in factor markets and make consumption and investment decisions, distinguishing between domestic and imported consumption goods. Firms maximize profits subject to production technology constraints within a nested constant elasticity of substitution (CES) structure. The dynamics in ADAGE are represented by 1) growth in the available effective labor supply from population growth and changes in labor productivity; 2) capital accumulation through savings and investment; 3) changes in stocks of natural resources; and 4) technological change from improvements in manufacturing, energy efficiency and land productivity, and advanced technologies that could be available in the future. The representation of the economy with detailed energy, transportation, agriculture, biofuels, and land use change activity, together with sectoral greenhouse gas (GHG) emissions and abatement, makes ADAGE suitable for analyzing a wide range of economic and environmental policies and estimating how all parts of an economy respond to those policies. Among the feasible set of policies are many types of economic, energy, environmental, trade, and advanced technology policies that can be investigated at the international and national levels.

The last full documentation for ADAGE was produced in 2009 (Ross, 2009) and focused on the forward-looking dynamic, U.S. regional version of the model. This document covers the recursive-dynamic, global version of the ADAGE model. In a forward-looking model, decisions about production and consumption, savings, and investment account for all future economic conditions, often referred to as “perfect foresight” expectations; economic agents see and respond to future economic conditions, optimizing their resource allocations over all time periods.

Throughout the remainder of this document, references to ADAGE are referring to the global recursive-dynamic version of the model unless noted otherwise. In a recursive-dynamic model, decisions about production and consumption, savings, and investment are only based on previous and current economic conditions, referred to as myopic expectations. Consumers do not alter their saving and consumption behavior based on expectations of changes in future returns on investment or the price of future consumption. Recursive-dynamic CGE models solve a sequence of static equilibria at each period. The equilibria at two periods are connected to each other through capital accumulation and resource depletion between these two periods. Given the uncertainty of what will happen in the future, a forward-looking model tends to overestimate the capability of agents to look forward, while recursive-dynamic models may underestimate this ability (Babiker et al., 2009). In general, it is possible to include greater levels of regional and/or sectoral disaggregation in a recursive-dynamic model than in a similar forward-looking model because recursive-dynamic models are less computationally intensive to solve. In the case of ADAGE, the recursive-dynamic version was developed primarily to incorporate additional sectoral detail, particularly for agriculture, bioenergy, electricity, transportation, and their associated advanced technologies.

ADAGE is a multiple-region[[1]](#footnote-2) global model in which the United States, China, and Brazil are defined as individual regions and the rest of the countries in the world are aggregated into five regions (see Figure 3-1). ADAGE relies on the Global Trade Analysis Project (GTAP) developed by Purdue University (Narayanan and Walmsley, 2008)[[2]](#footnote-3) as a key source of data for the underlying regional social accounting matrices.

ADAGE provides a detailed representation of agriculture, land use change, biofuels, electricity, and transportation, including advanced technology options in these sectors. Examples of advanced technologies include second-generation biofuels, certain electricity generation technologies, and alternative fuel vehicles (AFVs) (see Table 3-2 for a list of all sectors included in ADAGE). In addition to the monetary accounts characteristic of CGE models, ADAGE incorporates detailed estimates in terms of physical units for many variables of interest, such as energy production and consumption (quadrillion Btu), vehicle stock (millions of vehicles), vehicle fuel efficiency (miles per gallon), and endogenous agricultural yield improvements (metric tons per hectare). Such capabilities enable us to examine a wide range of important research and policy questions, including those focused on biofuels, land use change, transportation, and GHG emission mitigation.

ADAGE is programmed in the General Algebraic Modeling System (GAMS) software using the Mathematical Programming System for General Equilibrium analysis sublanguage and solved in 5-year intervals from 2010 through 2050 (Rutherford, 1999). Production activities and final demands are modeled using nested CES production functions. With respect to international trade, crude oil is treated as a homogenous good with a single global price, while all other commodities are differentiated by origin using Armington aggregation (Armington, 1969), which means that there is imperfect substitution between the same category of goods produced in different regions.

The remainder of this document is organized as follows: Section 2 provides a general overview of CGE modeling. Section 3 describes ADAGE’s modeling structure for production, consumption, and trade for goods and services that are produced by existing technologies in 2010, the base year, as well as those that could be produced in the future by novel (relative to the base year) “backstop” technologies (e.g., second-generation biofuels, AFV technologies, and certain electricity generation technologies) once proven and cost-competitive. Section 4 discusses the range of data sources, sector disaggregation procedures, and the linkage between physical quantities and monetary value. Section 5 describes GHG emissions data sources and the modeling framework for emissions abatement. Finally, Section 6 discusses the dynamic processes in the model that account for economic growth from changes in the quantity and productivity of labor, land, natural resources, and capital; energy efficiency improvements; and changes in consumer consumption patterns.

# Overview of CGE Modeling

CGE modeling is a widely accepted method for conducting empirical economic analyses that has been used in numerous applications over the last few decades, particularly in the analysis of changes in taxation, trade, development, and environmental policies. Numerous national, state, and local governments, as well as institutions such as the Organisation for Economic Co-operation and Development (OECD) World Bank, and International Monetary Fund (IMF) among others, rely on CGE models to analyze the economic effects of alternative policies.

CGE models integrate economic theory with real-world data to characterize all economic flows within an economy and ensure all markets are in equilibrium in the model solution. Within these models, each commodity is produced using a variety of inputs (e.g., capital, labor, energy, materials) and is purchased by firms, households, or governments using income earned by households providing those inputs (or through income transfers), government resources derived from taxation, or firms’ income earned from selling their outputs. Firms are assumed to maximize profits subject to available production technologies. Every commodity that is produced must be purchased domestically or exported to foreign consumers. In aggregate, all markets must clear, meaning that supplies of each commodity and each factor of production must equal their demand and the income of each household must equal its factor endowments plus any net transfers.

When assessing policy or other scenarios expected to affect multiple sectors of the economy, either directly or indirectly, through linkages between economic sectors, it may be important to account for these interactions and constraints to get a more complete picture of the potential impacts. For instance, policies that affect the price of energy or other key inputs are likely to have broad economy-wide impacts through their influence on the cost of production. Relative impacts across sectors will depend on their input sources and share of production costs attributable to distinct types of inputs. CGE models characterize the entire economy and explicitly account for linkages between sectors. This enables them to provide insights that cannot readily be assessed with other types of models that do not capture intersectoral linkages. CGE models can also represent the effects of income, input prices, trade, and production in one (or more) sector(s) on another sector (or sectors). In addition, because of the explicit representation of consumer preferences (in terms of utility or expenditure function), CGE models are generally able to estimate how a policy will affect consumers’ standard of living as measured by changes in welfare, or Hicksian equivalent variation. Models without a strong theoretical basis are only able to examine changes in variables like gross domestic product (GDP), which are not direct measures of household welfare. This section provides a brief overview of CGE modeling, including background on the history of CGE modeling, the theoretical foundation of these models, and some examples of applications to environmental policies.

## History of CGE Modeling

Advances in computing power and numerical simulation techniques have allowed modelers to move from simple partial equilibrium models to CGE models with many more sectors and complex behaviors. Early empirical applications began with Leontief (1936, 1951, 1953), who developed static input-output (I/O) models. This approach captured interactions between sectors of the economy but relied on fixed coefficients that did not allow for input substitution in response to changes in relative input costs or changes in production technology. Johansen (1960) developed a model that replaced the Leontief fixed coefficient production functions with more flexible production functions allowing input substitution and technical change. Initially, the models being applied were small enough to solve analytically. By the 1970s, the models being developed by researchers became too large and complex to solve analytically, necessitating the use of computers to solve the models numerically (Ballard and Johnson, 2016). Over the decades since, increasingly more complex CGE models have been developed to investigate a wide array of tax, trade, environmental, and other policies.

One of the key early applications of CGE models was examination of changes in tax policy given the economy-wide effects of changes in taxation. Analyses of the incidence and efficiency effects of taxes are based on the seminal works of Harberger (1959, 1962, 1966, 1974). The 1962 work laid out a two-sector general equilibrium model of taxes using standard neoclassical assumptions: supplies of capital and labor are fixed, factors are perfectly mobile across industries, and perfect competition exists in product and factor markets. While Harberger’s model provided valuable insights, it was solved analytically rather than numerically and was only tractable for a very limited number of goods, factors, and sectors (Ballard and Johnson, 2016). Shoven and Whalley (1972, 1973) were the first to analyze taxes using a full general equilibrium structure. Subsequent works, notably Ballard et al. (1985), extended previous models by adding more sectors and modeling dynamic consequences of policies for household savings behavior. More recent works (e.g., Bovenberg and Goulder, 1996; Babiker, Metcalf, and Reilly, 2002; and Bovenberg, Goulder, and Gurney, 2005) have examined how existing tax distortions in an economy may interact with economic policies and alter their effects.

Another key area where CGE models have been applied extensively is to analysis of trade policies, because of the ability of these models to examine implications for many industries and countries simultaneously. Deardorff and Stern (1981) developed one of the first large-scale CGE trade models. It had 34 countries and 29 industries and was used to investigate the effects of changes in tariff and nontariff barriers in the Tokyo Round. Analysis of major trade agreements, such as the North American Free Trade Agreement and the Uruguay Round of trade negotiations, relied heavily on CGE models for assessments of impacts. These studies include U.S. International Trade Commission (1992); Francois and Shiells (1994); Martin and Winters (1996); Robinson et al. (1991); and Burfisher, Robinson, and Theirfelder (1994). The GTAP, currently the largest CGE initiative in the world, was founded by Hertel in 1992 to facilitate research into trade policy, with the Uruguay Round negotiations serving as a driver for moving the GTAP initiative forward. This effort has subsequently expanded into many other topic areas and includes development and calibration of a database commonly used in global CGE models (including ADAGE). However, analysis of trade policy remains a key area of focus for the GTAP initiative as well as the CGE modeling literature more broadly (Dixon, Jerie, and Rimmer, 2016; Gilbert, Furusawa, and Scollay, 2017; Balistreri, Böhringer, and Rutherford, 2018).

Initially, CGE models were static representations of an economy and their solutions generally represented a medium-term comparative static adjustment of prices and quantities in response to a given policy shock. While static models still comprise the majority of CGE models, there has been an explosion in the number of dynamic CGE models. These dynamic models capture changes in stock variables over time and are typically used to assess policy effects over time. Forward-looking models are particularly valuable for analyzing investment and can be used to analyze responses in anticipation of future changes in market and policy conditions. These models provide useful insights into intertemporal investment and consumption decisions but have a high computational burden because the entire model must be solved simultaneously rather than solving period by period. Recursive-dynamic models are commonly used in studies where there is interest in assessing the effects of major policies expected to have varying impacts for decades into the future at a level of sectoral and regional disaggregation that cannot be readily solved within a forward-looking model.

CGE models continue to be widely used with numerous applications for policy analysis, including studies of environmental policy (see Section 2.3). In 2017, the U.S. Environmental Protection Agency’s (EPA’s) Science Advisory Board (SAB) reviewed the use of economy-wide models for assessing the benefits, costs, and economic impacts associated with air quality regulations. The SAB concluded that “The economy-wide approach that would be most useful for regulatory analysis is computable general equilibrium (CGE) modeling” and indicated that CGE models could be an important supplement to the EPA’s existing analytical tools (EPA SAB, 2017).

## Theoretical Foundation

The theoretical foundation of most CGE models is a Walrasian general equilibrium structure. As described by an Arrow-Debreu model (Arrow and Debreu, 1954; Arrow and Hahn, 1971), this type of structure includes the following components: 1) households in the economy have an initial endowment of factors of production and a set of preferences for goods; 2) market demands are the sum of all agents’ demands and depend on prices; 3) solution prices are consistent with Walras’ law (expenditures equal income for any set of prices); 4) producers maximize profits and have constant or decreasing returns-to-scale production functions; and 5) 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). CGE models combine this theoretical structure with numerical methods to quantify this characterization of the economy, enabling estimation of the effects of policy changes throughout the economy.

Unlike earlier I/O models, which focus on the production side of the economy and rely on exogenous multipliers to estimate demand effects, CGE models include income flows, distributional effects, and changes in behavior in response to price changes. By modeling both producer and consumer behavior, CGE models can estimate how policy effects will ripple through the entire economy in a manner consistent with economic theory.

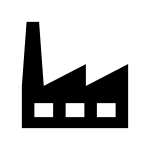
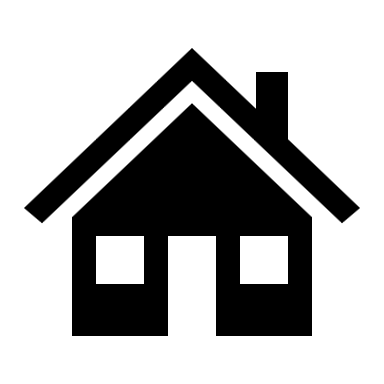
Within this theoretical structure, CGE models capture all flows of goods and factors of production (labor, capital, natural resources) in the economy (that are reflected within available data). Figure 2-1 illustrates the economic flows considered in a typical CGE model. Households own factors of production (capital, labor, and natural resources) that are supplied to firms. These factor sales generate income for households (e.g., wages paid for supplying labor). Firms produce output by combining productive factors with intermediate inputs of goods and services from other industries. The output of each industry is purchased by other industries and consumers using income received from selling outputs and/or factors of production. Governments can also purchase goods and services using revenues derived from taxation of households and firms. In addition, there are income transfers between economic agents. Goods and services produced domestically can also be exported and imported goods can be purchased from other countries.[[3]](#footnote-4) Capital flows among regions as they run trade deficits or surpluses.

Figure 2-1. Circular Economic Flows within CGE Models

**Region A**

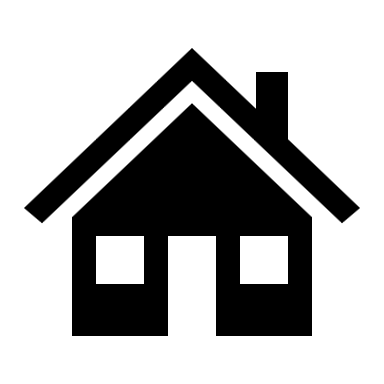
**Region B**

**Primary Factors**

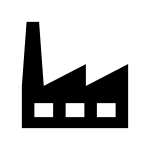


**Income**

**Households**



**Firms**



**Trade   
flows**

**Taxes**

**Social Transfers**

**Government**

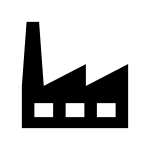
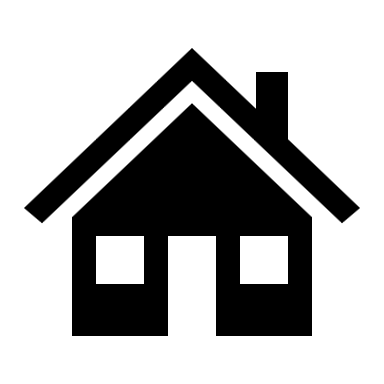
**Taxes**

**Govt.  
Purchases**

**Expenditures**

**Goods & Services**

**Region C**



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 total 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 commonly used to describe these utility functions (though some models rely on alternative functional forms such as Translog or Generalized Leontief), which show how willing and able households are to substitute among consumption goods in response to price changes.

Firms are assumed to maximize profits (defined as the difference between revenues from sales and payments for factors of production and intermediate inputs) subject to constraints imposed by available production technologies, while operating in perfectly competitive markets. These production technologies are also typically specified using CES functions that describe how different types of inputs can be substituted for each other. The extent of these substitutions is determined by elasticity parameters that control how easily trade-offs among inputs can be made. Unlike I/O models or partial equilibrium models using fixed coefficients in production, this model structure allows producers to change the technology employed to manufacture goods. If, for example, energy prices rise, an industry can shift away from energy by employing more capital, labor, or intermediate inputs as allowed for by the CES equations. According to economic theory of producer behavior, firms will use each type of input up to the point where the marginal revenue received from employing an additional unit of an input is equal to the marginal cost of purchasing that input.

## Application to Environmental Policies

As in other areas of economics, the use of CGE models in environmental policy applications expanded rapidly in the 1980s and 1990s (Adkins and Garbaccio, 1999) and has continued to grow over time as improvements in model structures, databases, and computer technology have reduced the costs of using these models. Environmental regulations and other policies may affect the economy through their influence on the rates of technological innovation, levels of private investment and trade, and decisions by firms and workers about where to locate. A major strength of CGE models for regulatory analysis is their ability to implicitly take these effects into account (EPA SAB, 2017). Regulations that directly raise costs of production and/or prices in an industry can indirectly discourage both investment in and exports from that industry as well as industries that rely on that sector for productive inputs. In CGE models, regulatory compliance costs lead to reductions in investment as a result of lower returns to capital, while exports are discouraged by higher terms of trade (the ratio of domestic to world prices).

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

Another early application of CGE models to environmental policy (and still one of the most common applications) was in the analysis of economy-wide impacts associated with restrictions on or required reductions for emissions of pollutants. Environmental standards, taxes, or tradable permits lead to direct costs, including payments to government (in the case of taxes or auctioned permits), permit trade expenditures, and abatement expenditures. However, direct costs do not necessarily measure social costs or the distributional implications that are important to policy makers/agencies who seek to design optimal policies from a societal viewpoint. To estimate the social costs of environmental programs, one must capture the sum of direct, indirect, and induced costs.[[4]](#footnote-5) This means modeling all relevant linkages, substitution possibilities, technical changes, and dynamic processes that are affected by environmental programs throughout the economy.

The CGE framework has proven to be a valuable tool for capturing these kinds of complex effects because of its ability to model the representative agent behavior, while at the same time depicting the workings of an entire economy. The Intertemporal General Equilibrium Model (IGEM), developed by Jorgenson, Ho, and Wilcoxen, is an example of a CGE model that has been used in many different studies of the impact of environmental regulations on economic growth since the early 1990s (e.g., Ho and Jorgenson, 1998; Jorgenson, 1998; Jorgenson and Wilcoxen, 1990a, 1990b, 1993a, 1993b, 1993c, 1993d, 1997, 1998), as well as an assessment of the social costs associated with the Clean Air Act. Hazilla and Kopp (1990) used a model that is very similar to IGEM in an analysis of the social costs of the Clean Air and Clean Water Acts.

As identified by the EPA SAB (2017), a key issue in applying CGE modeling to environmental policy analyses is the degree of disaggregation available in the model(s) being applied. Ideally, models used for environmental policy would include disaggregation of sectors, production processes, geographic regions, skills and occupations of the labor supply, and other demographic characteristics. For instance, given our current focus on applications of ADAGE to biofuels and other transportation-related issues, we focused on disaggregation of the transportation, biofuels, and agricultural sectors. However, given the challenges associated with developing and solving CGE models with a high level of detail across all sectors potentially affected by environmental policy, the SAB indicated that it will often be necessary to link CGE models with more detailed partial equilibrium (PE) models. Delzeit et al. (2020) discussed issues and considerations for linking CGE and PE models.

CGE models have also routinely been applied to evaluate impacts of climate change policies, including both carbon taxes and cap-and-trade policies. Inclusion of a tax on the quantity of carbon dioxide equivalent emitted is a relatively common and straightforward way to model climate policy. Cap-and-trade or other policies instituting a limit on emissions can be introduced into these models through the addition of a constraint that limits GHG emissions to a specific 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 to less carbon-intensive goods and technologies. Significant early studies include Rose and Oladosu (2002), Bernstein et al. (1999), Harrison and Rutherford (1998), Jorgenson and Wilcoxen (1993c), McKibbin et al. (1999), Manne and Richels (1997), and Bovenberg and Goulder (1996), among others. Most of these models provided results at the national level, but efforts have been made to model impacts on different regions of the United States as well (Balistreri and Rutherford, 2001). There continue to be a very large number of papers published each year examining different aspects of the economics of climate policy using CGE models (e.g., Böhringer et al., 2021; Faehn et al., 2020; Paltsev et al., 2022; Vandyck et al., 2021; Vrontisi, Charalampidis, and Paroussos, 2020).

Since the mid-1990s, numerous studies have relied on CGE models to examine the interaction between environmental regulations and tax-induced distortions in the labor market, often referred to as tax-interaction effects. Parry (1997), Goulder et al. (1999), and Fullerton and Metcalf (2001) are notable examples of this literature. The findings in this literature argue for the use of CGE models rather than single-sector models in estimating the social costs associated with regulation to account for the potentially large tax interaction effects that may result. If one performs a single-market analysis of a tax policy, say, or an environmental regulation, then one assumes that there are no other-market distortions or that the exacerbation and amelioration of other-market distortions caused by the intervention in question cancel one another out. The tax-interaction effect literature argues that in the case of environmental policy (as well as agricultural policy and trade policy; see Parry [1999] and Williams [1999]) the other-market effects do not cancel out. In particular, the nature of environmental regulation—through command and control, pollution taxes, or quota restrictions on pollution—systematically worsens the distortion in the labor market that arises from the existing income tax (i.e., any decrease in the real wage tends to further decrease labor supply from an already nonoptimal point). This literature has potentially important implications for the way that social costs of environmental regulations are calculated.

Additional studies have attempted to account for environmental benefits within CGE models. Perroni and Wigle (1994) argued that it is essential to build the benefits of environmental improvement into CGE models. In their model, there is an initial endowment of environmental quality, some of which is consumed by activities that generate pollution. Firms can abate pollution by substituting other inputs (e.g., capital investments in pollution control equipment) for emissions. The household utility function in this model includes environmental quality as a consumption good with increasing marginal utility as income rises. They used the model to explore the interactions between trade policy and environmental policy. Another example of this line of research is Smith et al. (2003), a study that estimated the benefits of ozone reductions in the Los Angeles Air Basin in a general equilibrium framework. EPA’s SAB (2017) discusses the advantages of modeling benefits and costs within the same framework, while acknowledging some of the practical barriers that need to be overcome for applications to government policy analysis.

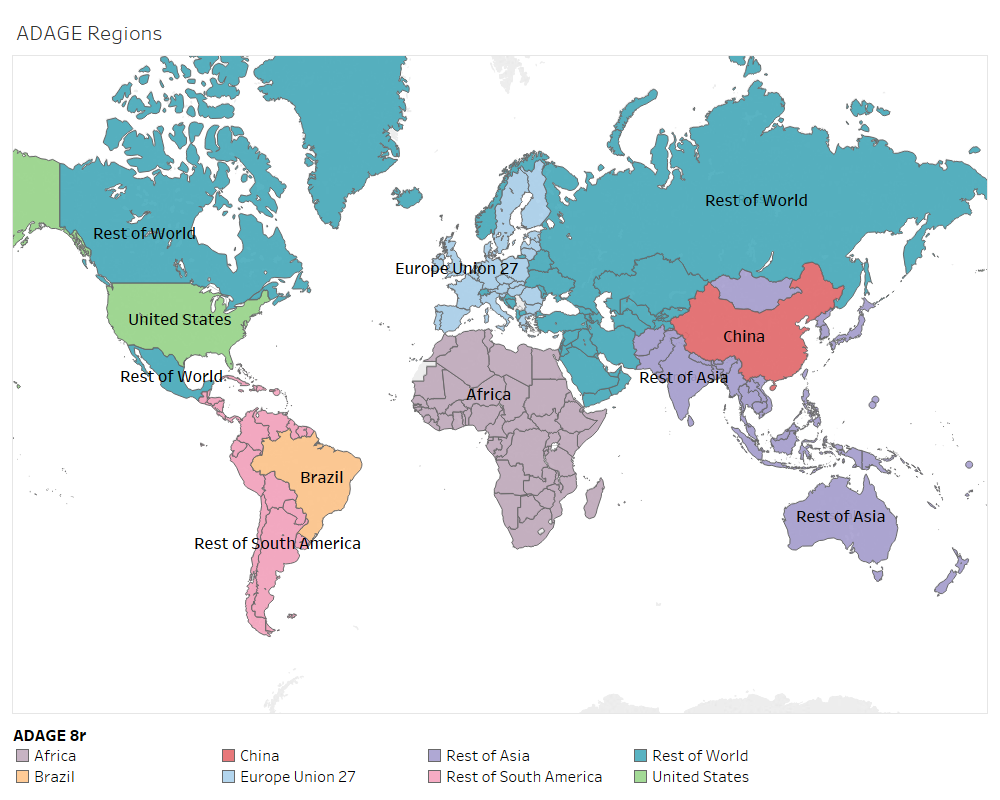
# Model Structure

Like other CGE models, the recursive-dynamic version of ADAGE (hereafter “ADAGE” or “the ADAGE model” unless otherwise specified) combines economic theory with empirical data to link all aspects of the economy together. Decisions on future production, consumption, investment, and trade are determined subject to resource endowment availability, technical I/O relationships for production, substitutability among goods and services, and technological progress over time. Some of the unique features of ADAGE distinguishing this model from other CGE models include the regional and sectoral coverage; detailed characterization of the energy, transportation, and agriculture sectors; accounting for key inputs and outputs in physical as well as monetary units; and inclusion of model specifications and constraints that reflect these physical relationships. To build up these unique features, we complement the key underlying database—the GTAP database version 7 (Narayanan and Walmsley, 2008)—with a variety of other data sources (e.g., information available from the International Energy Agency [IEA], U.S. Energy Information Administration [EIA], EPA, and United Nations Food and Agriculture Organization [FAO]).

|  |
| --- |
| Table 3-1. Regions Included in ADAGE |
| |  |  | | --- | --- | | Region | Definition | | AFR | Africa | | BRA | Brazil | | CHN | China | | EUR | European Union 27 | | USA | United States | | XAS | Rest of Asia | | XLM | Rest of Latin America | | ROW | Rest of World | |

ADAGE groups the world into eight regions (see Table 3-1 and Figure 3-1 for regional resolution). Brazil, China, and the United States are represented as individual countries, and the rest of the world’s countries are aggregated into five regions (Africa, European Union 27, Rest of Asia, Rest of Latin America, and Rest of World).

Figure 3-1. Global Regions in ADAGE



One of the key features of the recursive-dynamic version of ADAGE is a more disaggregated representation of transportation, energy, agriculture, land use, and bioenergy, which enables examination of policy impacts affecting these sectors at a finer scale than was possible in the forward-looking version of ADAGE. The model includes 71 sectors and subsectors representing both conventional technology currently available in the market and advanced technologies that are still under development. ADAGE includes the greatest level of detail on energy, agriculture, biofuels, and transportation (see Table 3-2 below), including detailed GHG accounting. The model includes four types of fossil fuels (coal, natural gas, crude oil, and refined oil), electricity generation, and biofuels. Electricity includes 10 categories of electricity generation technologies: four types of fossil fuel plants (conventional coal, conventional [combustion turbine] natural gas, conventional oil, combined-cycle natural gas), nuclear, and five categories of renewables generation (hydropower, geothermal, wind, solar, and biomass). These types of electricity generation technologies can be substituted for one another to meet overall electricity demand while satisfying other constraints on technology availability, emissions, and other factors. Six types of GHGs and their respective abatement costs are represented in ADAGE (see Section 5).

Table 3-2. Sectoral Disaggregation in ADAGE

|  |  |  |  |
| --- | --- | --- | --- |
| **Sectors** | **Definition** | **Sectors** | **Definition** |
| **Energy Industries** | | **Electricity Generation**a | |
| Col | Coal | Conv\_Col | Conventional coal generation |
| Cru | Crude oil | Conv\_Gas | Conventional (combustion turbine) gas electricity generation |
| Ele | Electricity | Conv\_Oil | Conventional oil electricity generation |
| Gas | Natural gas | CC\_Gas | Combined cycle natural gas |
| Oil | Refined oil | CC\_Gas | Combined cycle natural gas with carbon capture and storage |
| **Industry & Other** | | Hyd | Hydropower |
| Eim | Energy-intensive manufacturing | Geo | Geothermal |
| Man | Other manufacturing | Bio | Bioelectricity |
| Srv | Services | Sol | Solar |
| House | Housing | Wnd | Wind |
| **Food** | | **By-products** | |
| Mea | Meat | Ddgsc | Distillers grains with solubles |
| Vol | Vegetable oils | Omelc | Vegetable oil meal |
| **Agriculture** | | **Transportation** | |
| Wht | Wheat | AirP | Airline transportation (passenger) |
| Corn | Corn | WtrT | Marine transportation (freight) |
| Gron | Rest of cereal grains | RalF | Rail freight |
| Soyb | Soybean | RalP | Rail passenger |
| Osdn | Rest of oilseeds | Autoa | Light-duty vehicle (LDV) |
| Srcn | Sugarcane | RodFa | Road freight (truck) |
| Srbt | Sugar beet | RodPa | Road passenger (bus) |
| Ocr | Rest of crops | Otrn | Other transportation (off-road, pipeline) |
| Liv | Livestock | **Light-Duty Passenger Transportation** | |
| Frs | Forestry | Auto\_OEV | Traditional gasoline-biofuel vehicle |
| **First-Generation Biofuels** | | Auto\_BEV | Battery electric vehicle |
| Ceth | Corn ethanol | Auto\_HEV | Hybrid electric vehicle |
| Weth | Wheat ethanol | Auto\_FCEV | Hydrogen fuel cell electric vehicle |

(continued)

Table 3-2. Sectoral Disaggregation in ADAGE (continued)

|  |  |  |  |
| --- | --- | --- | --- |
| **Sectors** | **Definition** | **Sectors** | **Definition** |
| Scet | Sugarcane ethanol | **On-Road Freight Transportation** | |
| Sbet | Sugar beet ethanol | RodF\_OEV | Traditional diesel-biofuel vehicle |
| Sybd | Soy biodiesel | RodF\_GasV | Compressed natural gas vehicle |
| Rpbd | Rape-mustard biodiesel | RodF\_BEV | Battery electric vehicle |
| Plbd | Palm-kernel biodiesel | RodF\_HEV | Hybrid electric vehicle |
| Cobdb | Corn oil biodiesel | RodF\_FCEV | Hydrogen fuel cell electric vehicle |
| **Second-Generation Biofuels** | | **On-Road Heavy Duty Passenger Transportation** | |
| Swge | Ethanol from switchgrass | RodP\_OEV | Traditional diesel-biofuel vehicle |
| Msce | Ethanol from miscanthus | RodP\_GasV | Compressed natural gas vehicle |
| Arse | Ethanol from agricultural residue | RodP\_BEV | Battery electric vehicle |
| Frse | Ethanol from forest residue | RodP\_HEV | Hybrid electric vehicle |
| Frwe | Ethanol from forest pulpwood | RodP\_FCEV | Hydrogen fuel cell electric vehicle |

a Aggregate sectors combine all of the disaggregated sectors identified below them. Production in this sector is supported by multiple technologies that are listed at the bottom of the table (e.g., five technologies including OEVs and four types of AFVs).

b Distillers grains with solubles and corn oil biodiesel are coproducts of corn ethanol. Vegetable oil meal is a coproduct of vegetable oils.

In addition, agriculture includes eight types of crops (corn, wheat, soybean, sugarcane, sugar beet, other cereal grains, other oilseeds, and an aggregate of all remaining crops), one type of livestock, and one type of forestry. Agricultural goods can be directly consumed by households and governments, processed into food (vegetable oil, meat, and other food products), or used as intermediate goods in other production. Eight types of first-generation biofuels (ethanol made from corn, wheat, sugar cane, and sugar beet; biodiesel made from soybean, palm seed, and rapeseed;[[5]](#footnote-6) and corn oil biodiesel made using corn oil generated as a coproduct of corn ethanol production) and five types of second-generation biofuels (biofuels from switchgrass, miscanthus, agricultural residue, forest residue, and forest wood products) are included in the model and provide comprehensive coverage of biofuels production. These biofuels are used as substitutes for refined oil in on-road transportation.

Furthermore, transportation is represented by eight modes (light-duty vehicles [LDV], road passenger buses [RodP], road freight [RodF], rail passenger [RalP], rail freight [RalF], air, water, and other), each with a conventional technology and three of those modes (LDV, RodP, RodF) include four types of AFV technologies (battery electric vehicles [BEV], hybrid electric vehicles [HEV], compressed natural gas vehicles [GAS], and hydrogen fuel cell vehicles [FCEV]). The details on the transportation industry allow us to assess the competition among conventional and AFV technologies and simulate how AFVs could factor in the future of transportation.

|  |  |
| --- | --- |
| Table 3-3. Primary Factors in ADAGE | |
| **Capital** | **Fossil Fuel Energy** |
|  | Crude oil |
| **Labor** | Natural gas |
|  | Coal |
| **Land** | **Nuclear and Renewable** |
| Cropland | Nuclear |
| Pastureland | Hydro |
| Managed forestry | Geothermal |
| Natural grassland | Biomass for electricity |
| Natural forestland | Solar |
|  | Wind |

Endowments of primary factors include capital, labor, and land, as well as natural resources for fossil fuels, nuclear, and renewables (see Table 3-3). Capital and labor are generally included as inputs into production for all sectors. Land is only used as a resource in agricultural production and land-based biofuel production (biofuels from switchgrass, miscanthus, pulpwood). For example, cropland is used in eight types of traditional crops and two types of energy crops used to make second-generation biofuels (switchgrass and miscanthus). Land can be converted from one type to another to change agricultural production, incurring land conversion costs when there is a change in land cover (e.g., pasture to cropland) but not for a change in land use (e.g., corn to soybeans). Natural resources for fossil fuels and renewables are included in the energy production function to ensure a realistic supply of fossil fuels and renewables (i.e., they cannot be produced with only labor, capital, and materials).

ADAGE simulates regional and global economic activity from 2010 through 2050 in 5-year increments. Economic activity in the base year, 2010, is calibrated to resemble projected output levels available from external data sources. Economic growth is set to match the GDP growth trends from International Energy Outlook 2017 (IEO 2017) (U.S Department of Energy [DOE], EIA, 2017a). In addition, physical quantities for energy, agriculture, land, and transportation are linked to the monetary values included in the CGE model for production, consumption, and trade, allowing us to implement detailed policy analysis while taking physical relationships in these sectors into account.

The CES equations used in the ADAGE model represent household behavior, government activity, trade flows, and production activities. The remainder of this section is organized into four subsections, describing activities related to households, government, trade, and producers. The producer’s activities are manufacturing and services, electricity generation, fossil fuels, transportation, agriculture, first-generation biofuels, and land conversion. CES equations representing each activity are parameterized with elasticity values that guide ADAGE’s response to changes in prices. Elasticity parameters are drawn from a variety of sources including the MIT Emissions Prediction and Policy Analysis (EPPA) model (Paltsev et al., 2005), and Ross (2009) and are reported in Table 3-4 below.

## Households’ Utility Function

Each region in ADAGE contains a representative household that maximizes utility in each period subject to a budget constraint. Each representative household is endowed with primary factors, including capital, labor, natural resources, and land inputs. The value of the production factors owned by each representative household depends on market conditions in each region. Household income comes from the sale or rental of primary factors to the firms that use these factors to produce goods and services that are purchased as production inputs, public and private consumption, investment, and foreign demand (i.e., exports).

Table 3-4. Elasticity of Substitution in ADAGE

|  |  |  |  |
| --- | --- | --- | --- |
| σj | Description | Value | Comments |
| **Household Consumption** | |  |  |
| σ*cl* | Total consumption and leisure | 0.68–1.24 | Differs by region |
| σ*ct* | Transportation and other goods’ aggregates | 0.5 | Household consumption |
| σ*tr* | Passenger and non-passenger transportation | 0 | Household consumption |
| σ*tp* | Among passenger transportation | 0.5 | Household consumption |
| σ*tf* | Among non-passenger transportation | 0 | Household consumption |
| σ*tpf* | Among conventional and AFVs transportation | ∞ | Household consumption |
| σ*ch* | Housing and energy-food-goods-services | 1 | Household consumption |
| σ*c* | Among energy, food, goods, and services | 0.5 | Household consumption |
| **Trade** | | | |
| σ*dm* | Domestic goods and imports | 4 | All sectors other than electricity and ag |
| 0.3 | Electricity and ag |
| σ*mm* | Among imports from different regions | 5 | All sectors other than electricity and ag |
| 0.5 | Electricity and ag |

(continued)

Table 3-4. Elasticity of Substitution in ADAGE (continued)

|  |  |  |  |
| --- | --- | --- | --- |
| σj | Description | Value | Comments |
| **Sectoral Production** | | | |
| σ*mat* | Materials and energy/value-added | 0 | All sectors |
| σ*eva* | Energy and value-added | 1–1.5 | Start at 1 in 2010 and grow to 1.5 linearly in 2050 for most sectors other than electricity |
| 0 | On-road transportation |
| 0 | Conventional electricity generation |
| σ*enoe* | Electricity and nonelectricity | 0.5 | Most sectors other than electricity |
| 0 | Electricity and second-generation biofuels |
| σ*el* | Among electricity generation technologies | 0.3 | All electricity usage |
| σ*en* | Among coal, gas, and oil | 1 | Most sectors |
| σ*oeg* | Refined oil and biofuels |  | On-road conventional transportation |
| σ*ff* | Fixed factor and rest inputs | 0.1 or 0.2 | 0.1 for natural gas and fuel cell vehicles, 0.2 for the rest AFVs |
| σ*va* | Labor and capital | 1 | All sectors |
| σ*nr* | Natural resource and rest input | 0.6 | Fossil fuel |
| 0.15–0.3 | Land use change |
| σ*erva* | Energy-resource and value-added | 1 | Ag and land use change |
| σ*er* | Land and material-energy | 0.6 | Ag and land use change |
| σ*ae* | Materials and energy | 0.3 | Ag and land use change |
| σ*bio* | Feedstock, value-added/materials, and energy | 0 | First-generation biofuels |
| σ*en* | Among coal, gas, and oil | 1 | Most sectors |

Note: Elasticity parameters were drawn from a combination of Paltsev et al. (2005), Ross (2009), and expert judgment of the authors.

The ADAGE model uses a nested CES structure to represent the consumption preferences of the household. In each period, households generate utility from consumption of leisure and composite goods (see Figure 3-2). Consumption of the consumer’s composite good, an aggregate of energy, food, manufacturing, transportation, and all other represented commodities, can be substituted with leisure time to obtain a specific utility in each period. The elasticity of substitution between the composite goods and leisure represents how households are willing to give up leisure time, earning additional income to support additional consumption. This substitution responds to relative prices of consumption and the wage rate. This elasticity of labor-leisure substitution, , is calculated according to the formulas in Eq. 3.1 and Eq. 3.2:

(3.1)

(3.2)

where *lsecomp*(assumed to equal 0.40 in ADAGE) and *lseuncomp* (0.15 in ADAGE) are compensated and uncompensated labor supply elasticities, respectively, with the chosen values drawn from Ross (2009). The parameter is the difference between the compensated and uncompensated labor supply elasticities (equal to 0.25), which defines the share of leisure in household utility. and *Leis0* represent regionally specific household labor endowment and leisure time endowment, respectively. Thus, is regionally specific in ADAGE with a range between 0.68 and 1.24.

Figure 3-2. Structure of Household Sector

Leisure

Composite good

Utility,

Other Goods Aggregate

Transportation Aggregate

Passenger Transportation

Non-passenger Transportation

Air

Auto

Road

Rail

Gas

Fuel Cell

Battery

Hybrid

Water

Other

Road

Rail

Housing

Energy, Food, Goods and Services

Armington Commodities 1….n

Conv

The household composite good includes transportation (separated into passenger and freight transportation), housing, energy, food, other goods, and services. Passenger transportation is from airline, bus, train, and auto. Nonpassenger transportation includes transportation from water, rail, truck, and other modes (e.g., pipeline and off-road transportation, such as construction vehicles and tractors). Each on-road transportation choice is a function of the different fuel types consumed by the specific vehicle types, including conventional transportation and newer technologies, such as electric cars, hybrid vehicles, and fuel-cell vehicles. The elasticity of substitution at each level is shown in Table 3-4 and taken from Paltsev et al. (2005), measuring the flexibility of substitution between choices of transportation.

The other goods’ aggregate consists of a combination of everything other than transportation, including housing, energy, food, other goods, and a service aggregate and has an elasticity of substitution, , equal to 1.0. The energy (coal, gas, electricity, and oil), food, goods, and services aggregates have an elasticity of substitution, , of 0.5. These elasticities are taken from Ross (2009).

This nested CES structure for the household has an elasticity of substitution at each level, offering flexibility for a household to substitute between goods to maximize their utility. Following the approach used in Paltsev et al. (2005); Lahiri, Babiker, and Eckaus (2000); and Dargay, Gately, and Sommerdue (2007), dynamic economic growth and changing preferences in household consumption are incorporated into ADAGE. As per capita income rises, consumption shares change depending on the income elasticity of different goods. For example, consumption shares in each period for household light-duty and bus vehicle-mile-traveled (VMT) consumption update as a function of per capita income growth, population growth, and region-specific preference for each period. In addition, the share of agricultural goods in the consumption basket falls over time as income rises, while the shares of energy-intensive sectors and service sectors rise because their demand has a larger proportionate response to increases in income than in agricultural goods.

The household utility function allows for measurement of welfare changes associated with different policies or other economic shocks, capturing their economy-wide impacts on household welfare. These welfare impacts are typically measured by Hicksian equivalent variation, which is a measure of the change in welfare at current prices that would have been equivalent to the welfare gain or loss experienced under the policy.

## International Trade

All goods are traded in a world market, subject to tariffs, export taxes, and international transport margins. Like the EPPA model (Paltsev et al., 2005), crude oil is assumed to be a homogeneous product trading at a single world price with adjustments for tariffs, export taxes, and transport margins. Coal, gas, refined oil, and electricity energy products are differentiated by domestic and foreign sources and aggregated into a single good for local consumption using an Armington assumption (see Figure 3-3), which has consumers treat domestic and imported goods as imperfect substitutes (Feenstra et al., 2014). The Armington structure is characterized by a nested CES production function, where the elasticity of substitution between domestic goods and import aggregates, defined as is set to 4.0 for all goods except electricity and biofuels, which is set to 0.3. The imported aggregates come from different regions abroad and have an elasticity of substitution, , of 5.0 between different regions for all imported goods and 0.5 for electricity and biofuels (Figure 3-3). The structure and the elasticities of substitution between inputs selected follow Paltsev et al. (2005), Ross (2009), or expert judgement of authors.

Figure 3-3. Structure of International Trade

Armington Commodity

0.3 for electricity and ag).

Imports (Foreign)

Export

Region 1…n

Domestic Production

Domestic Commodities

Foreign Region 1….n

0.5 for electricity and ag)

Note: Armington elasticities were based on Paltsev et al*.* (2005) and Ross (2009).

Goods produced domestically are either consumed by the domestic market or exported to other regions, assuming no product differentiation. In other words, the elasticity of substitution between domestic consumption and exports, defined *σde*, is assumed to be infinity.

This trade structure in ADAGE ensures a bilateral representation of trade flows, calibrated to the base year 2010, so that the regions can be both exporters and importers of certain goods (because domestically produced and imported goods are imperfect substitutes in an Armington structure). The bilateral trade flows include taxes on exports, tariffs on imports, and international margins of transportation, all explicitly represented in ADAGE.

## Government

The government is modeled as a separate agent in ADAGE that collects taxes. Tax rates are discussed in Section 4. Government purchases of goods and services are financed by taxes on output, personal income, consumption, capital, and imports/exports. Goods and services purchased by government have a Leontief demand structure, indicating there is no substitution between them. Government purchases of goods and services and the balance of payments deficit in the base period are set to grow at the same growth rate of simulated GDP. Section 6 provides additional information on ADAGE’s growth dynamics.

## Production

Markets are assumed to be perfectly competitive with firms unable to influence market prices. Firms are assumed to maximize profits subject to available production technologies with constant returns to scale. Actual returns to scale observed in the model may not be constant to the extent they rely on fixed factors of production. Production technologies are characterized by nested CES equations that allow firms to change the technologies used to manufacture goods. The nesting structure is designed to allow for setting multiple elasticities of substitution among different groups of inputs. The elasticities of substitution between inputs were taken from Paltsev et al. (2005) and Ross (2009), as shown previously in Table 3-4.

Most production technologies in the model share a common nested CES structure, illustrated in Figure 3-4: 1) Intermediate inputs (nonenergy, nonfactor inputs) generally enter production using fixed proportions, or a Leontief structure; 2) capital and labor are combined using a Cobb-Douglas function (*σva* of 1) to form the value-added goods; 3) the energy composite good, made up of electricity and nonelectricity, has an elasticity of substitution, , of 0.5. This measure controls the ability to shift between electricity and nonelectricity goods. Electricity is generated by conventional fossil fuel types and by renewable sources, such as hydropower, geothermal, nuclear, solar, wind, and bioelectricity. There also exists an elasticity of substitution, as 0.3 among electricity generation sources so firms can freely choose any type of electricity generation to maximize profit. Nonelectricity is composed of coal, natural gas, and refined oil, with an elasticity of substitution () of 1.0. Thus, coal, natural gas, and refined oil can be substituted for each other.

The nested CES structure of production technologies in ADAGE allows for energy-efficiency improvements. Producers can adjust their energy consumption by changing total output, substituting one type of energy for another, or using additional labor or capital to achieve energy-efficiency improvements. Substitution elasticities related to energy consumption are also important when investigating energy price impacts. If, for instance, an industry can improve its energy efficiency with relative ease or substitute from one type of energy to another, the price of its output will be less affected by changes in the price of one type of energy. The remaining subsections outline the specific model structure across sectors included in the ADAGE model.

### General Industry and Services

The sectors for general industry and services covered in this subsection are food (Mea, Vol, Ofd), manufacturing (Eim, Man), services (Srv), and conventional nonroad transportation services (AirP, WtrP, RalF, RalP, Otrn). These industry and service sectors have similar production structures and represent most gross output produced in many of the world’s economies. The production structure for conventional on-road transportation services has a slightly different CES structure; thus, it is discussed separately in Section 3.4.4.

The nested CES production structure for general industry and services sectors (other than on-road transportation) is shown in Figure 3-4. Intermediate inputs (materials), which are purchased as Armington aggregates of domestic and imported goods in conjunction with the energy composite and value-added (capital and labor), are at the top of the CES nest with fixed proportions (*σmat*). In figures that represent production structures, we use horizontal lines to represent fixed-proportion, Leontief production structures. The energy/value-added, composed from the energy composite and value-added from labor and capital, possesses an elasticity of substitution (*σeva*) of 1 at the reference year and grows to 1.5 linearly by 2050. This measure controls overall energy-efficiency improvements that can be achieved by substituting capital and labor for energy in production. Within this structure, the elasticity for energy/valued-added (*σeva*) and the two energy elasticities (*σenoe* and *σen*) have the greatest impact on production possibilities when examining energy and environmental policies because they control both efficiency improvements and fuel switching.

If a sector jointly produces multiple goods (e.g., in biofuels production), a constant elasticity of transformation (CET) is introduced to account for the relationship between the sector and its coproduct. Oil meal (), which is a coproduct of vegetable oil production, is included in the vegetable oil production structure (Vol) with a fixed production share relative to vegetable oil production (1 ton of soybean produces 0.80 tons of Omel and 0.19 tons of Vol). This relationship assumes that any improvement to the conversion rate of vegetable oil will have an equivalent effect on oil meal.

Figure 3-4. General Industry and Services Production Structure\*

Energy Composite

Electricity

Coal, Gas, Oil, Nuclear, Hydro….

Capital

Labor

Non-electricity

Output

Material Inputs Bundle 1…n

Energy/Value-Added Composite

Value-Added Composite

Coal

Gas

Refined Oil

\* Electricity includes generation from all technologies which is simplified here. More information is described in Section 3.4.3.

### Fossil Fuels

The supply of various fossil fuels is limited by the availability of their corresponding natural resource reservoirs. A fixed factor in the production of coal, natural gas, and crude oil is introduced into the model to represent this natural resource constraint based on data from the EIA’s International Energy Statistics (DOE, EIA, 2013). The presence of this factor also leads to decreasing returns to scale. The formulation of the CES equations (Figure 3-5) captures the idea that, while it is possible to develop more efficient mining equipment or invest in new deposit discoveries, it is not possible to produce these natural resources using only other inputs like capital, labor, or materials (Thomas and Gilbert, 2014). In the production functions, the natural resource is combined with the materials/value-added composite to extract and make the resource available for use by other industries. Natural resources, together with the materials/value-added composite, enter the top nest of the production function at proportions specified in the reference year. The elasticity of substitution for a fossil fuel natural resource (nr), *σnr,* is assumed to be 0.6 for all regions. Refined oil is not a natural resource sector that relies directly on extraction, but its production depends on the input of crude oil. The CES functions, as seen in Figure 3-6, capture this idea by allowing some substitution of factors (elasticity *σva*) but also assume 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 increase output of refined oil solely by using other inputs.

Figure 3-5. Fossil Fuel Production (Coal, Crude Oil, and Natural Gas)

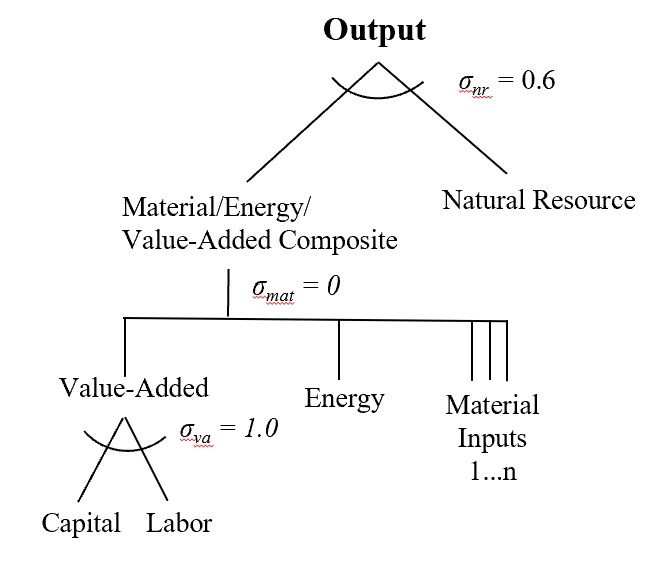


Figure 3-6. Refined Oil Production

Output

Materials

1...n

*σva = 1.0*

Crude Oil

Capital

Labor

Value-Added

Composite

### Electricity

The electricity sector and generation technologies are different from general industry and services sectors because of their heavy dependence on primary energy inputs and complex technology details. Established theoretical and physical engineering bounds on how efficiently fossil fuel inputs can be converted into electricity limit substitution opportunities. As a result of these considerations and the need to estimate impacts of energy and environmental policy on electricity markets, the production of electricity is modeled differently from other industries. Figure 3-7 shows the production structure for electricity generation technologies and how they are combined into a single electricity output aggregate. Combustion turbines for coal, oil, and natural gas along with combined cycle natural gas combustion are existing conventional fossil fuel technologies and have the same production structure as shown in the block of Conv\_Gas, while nuclear and renewable (hydroelectric, wind, solar, geothermal, and biomass) use a different production structure represented in the block of Hydro. All generation technologies have a fixed factor on the top nest. The fixed factor constrains how rapidly new technologies can be adopted and old technologies retired. An elasticity of substitution () of 0.3 governs substitution with the rest of the generation technology’s inputs and grows at 0.6% annually to reflect a greater ability to alter the generation mix farther into the future (Paltsev et al., 2005). The fixed factor moderates the speed of transition as generation technology costs shift over time (see Section 6.3 for more information). In the subnest of conventional fossil fuel generation, material inputs and energy/value-added composites enter in fixed proportions (= 0). The energy/value-added composite combines energy and a value-added aggregate in fixed proportions (*σeva* = 0). In the nuclear/renewable production block, the materials inputs and value-added in the subnest are entirely Leontief (= 0) except for labor-capital substitution with an elasticity (= 1).

Finally, electricity generated by each technology type is combined with an elasticity of 0.3 () to produce a single Armington electricity good that can be purchased for use by households, government, and other producers or exported. With this structure, ADAGE allows for the possibility of fuel switching between fossil fuel, nuclear, and renewable technologies, allowing for the expansion of zero-emissions energy sources when conditions are favorable, such as when those technologies have lower technology costs or policy incentives.

Figure 3-7. Electricity Generation

|  |
| --- |
|  |

### On-Road Transportation

There are three on-road transportation modes (light-duty, freight truck, and passenger bus) and each has five technologies: one conventional or “original equipment vehicle” fueled by oil-biofuel (OEV) technology that is available in the base year using refined oil as the main energy sources and four alternative fuel technologies (HEV, BEV, GASV, FCEV) that are not available in the base year but can enter the market if their cost becomes competitive in the future. Figure 3-8 shows the production structure by technology and how these technologies are combined for the corresponding transportation service for the mode. AFVs are illustrated by HEV in the figure and have the same production structure as OEV but different input shares. Transportation service, the monetary value for VMT for OEV and AFVs, are represented with nested CES functions using fixed factor, energy, capital, labor, and materials as inputs to produce the transportation service for the mode where the elasticity between the fixed factor and the rest of the inputs is assumed to be 0.1 for OEV, GASV, and FCEV and 0.2 for BEV and HEV in the top nest. Introducing an elasticity of substitution between the fixed factor and the rest of the inputs in the top nest of each technology’s CES production function moderates the pace of adoption for new technologies or phase-out of existing conventional technologies. The fixed factor represents nonmarket factors that may slow adoption (e.g., consumer willingness to adopt different technology, differences in utility or functionality). The remaining inputs are an energy/capital composite, labor, and materials at a fixed ratio () at the second nest of OEV and AFVs. The capital, together with the energy composite, forms the energy/capital composite with an elasticity of substitution of 0.01 () at the third nest. This structure allows for slight flexibility in substitution between energy and capital for new vehicles to reflect the fact that manufacturers can choose to produce more efficient vehicles in any given period (to some extent). The materials bundle includes service, energy-intensive manufacturing, other manufacturing, and various types of transportation with fixed ratios.

Energy used in transportation varies by mode and technology, as shown in Figure 3-8. Currently, most finished gasoline in the United States contains up to 10% ethanol by volume (E10), whereas a smaller amount of biodiesel is blended into petroleum diesel. Overall, biofuels accounted for about 5% of total U.S. energy consumption in the transportation sector in 2020, with ethanol supplying about 4% and biodiesel and renewable diesel combined supplying about 1% (EIA, 2021). First- and second-generation biofuels can be blended with refined oil substituting according to an elasticity () of 0.25. Substitution toward more biofuels displaces refined oil used in all on-road transportation modes and technologies. The fuel blending ratio differs for LDVs, freight trucks, and passenger buses with relatively more ethanol than biodiesel in LDVs and more biodiesel in heavy-duty vehicles. Refined oil-biofuel blends and electricity are used in hybrid vehicles at a fixed ratio (=0) to represent the average hybrid vehicle in each global region. Because hydrogen is not presently modeled as a commodity in ADAGE, we collapsed the production of hydrogen into the vehicle technology, which uses electricity and natural gas as inputs with an elasticity of 0.1 (), and the production of transportation services, which uses hydrogen and other inputs, into one composite production function for fuel cell technologies. Natural gas vehicles represent the combination of natural gas–only vehicles and dual-fuel vehicles (i.e., gasoline and natural gas), where natural gas and refined oil cannot substitute with each other in ADAGE (=0). Battery vehicles use electricity from the grid, meaning they draw on fossil fuel and renewable resources according to electricity production. Figure 3-9 diagrams the energy type inputs to each technology.

ADAGE’s vehicle technology representation supports assessing the potential implications of fuel economy standards for all new on-road technologies. Technologies purchase “permits” for their fuel use and produce permits at a rate of the efficiency standard. The input permit has a fixed ratio with fuel use, while the output permit is a coproduct and has a fixed ratio with the output of transportation service production. Therefore, technologies more efficient than the standard are subsidized at the expense of those less efficient that require more permits than they produce.

On-road transportation services are demanded by producers, governments, and households with completely elastic preferences over technologies within a mode. That is, services produced from OEV and AFVs within a mode are homogenous goods with perfect substitution ().

Figure 3-8. On-Road Transportation Service Production

\*Note: here BEV, GASV, FCEV have same production structure as HEV .

*σek*= 0.01

Capital

Labor

Materials 1…. n

OEV

Energy/Capital Composite

Refined Oil

Biofuels 1…. n

*σmat* = 0

Materials/Labor/Energy/Capital Composite

Fixed Factor

*σf = 0.1*

Oil-Biofuels

Other Energy

1 .… n

*= 0.25*

*= {0,0.1}*

Fixed Factor

*σf = {0.1,0.2}*

Materials/Labor/Energy/Capital Composite

Energy/Capital Composite

Energy

Materials 1…. n

Capital

GASV

BEV

FCEV

HEV

Labor

*σek= 0.01*

*σmat = 0*

**Output**

*σ = ∞*

Oil-Biofuels

*= 0.25*

Biofuels 1…. n

Refined Oil

Figure 3-9. Energy Used in On-Road Transportation by Technology

|  |
| --- |
|  |

### Agriculture and Forestry

The sectors for agriculture and forestry comprise eight types of crops, one livestock category, and one forest category. Their production in ADAGE is represented by the CES production structure shown in Figure 3-10. The CES nesting structure is designed to account for the use of land inputs, which are an essential fixed factor that is limited in supply. The formulation allows us to measure agricultural yield (e.g., tonnes per hectare of land) and allows agricultural output to be increased by conversion of other types of land to cropland (if possible) or the addition of materials, energy, or capital and labor. At the top nest in Figure 3-10, value-added is substituted against a resource-materials-energy bundle (σerva), allowing agricultural yield (per hectare of land) to be improved by using additional capital or labor. Energy and materials (σae) can be substituted for the natural resource (land in the case of agriculture and forestry) (σer), 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 produce the energy composite are the same as in the general industry and services sectors, discussed earlier in Section 3.4.1.

Figure 3-10. Agriculture and Forestry Production

Output

Natural Resource

(Land)

Value-Added

Composite

Resource-Materials-Energy

Composite

Materials-Energy

Composite

Capital

Labor

Material Inputs

Energy Composite

(same as services sector)

Materials 1…n

Note: Elasticity of substitution parameters were based on Paltsev et al. (2005) and Ross (2009).

### Biofuels

Biofuels in ADAGE are divided into two groups: the first-generation biofuels that are already available in the base year and second-generation biofuels that are not available in the base year but could be available in the future. The first-generation biofuels in ADAGE include corn ethanol (Ceth), wheat ethanol (Weth), sugarcane ethanol (Scet), sugar beet ethanol (Sbet), soybean biodiesel (Sybd), rapeseed-mustard biodiesel (Rpbd), and palm-kernel biodiesel (Plbd). They are produced in a nested CES function where the feedstock crop (e.g., corn for Ceth, wheat for Weth, and so on), value-added/material composites, and energy composite enter the top nest in fixed proportions (see Figure 3-11). Value-added and intermediate materials enter the second nest of value-added/material composites at a fixed proportion. The feedstocks for Ceth, Weth, Scet, Sbet, and Sybd are corn, wheat, sugarcane, sugar beet, and soybeans represented in ADAGE. However, oil palms and rapeseed are not broken out as individual crops but grouped into the rest of oilseed category (Osdn) in ADAGE. The input shares of Osdn in production of Plbd and Rpbd are built on their corresponding region-specific palm oil and rapeseed yield rates (gallon of biodiesel produced per ton of feedstock[[6]](#footnote-7)). Distillers’ grains with solubles (Ddgs) and corn oil biodiesel (Cobd) are introduced to the corn ethanol production function as coproducts, produced in fixed proportions. Soybean biodiesel production is slightly different from other biofuel production because vegetable oil and soybeans are both used as feedstocks. Given that oil meal is a coproduct of vegetable oil production, the proportion of oil meal from soybeans enters as a coproduct of soybean biodiesel. This CES structure ensures the conversion yield/rate from feedstock to biofuels and coproducts is calibrated to conversion data in terms of gallons of biofuel or pounds of coproducts per ton of feedstock. For example, 1 dry ton of corn yields 108 gallons of corn ethanol, 0.29 ton of Ddgs, and 2.74 gallons of Cobd in 2010.

Figure 3-11. First-Generation Biofuels Production

Output

Material Inputs

Value-Added

/ Material

Value-Added Composite

Coproducts

Feedstock

Energy Composite

Labor

Capital

Second-generation biofuels can employ inedible feedstock sourced from agriculture, forestry, and wastes. To estimate the role of second-generation biofuels in our economy and the interaction between energy, food, transportation, and the environment, we introduced five types of second-generation biofuels into ADAGE:

* switchgrass
* miscanthus
* agricultural residue (e.g., corn stover)
* forest residue (e.g., milling and harvest residues)
* forest wood (e.g., pulp logs and roundwood)

These five types of second-generation biofuels have similar Leontief production structures to many of the energy-related processes discussed previously. The labor-capital composite, material bundle (composed from energy-intensive manufacturing, road freight transportation, and service), energy bundle (includes oil, gas, and electricity[[7]](#footnote-8)), and land are in the top nest of the production function with an elasticity of substitution of zero (see Figure 3-12). Biofuels produced from agricultural residue and forest residue are two exceptions where land is not directly used as an input. The production of feedstock and conversion of the feedstock into biofuel were collapsed into one component of the production function (i.e., the capital and labor needed for both growing feedstock and converting the feedstock to a final fuel are combined), which is different from first-generation biofuels, where feedstock production is entirely separated from the biofuel process.

Figure 3-12. Second-Generation Biofuels Production in ADAGE

Output

Capital

Material

Inputs

Value-Added

Composite

Labor

Land

Energy-Intensive Manufacturing

Road Freight (truck)

Service

Energy

Composites

Electricity

Oil

Gas

### Land Conversion

Land use change in CGE models is typically divided into two approaches:[[8]](#footnote-9) a nested CET function, represented within the GTAP family of models (e.g., Ahmed, Hertel, and Lubowski, 2008; Golub, Hertel, and Sohngen, 2008; Hertel, 1997) and a nested CES function used in versions of the MIT EPPA model (e.g., Gurgel et al., 2016; Gurgel, Reilly, and Paltsev, 2007). In the CET approach, land is distributed to different land types (e.g., cropland, pastureland, and forestland) by an output nest. These land types can be used for different production uses (e.g., cropland for corn, wheat, soybean production, pastureland for livestock production). Additionally, the substitution parameters define the ease of shifting between land types. The CET approach has two disadvantages: 1) there is no explicit accounting for conversion costs between land types and 2) it does not conserve physical quantities such that the sum of acreage across land types equals the initial total acreage of all land types. The CET approach has been critiqued for use in long-term analysis because of its share-preserving feature (Gurgel et al., 2016).

In contrast, under the CES approach, each land type has its own endowment, land rent, and usage. The conversion cost between two land types will be equal to the difference in land rent between them in the competitive markets. The presence of conversion costs allows for persistent differences in rents across land types in competitive markets. Conversion occurs where additional benefits such as carbon credit incentives make the conversion costs worth bearing.

ADAGE uses a CES approach for land use change similar to Gurgel, Reilly, and Paltsev (2007). Land is separated into five types: cropland, pastureland, managed forestry land, natural forest, and natural grassland.[[9]](#footnote-10) Cropland can be used to produce various crops and second-generation biofuel feedstock. The livestock and forestry sectors exclusively use pastureland and managed forestland, respectively. Natural grassland and natural forestland are not used for market production (though they could potentially be converted to managed land types) but provide nonmarket environmental and species biodiversity benefits. To retain consistent land accounting, we structured land conversion to preserve physical units of land when converted (e.g., if 1 ha of land is converted, it must result in a total of 1 ha of other land types). Thus, the total amount of land remains constant. Through land conversion, the land gives up its original productivity level and land rent and takes on a new productivity level and land rent. In this process, the land conversion cost is equal to the difference of land rents between the two converting land types.

The nested CES function for land use change is shown in Figure 3-13. When land is converted from type *i* to type *j*, land type *i* and the other input bundle enter the top nest in fixed proportions, representing the restriction that conversion of 1 ha of land type *i* into type *j* must result in exactly 1 ha of land type *j*. Timber is produced as a coproduct when natural forestland is converted to managed forestland. A fixed factor is introduced to the subsequent nest with an elasticity of substitution ranging from 0.15 to 0.30, which is calibrated to observed historical land use change patterns during 1980 to 2005 (Gurgel, Reilly, and Paltsev, 2007). Material-energy/value-added composite, the lower-level nest, follows the same structure as the agriculture production function. In general, cropland has higher land rent, followed by pastureland, then managed forestland and natural land. When incentives are available for certain practices, such as payments for ecosystem services, landowners may adjust land cover and land use in response to the net returns provided by a combination of marketed goods and nonmarket goods for which they receive compensation. For instance, under programs such as the Conservation Reserve Program in the United States, farmers may voluntarily remove environmentally sensitive land from agricultural production in exchange for cost-share and rental payments from the U.S. Department of Agriculture (USDA).

Figure 3-13. Land Use Change

Landj ()

Material-Energy/

Value-Added Composite

Fixed Factor

Landi ()

Land-Materials-Energy Composite

Value-Added

Labor

Capital

Material-Energy/

Composite

Material Inputs

1…n

Material

Energy Composite

(Same as General Industry and Services)

Timber

# Base-Year Data and Linkage Between Monetary Accounts and Physical Quantity

This section discusses data requirements and sources for ADAGE and the methodologies for establishing the base-year data for 2010. The section also covers the methodologies used to link monetary accounts to corresponding physical accounts for the base year. The procedures developed by Babiker and Rutherford (1997) further described in Rutherford and Paltsev (2000) and adopted by Ross (2009) in development of the forward-looking version of ADAGE were used to move the GTAP base-year data from 2004 to 2010; integrate the economic, physical energy, agriculture, and transportation data; and rebalance the economic and physical data. These procedures are discussed extensively in this section, including incorporation of additional data sources. First, the primary data source (GTAP database v7.1) is detailed in Section 4.1, followed by data sources by sector over the remaining sections, covering agriculture (4.2), energy (4.3), transportation (4.4), and land use (4.5). Lastly, in Section 4.6, we discuss procedures employed to balance both economic and physical data.

## Main Database: GTAP v7.1

The major underlying database for the current version of ADAGE is the GTAP v7.1 database, a global economic database containing I/O data, detailed bilateral trade, and tax rates for 57 sectors and 112 regions for a single year, 2004 (Narayanan and Walmsley, 2008).[[10]](#footnote-11) These 112 regions cover the globe, where some are individual countries and others are aggregated regions. For example, “Rest of Western Asia” (XWS) includes Bahrain, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Palestinian Territory, Qatar, Saudi Arabia, Syrian Arab Republic, United Arab Emirates, and Yemen. The 57 sectors included in this dataset represent the entire economy with detail in agriculture and energy. The GTAPinGAMS package (Rutherford, 1997) was used to convert the GTAP v7.1 database into a dataset that can be directly used in the GAMS programming language.

To implement the GTAP database in ADAGE, country-level GDP data for 2004 and 2010 in the World Economic Outlook database 2010 from the IMF (IMF, 2010) were aggregated to these 112 regions and then used to extend the GTAP v7.1 data from 2004 through 2010, the base year in ADAGE. We then scaled all economic activity based on the change in GDP between 2004 and 2010 as a starting point for developing the 2010 base-year data. This method implies that the entire economy, including production, household consumption, intermediate demand, government demand, bilateral trade, and fixed factors such as capital, labor, and resources, were assumed to grow at the rate of GDP growth between 2004 and 2010. In this way, three basic conditions (market clearance, zero-profit condition, and income balance) that hold in the 2004 base year data were maintained in 2010 (Babiker and Rutherford, 1997; Paltsev, 2000) (because all factors in the balanced 2004 economy were assumed to grow at the same rate, leaving the economy balanced). Although this simple procedure provides a balanced dataset for 2010, it is not sufficient for our modeling purposes because it does not yield a dataset consistent with secondary data sources for our key sectors in 2010.[[11]](#footnote-12)

One important feature of ADAGE is that the model represents detailed information on agriculture, biofuels, land use change, and transportation. To ensure consistency with secondary data (including physical units) in these sectors, numerous adjustments were made to the starting base-year data for 2010 described above. The 57 sectors represented in GTAP v7.1 do not have details on biofuel and land use change and have very limited coverage for transportation. In addition, energy is a key sector for analyses of environmental policy and one for which we wish to ensure consistency with secondary data in physical units. Thus, procedures to split these existing sectors into those covered in ADAGE are described in Section 4.2 (agriculture), 4.3 (energy), 4.4 (transportation), and 4.5 (land use and land cover). In general, existing sectors were split into new sectors based on the I/O flow in a region. This method required information on the more disaggregated sectors’ consumption shares, cost shares, and trade shares to split them out from the existing aggregated sector. The consumption shares indicate how consumption in the new sectors (e.g., individual crops, biofuels, by-products) flows through household, intermediate, and government demands. Production cost shares define the new sectors’ cost structure and how the production of the existing sector was split into the new sectors. Trade shares were included to represent trade activity within the new subsectors relative to the existing aggregated sectors.

## Agriculture and First-Generation Biofuels Disaggregation

In ADAGE, we included eight types of first-generation biofuels that are not explicitly specified in the GTAP v7.1 database. These are four types of ethanol (made from either corn, wheat, sugarcane, or sugar beets) and four types of biodiesel (made from either soybean, rape-mustard, palm-kernel, or corn oil). We introduced these sectors into the database by disaggregating them from the existing GTAP sectors. Because several of the feedstock crops used to produce these first-generation biofuels in the GTAP database are aggregated (e.g., soybean, rapeseed, and palm seed are all included within the GTAP sector “oil seeds”), we split out some of these important feedstock crops and then introduced the biofuels and their by-products. Second-generation biofuels, such as cellulosic ethanol, are not available in the base year 2010 but may enter the market in future years. Thus, their production and consumption structures were not incorporated within the base-year database but are specified within the model so that they can enter the market in future years, as discussed in Section 6.

Table 4-1 depicts the agriculture and biofuel sectors in ADAGE and the existing sectors that are explicitly represented in the revised GTAP database (the complete list of sectors is given in Table A-2 in Appendix A).

* For crops, corn (*Corn*) and the rest of the grain category (*Gron*) were split from GTAP’s “cereal grains nec.”[[12]](#footnote-13) (*GRO*) sector, soybeans (*Soyb*), and the rest of the oil seeds (*Osdn*) (an aggregate for rapeseed, palm seed, and all other oil seeds not elsewhere classified) were split from oilseeds (*OSD*); sugarcane (*Srcn*) and sugar beet (*Srbt*) were separated from the aggregate sugar category (*C*\_*B*).
* For first-generation biofuels, both corn-ethanol (*Ceth*) and wheat-ethanol (*Weth*) were generated by splitting the food products sector (*OFD*), which receives inputs from corn and wheat; sugarcane ethanol and sugar beet ethanol were broken out from the chemicals sector (*CRP*); biodiesel produced from soybean, rapeseed, and palm oil seed were disaggregated from the vegetable oils and fats (*VOL*) sector.
* The by-products distillers dried grains with solubles (*Ddgs*) and corn oil biodiesel (*Cobd*) were introduced such that the total corn-ethanol industry jointly produces both corn-ethanol and these coproducts; the by-product oil meal (*Omel*) was split from the vegetable oil (*VOL*) sector in the GTAP database. These by-products, Ddgs and oil meal, are sold as feedstock to the livestock sector, while corn oil biodiesel is directly used by conventional on-road transportation industries.

Table 4-1. Explicit Biofuels and Feedstock Sectors Split from the Existing GTAP Sectors

|  |  |  |  |
| --- | --- | --- | --- |
| ID | Code in GTAP v7.1 | Description | Sectors in ADAGE |
| 3 | GRO | Cereal grains nec. | Corn + Gron |
| 5 | OSD | Oil seeds | Soyb + Osdn |
| 6 | C\_B | Sugarcane, sugar beet | Srcn + Srbt |
| 21 | VOL | Vegetable oils and fats | Sybd + Rpbd + Plbd + Vol + Omel |
| 25 | OFD | Food products nec. | Ceth + Ddgs + Weth + Ofd |
| 33 | CRP | Chemical, rubber, and plastic | Scet + Sbet + Eim |

Note: “nec” is the abbreviation of “not elsewhere classified.” Biofuels made from different feedstocks were split out from different GTAP sectors based on review of the existing GTAP v7.1 I/O tables to determine the initial allocation of agricultural commodity output value. Based on the sectors identified as using each of the relevant agricultural commodities, we modified the GTAP database to introduce bioenergy outputs as an explicit output generated during processing.

For splitting the agriculture and biofuel sectors in the GTAP database, we used a utility called SplitCom, software developed by Horridge, Madden, and Wittwer (2005). Taheripour et al. (2007; 2010) discussed the methodology to introduce three biofuel sectors (corn ethanol, sugarcane ethanol, biodiesel) and their coproducts (Ddgs from corn ethanol, oil meals from biodiesel) into the GTAP6 database using SplitCom. Beach et al. (2011) made the first effort to document the splitting process for agriculture using seven types of biofuels (corn ethanol, wheat ethanol, sugarcane ethanol, sugar beet ethanol, soybean biodiesel, rape biodiesel, and palm biodiesel) for ADAGE. This document discusses this process in more detail, focusing on data requirements and the linkage between physical and monetary accounts for both agriculture and biofuels. Below is an outline of the secondary data sources used in this process:

* The United Nations Food and Agricultural Organization (FAO) (2012) has developed a database called FAOSTAT that provides annual data on country-level production, consumption, price, imports and exports for crops, livestock, and food balance sheets in both physical and monetary units.
* USDA’s Economic Research Service (ERS) (2012) has a collection of data sources on production, consumption, prices, and trade in biofuel feedstocks, coproducts, and biofuels themselves.
* DOE’s EIA (2012) publishes monthly and annual data on biofuels production, consumption, and import and export data by country.
* [International Trade Statistics Database](https://comtrade.un.org/) from UN Comtrade data provides up-to-date bilateral country-level trade statistics for 99 goods and 11 services as far back as 1993 (United Nations, 2012).

Building up the physical accounts for the existing GTAP sectors and the new ADAGE sectors required significant production, consumption, and bilateral trade data. These data are available from the datasets in physical quantities, so the first step was to ensure the market clearance condition holds in these physical accounts. This condition needs to hold for both existing and new sectors and at each region/country level; then price was applied to the physical quantity to get the accounts in monetary units. By aggregating the FAOSTAT data categories into their corresponding agricultural and food sectors from GTAP v7.1, we generated the new agriculture and food sectors’ consumption shares. Production shares in monetary units used for splitting the GTAP sectors were computed by merging price and physical account information. Crop consumption was grouped into three types: 1) direct consumption by household; 2) intermediate consumption by industrial use, livestock feedstock, and seed demand; and 3) intermediate use for biofuel production, including corn, wheat, sugarcane, sugar beet, and oilseeds.

We combined the data from EIA, ERS, and GTAP v7.1 to obtain production and consumption of biofuels and their coproducts at the country level in both physical and monetary units and then computed their production and consumption shares from the aggregate sector data. The outputs of these new biofuel sectors were not used by themselves but were used in blending with petroleum, then that blended fuel was used by light-duty transportation vehicles. Although biofuel use in conventional heavy-duty transportation was not included in the 2010 base year, this technology is available in subsequent model years.

FAO, ERS, and EIA data were also combined with data from UN Comtrade to generate the bilateral trade shares for each new sector from their corresponding aggregated sectors. The trade margins (service and transport) were assumed to be the same as the margins in the existing aggregated sector.

After the steps above, we successfully broke out the new sectors from the existing sectors in the GTAP v7.1 dataset at the country level. We then aggregated all sectors and regions from GTAP v7.1 into the sectors and regions in the ADAGE model (see Appendix Table A-1 and Table A-2 for regional and sectoral aggregation, respectively, between ADAGE and GTAP v7.1).

The production cost data were collected from various secondary sources for cultivation and plant-specific processing costs of biofuels (Tiffany and Eidman, 2003; USDA ERS, 2006; Geller, 1985; OECD, 2006; Haas et al., 2005). ADAGE follows Taheripour et al. (2007) to determine the production cost structure for new agriculture and biofuel processes and their coproduct streams. The cost structure for the biofuels in 2010 for ADAGE regions is shown in Table 4-2. The price of biofuels was assumed to be $1.61/gallon of ethanol and $2.50/gallon of biodiesel globally, which is energy equivalent to $2.48/gallon of refined oil in 2010.

Table 4-2. Production Costs for Biofuel Products (2010$/gallon)

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Region | Sector | Input | | | | | | Output | |
| Feedstock\* | Energy\*\* | Chemical\*\*\* | Other\*\*\*\* | Labor | Capital | Biofuel | Ddgs |
| USA | Ceth | 0.85 | 0.01 | 0.15 | 0.04 | 0.06 | 0.81 | 1.61 | 0.32 |
| Sbet | 0.19 | 0.09 | 0.23 | 0.18 | 0.42 | 0.51 | 1.61 |  |
| Sybd | 2.12 | 0.02 | 0.07 | 0.00 | 0.11 | 0.18 | 2.50 |  |
| BRA | Scet | 0.28 | 0.07 | 0.05 | 0.17 | 0.34 | 0.69 | 1.61 |  |
| Sybd | 1.94 | 0.02 | 0.06 | 0.00 | 0.20 | 0.28 | 2.50 |  |
| CHN | Ceth | 0.70 | 0.41 | 0.15 | 0.04 | 0.05 | 0.58 | 1.61 | 0.32 |
| Sybd | 1.95 | 0.08 | 0.17 | 0.01 | 0.11 | 0.18 | 2.50 |  |
| EUR | Weth | 0.39 | 0.16 | 0.15 | 0.21 | 0.08 | 0.62 | 1.61 |  |
| Sbet | 0.10 | 0.16 | 0.13 | 0.15 | 0.50 | 0.58 | 1.61 |  |
| Plbd | 2.45 | 0.01 | 0.04 | 0.00 | 0.00 | 0.00 | 2.50 |  |
| XLM | Scet | 0.19 | 0.10 | 0.06 | 0.26 | 0.31 | 0.71 | 1.61 |  |
| Sybd | 2.35 | 0.04 | 0.07 | 0.00 | 0.01 | 0.02 | 2.50 |  |
| XAS | Weth | 0.56 | 0.24 | 0.14 | 0.05 | 0.06 | 0.57 | 1.61 |  |
| Scet | 0.03 | 0.04 | 0.06 | 0.44 | 0.31 | 0.74 | 1.61 |  |
| Sybd | 1.96 | 0.05 | 0.17 | 0.00 | 0.12 | 0.19 | 2.50 |  |
| Plbd | 1.60 | 0.02 | 0.06 | 0.00 | 0.32 | 0.50 | 2.50 |  |
| ROW | Ceth | 0.69 | 0.11 | 0.15 | 0.04 | 0.07 | 0.87 | 1.61 | 0.32 |
| Weth | 0.57 | 0.08 | 0.14 | 0.04 | 0.07 | 0.71 | 1.61 |  |

\* Feedstocks are corn for Ceth, sugar beet for Sbet, sugarcane for Scet, vegetable oil and soybean for Sybd, wheat for Weth, other oil seeds for Plbd.

\*\* Energy includes oil, natural gas, and electricity.

\*\*\* Chemical includes Eim and Man in ADAGE.

\*\*\*\* Other includes services, materials, and transportation.

## Energy

While other sectors were scaled from 2004 to 2010 to prepare the base-year data, the energy market required sector-specific changes to ensure the model accurately reflected 2010. The energy data in the GTAP v7.1 database are from IEA’s Energy Statistics (WES2007) (IEA, 2007), but no physical quantities are included in GTAP v7.1. The goal of this process was to align the energy data in the base year in ADAGE with actual energy statistics from 2010, rather than relying on GDP projections. Also, it is important to have physical energy accounts in the CGE framework for regulatory policy analysis. To achieve these two objectives, the following energy-related databases were incorporated into the model to replace the energy data generated by the scaled GTAP v7.1 dataset:

* World Energy Statistics from IEA (IEA, 2007) contains energy balance data for over 150 countries and regions in 2007, including energy import, export, and sectoral and household consumption in physical units (thousand tons of oil equivalent) for coal, gas, crude/refined oil, electricity, and renewable energy. Electricity generation is separated by generation type, for example, coal, gas, refined oil, and other renewables sources such as nuclear, bioelectricity, wind, solar, geothermal, and hydropower.
* EIA’s International Energy Outlook 2010 (IEO 2010) (DOE, EIA, 2010) provides projections of regional/country energy consumption and production from 2007 through 2035 for 16 regions, with the United States, Canada, Mexico, Japan, South Korea, Australia/New Zealand, Russia, China, India, and Brazil as stand-alone countries and the rest of the world grouped into six regions. The energy consumption sectors include four categories: residential, commercial, industrial, and transportation.
* Energy Prices and Taxes online data service in 2010 (IEA, 2010) from the OECD library provides end-use energy prices and taxes for coal, gas, crude/refined oil, and electricity generated from different types of sources for OECD and non-OECD countries.
* The National Renewable Energy Lab Annual Technology Baseline (ATB) (NREL, 2020) provides annual cost and generation data for electricity and transportation sectors within the United States. The electricity data include capital expenditures, operation and maintenance expenditures, capacity factors, and levelized costs with projections through 2050. The ATB data were used in conjunction with the IEO data to disaggregate electricity technologies and update generation costs.

The energy data from WES2007 were first aggregated into the 112 regions used in GTAP v7.1. Because the WES data represented a 2007 snapshot, growth rates between 2007 and 2010 from IEO2010 were used to extend the WES2007 data to 2010. For all countries found in the 16 IEO2010 regions, the production growth rate was applied to both energy production and exports, while sectoral consumption growth rates for residential, commercial, industrial, and transportation were applied to the sectors falling into these four categories. Imports were assumed to grow at the same rate as their aggregated sectoral consumption growth rates. Where there exists further sectoral disaggregation, for example, in the transportation, agricultural, and biofuel sectors previously discussed, relative shares were assigned to disaggregate each sector’s energy demand. During this process, the physical energy accounts had to remain in balance for 2010. After that, we obtained corresponding monetary accounts by multiplying the physical accounts with energy price and tax information for 2010 from the OECD library database. The cleaned energy data were named by the authors for convenience as our world energy dataset 2010 (WED2010) and used in transportation disaggregation.

## Transportation Disaggregation

In the transportation industry, technology improvements, represented by decreased energy usage per unit of output, vary significantly by transportation mode. Disaggregation of the transportation sector can improve the representation of energy substitution possibilities among and across transportation modes. To gain a fuller understanding of the GHG mitigation potential of the transportation sector, the model disaggregates the transportation sector into eight types (light-duty passenger, road freight, road passenger, rail freight, rail passenger, air, water, and all other transportation). The GTAP v7.1 database has only three types of transportation (air, water, and the rest), and WED2010 has six transportation sectors (road, rail, air, water, pipeline, and other). Thus, to achieve our target level of transportation sector disaggregation of the eight types named above, modifications to the sectors in both the GTAP v7.1 and IEA databases were necessary. Although we used SplitCom for the agriculture and biofuel disaggregation, we broke up the transportation sector using a combination of the GTAP v7.1 and WED2010. Tables 4-3 and 4-4 show the transportation sector mapping between ADAGE and GTAP v7.1 and between ADAGE and IEA, respectively. The diagram in Figure 4-1 shows the data sources and process used for the transportation split and is discussed in the following sections. The additional data sources required to construct the consumption shares, production shares, trade shares, and production cost shares in the existing GTAP and WED2010 sectors are as follows:

* Input and output data from Global Change Analysis Model 4.2 (GCAM), an integrated assessment model developed and maintained by Pacific Northwest National Laboratory (PNNL) (PNNL, 2015; Kim et al., 2006). The transportation module in GCAM includes simulated output, such as transportation service production in physical (VMT) and monetary units [$], service unit cost [$/VMT], energy consumption [Quad], energy intensity [Quad/VMT], energy price [$/Quad] for various modes, and size class for 14 regions worldwide. Key input data used in ADAGE, such as load factor defined as the average number of passengers (passenger transportation) or average tonnes per vehicle (freight transportation) (persons or tonnes per vehicle), nonenergy unit cost ($/VMT), and fuel economy (miles/gallon of refined oil equivalent) by transportation mode, size class, and region, were updated to align with the values in PNNL (2015).
* I/O accounts data from the Bureau of Economic Analysis (BEA) within the U.S. Department of Commerce (BEA, 2016) provide detailed consumption by end use, gross production, and input usage for seven types of transportation (air, rail, water, truck, transit and ground passenger transportation, pipeline, and other transportation) in the United States.

Table 4-3. Explicit Transportation Sectors Split from the Existing GTAP v7.1 Sectors

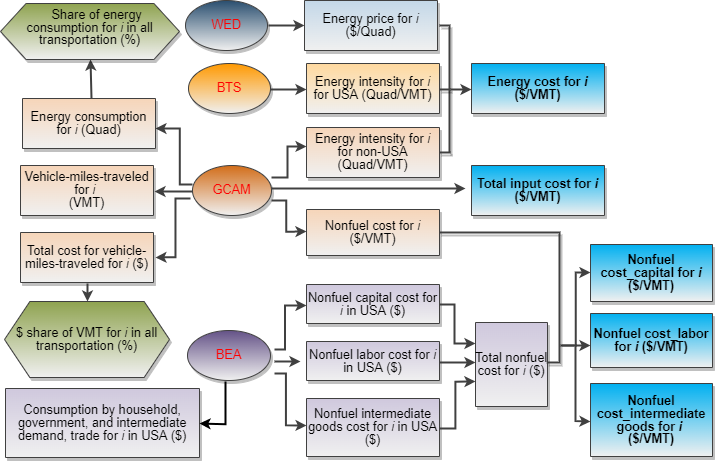
|  |  |  |  |
| --- | --- | --- | --- |
| GTAP | | ADAGE | |
| Existing Sectors | Definition | New Sectors | Definition |
| ATP | Air transport | AirP | Airline transportation (passenger) |
| WTP | Water transport | WtrT | Marine transportation (freight and passenger) |
| OTP | Transport nec. | RalF | Rail freight |
|  |  | RalP | Rail passenger |
|  |  | RodF | Road freight (truck) |
|  |  | RodP | Road passenger (bus) |
|  |  | Auto | LDV passenger |
|  |  | Otrn | All other transportation (off road and pipeline) |

Table 4-4. Explicit Transportation Sectors Split from the Existing WED2010 Sectors

| IEA | | ADAGE | |
| --- | --- | --- | --- |
| Existing Sectors | Definition | New Sectors | Definition |
| Air | Air transport | AirP | Airline transportation (passenger) |
| Water | Water transport | WtrT | Marine transportation (freight and passenger) |
| Rail | Rail transport | RalF | Rail freight |
| RalP | Rail passenger |
| Road | Road transport | RodF | Road freight (truck) |
| RodP | Road passenger (bus) |
| Auto | LDV passenger |
| Pipeline | Pipeline transport | Otrn | All other transportation (off road and pipeline) |
| Other | The rest transport |

The modes and size classes defined in GCAM provide enough information for us to aggregate the transportation service production output and energy consumption output into the eight types of transportation included in ADAGE. The transportation service production shares in 2010 (in dollars) were used to split the Transport nec (“OTP”) sector within the GTAP data into the six land-based transportation sectors in ADAGE. Meanwhile, the energy consumption shares used in transportation (defined in quads) in 2010 were used to break “Rail” into rail freight (“RalF”) and passenger (“RalP”); “Road” into road freight (“RodF”), road passenger (i.e., public road transit; “RodP”), and private road transportation (“Auto”); and aggregate pipeline and “Other” into “Otrn” from the WED2010 data into the sectors defined in ADAGE.

Figure 4-1. Data Processing Diagram Used in Transportation Sector Disaggregation



Note: Blue boxes represent the final datasets used in ADAGE.

Data sources: GCAM represents Global Change Assessment Model 4.2; WED represents the cleaned energy data from WES2007 (IEA, 2007), IEO2010 (DOE, EIA, 2010), and IEA2010 (IEA, 2010); BTS represents Bureau of Transportation Statistics (BTS) within the U.S. Department of Transportation (BTS, 2015); BEA: I/O accounts data from BEA within the U.S. Department of Commerce (BEA, 2016); year 2010 in these data sources is used for transportation disaggregation.

As in the agricultural disaggregation, we brought in more data to generate consumption shares and trade shares of new transportation sectors from the existing three types of transportation in the GTAP v7.1 database. There are multiple sources of demand for each ADAGE transportation type, including household consumption, government consumption, and intermediate demand from all industrial sectors. Detailed data on the household consumption, government consumption, and intermediate demand by industries are not easily available in a partial equilibrium model such as GCAM but are normally available in a national I/O database, as required by a CGE model. Thus, I/O data covering 1997 through 2015 were collected from BEA.

After we applied this data process to all types of production and consumption data in BEA, we obtained the transportation consumption from household, government, and intermediate demand, as well as imports and exports for the eight new types of transportation in the United States. Because no analogous I/O data are available for non-U.S. regions, the share of each individual type of transportation over the entire transportation sector in the United States in 2010 was also applied to the seven non-U.S. regions in ADAGE, splitting the three types of GTAP transportation data into eight types for household consumption, government consumption, and intermediate demand from other sectors, imports, and exports.[[13]](#footnote-14)

The next step in the transportation sector disaggregation process was to develop a production cost share structure for the new transportation sectors. In other words, we needed to determine the amount of energy, labor, capital, and intermediate goods used to produce the disaggregated forms of transportation service. We began with a unit cost structure where unit input cost is based on the cost per VMT for all passenger transportation. For non-U.S. regions, the energy unit cost for each type is the product of energy price ($/Quad) from the WED2010 and 2010 energy intensity input data (Quad/VMT) from GCAM inputs. The nonenergy unit cost (sum of capital, labor, intermediate goods) in GCAM for new transportation sectors is available in aggregate and was split into labor, capital, and intermediate goods. Because the United States is our region of primary focus and because more detailed data are available for this region, we replaced the U.S. energy intensity data (Quad/VMT) from GCAM with data from the 2010 BTS from the U.S. Department of Transportation. We disaggregated these U.S. data using the shares of labor, capital, and intermediate inputs from BEA. In the absence of better information for non-U.S. regions, we applied the share estimated for the United States in all eight regions. The unit cost for all inputs ($/VMT) was multiplied by the corresponding output of transportation service to obtain the amount of energy, labor, capital, and intermediate goods used as inputs to produce the transportation service.

Production in the eight disaggregated transportation sectors in ADAGE is represented as nested CES functions that use energy, capital, labor, and services as inputs to produce transportation services. The labor-capital bundle, together with the energy bundle comprising refined oil and biofuel, forms the labor-capital-energy composite. Transportation service is then produced using the labor-capital-energy composite and services at a fixed ratio. Section 3.4.4 provides details on the transportation production structure.

## Land Use and Land Cover

Growing populations and economies increase the demand for food, putting more pressure on cropland and pastureland. In contrast, natural land does not provide market outputs but has GHG mitigation potential and provides ecosystem services. Land competition between cropland, pastureland, and natural land is very important for evaluating the potential trade-offs between social welfare (e.g., food security, energy security), environmental services, and economic welfare. Thus, we introduced five land types (cropland, pastureland, managed forestland, natural forestland, and natural grassland), their land conversion, and the associated GHG emissions from land use change into ADAGE.

Data sources for land use and land cover are:

* FAOSTAT from FAO (2012), which provides yields and harvested acreage from 1963 through 2013, and
* Land cover from a linked modeling system: EPPA-TEM, a CGE model of the world economy; EPPA, developed by MIT’s Joint Program; and the Terrestrial Ecosystem Model (TEM), developed by the Marine Biology Laboratory (Reilly et al., 2012).

First, individual 2010 crop acreage data from FAOSTAT by country were aggregated to the eight types of crops and eight regions in the ADAGE model. Second, the 0.5° latitude × 0.5° longitude 2010 grid-level land cover from TEM was aggregated to the five land types and eight regions in ADAGE. Total crop acreage is available in both datasets, and the percentage deviation from FAOSTAT relative to EPPA-TEM ranges between −44% and 34%. Some regions were found to have larger crop acreage in FAOSTAT than in EPPA-TEM, for example, Brazil, China, Rest of Asia, and Africa.[[14]](#footnote-15) At the same time, the crop yields in those regions were found to be lower compared with other regions. To merge these datasets while maintaining total land area, we chose the lowest cropland acreage between these two datasets. In the case where acreage from EPPA-TEM was chosen, the individual crop acreage was then scaled to ensure that the total cropland acreage aggregated from FAOSTAT was equal to the total cropland acreage from TEM. A direct effect from this assumption is crop production remains the same, but crop yield for these regions increases implicitly where the acreage decreases. The resulting land distribution in ADAGE in 2010 is displayed in Table 4-5.

Table 4-5. Land Area by Region and Land Type in 2010 (Mha)

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Land** | **USA** | **BRA** | **CHN** | **EUR** | **XLM** | **XAS** | **AFR** | **ROW** |
| Cropland | 132.8 | 74.6 | 199.5 | 128.0 | 74.1 | 339.4 | 176.9 | 238.7 |
| Wht | 22.9 | 2.7 | 17.8 | 31.0 | 6.3 | 45.7 | 7.3 | 75.0 |
| Corn | 32.6 | 16.5 | 18.0 | 10.2 | 10.1 | 18.5 | 25.2 | 15.0 |
| Gron | 5.5 | 1.3 | 0.9 | 28.9 | 3.2 | 12.4 | 46.8 | 39.4 |
| Soyb | 30.8 | 24.0 | 8.9 | 0.3 | 21.7 | 9.4 | 1.0 | 2.7 |
| Osdn | 2.3 | 1.0 | 5.4 | 17.6 | 4.9 | 38.6 | 20.7 | 22.8 |
| Srcn | 0.4 | 9.3 | 1.7 | 0.0 | 2.7 | 9.0 | 1.3 | 0.7 |
| Srbt | 0.4 | 0.0 | 0.2 | 1.8 | 0.0 | 0.1 | 0.2 | 1.6 |
| Ocr | 36.7 | 16.2 | 105.0 | 37.9 | 22.1 | 72.3 | 64.6 | 80.4 |
| Pastureland | 119.2 | 121.3 | 184.8 | 55.7 | 244.9 | 147.2 | 744.4 | 955.0 |
| Managed forestland | 80.3 | 60.9 | 35.8 | 68.8 | 69.8 | 64.7 | 151.2 | 196.7 |
| Natural forestland | 195.1 | 478.8 | 93.8 | 141.1 | 336.0 | 456.1 | 564.1 | 1182.3 |
| Natural grassland | 242.8 | 95.4 | 178.4 | 37.3 | 150.7 | 135.9 | 530.9 | 900.3 |
| Other land | 106.4 | 23.6 | 241.1 | 29.6 | 152.1 | 166.8 | 851.0 | 1086.6 |
| Total land | 875.3 | 851.0 | 891.8 | 460.2 | 1024.4 | 1176.5 | 3008.8 | 4558.4 |

Note: Srcn and Srbt acreage is relatively small globally, though important for bioenergy production. In general, regions with 0 values for those crops do have some acreage devoted to Srcn and/or Srbt, but the acreage is <0.05 Mha so it was rounded to 0.

In general, agriculture land can be converted to another type of agriculture land or natural land. Natural land can be converted to the corresponding managed land, for example natural forest land to managed forestland. Land conversion depends on the relative land unit price between two land types and the willingness to convert. To enable land use change, each of the five land types, including natural land, must have a region-specific unit land price. The regional cropland unit price was assumed to be the same for all eight types of crops (Gurgel, Reilly, and Paltsev, 2007). Regional land price per hectare is the regional land value divided by regional land acreage for cropland, forestland, and pastureland. Following the approach in Reilly et al. (2012), we derived natural forest and grassland prices from managed forest and pasture data from EPPA-TEM in 2010, assuming the price ratio of natural grassland to pastureland is equal to the price ratio of natural forestland to managed forestland for all regions except USA and EUR, which were adjusted to avoid unrealistic land prices. Table 4-6 displays the land unit price by region and by land type in 2010.

The elasticity for willingness to convert and the fixed factor when natural land is converted to other land were taken from the Observed Land Supply Response model of EPPA in the study by Gurgel, Reilly, and Paltsev (2007).

Table 4-6. Land Unit Price by Region and Land Type in 2010 (2010$/ha)

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Land Type | USA | BRA | CHN | EUR | XLM | XAS | AFR | ROW |
| Cropland | 250 | 105 | 250 | 615 | 319 | 493 | 99 | 172 |
| Pastureland | 88 | 24 | 129 | 324 | 34 | 182 | 4 | 17 |
| Managed forestland | 24 | 15 | 334 | 64 | 23 | 142 | 24 | 36 |
| Natural forestland | 8 | 1 | 20 | 13 | 11 | 58 | 2 | 11 |
| Natural grassland | 1 | 2 | 8 | 6 | 16 | 75 | 0 | 5 |

## Data Process to Satisfy Zero Profit, Market Clearance Condition, and Income Balance

We have discussed sector aggregation and disaggregation for agriculture, biofuel, transportation, and energy data replacement for the GTAP v7.1 database. Consequently, market clearance, zero-profit conditions, and the income constraint no longer hold following these modifications to the original GTAP v7.1 database, and additional modifications are needed to rebalance the dataset. A key challenge was ensuring all conditions continue to be met following the creation of additional disaggregated markets for all markets and region-wide budget constraints.

In the agriculture and biofuel disaggregation, SplitCom was used on the GTAP data, which allowed for rebalancing of the new base-year data within the software to preserve these conditions and accounting identities. For energy replacement from the new WED2010 data and the disaggregated transportation sector, it was less straightforward. We developed an optimization model to minimize the sum of the squares of the deviation between the initial data and the adjusted data for all goods while simultaneously satisfying the three accounting identities (i.e., zero profit, market clearance, and income balance). Sectoral domestic production and energy input requirements were assumed to remain fixed at the initial level, while labor, capital, and other nonenergy intermediate goods were adjusted to satisfy the zero-profit condition. Similarly, consumption for household, government, and bilateral trade were adjusted to ensure market clearance conditions hold. Finally, labor, capital, and other resource endowments were restricted to equal the demand of labor, capital, and resources used across all sectors, households, the government, and balance of payment deficit to satisfy the income constraint. The modified data preserve these three accounting identities and become the final base-year data used in ADAGE.

# GHG Emissions

ADAGE accounts for six types of Kyoto GHG emissions: carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), perfluorocarbons (PFCs), hydrofluorocarbons (HFCs), and sulfur hexafluoride (SF6), gases that have direct radiative forcing effects in the atmosphere. This section discusses the data sources and procedures used to prepare GHG emissions accounting in ADAGE for the 2010 base year and for future emissions pathways through 2050. CO2 emissions from fossil fuel use are tied directly to the combustion of fossil fuels, while CO2 emissions from land use change are tied to changes in the carbon stock in various land types. Other GHG emissions are linked to various sectoral production activities, described later in the section. This section is organized into three subsections: 1) CO2 emissions from fossil fuel energy combustion in Section 5.1, 2) CO2 emissions from land use change in Section 5.2, and 3) GHG emissions other than CO2 emissions from fossil fuel and land use change in Section 5.3.

## CO2 from Fossil Energy Combustion

Previous sections discuss how ADAGE models fossil fuel production, consumption, and trade, not only in terms of value, but also in physical units (quad Btu). CO2 emissions from fossil fuel use are directly tied to the combustion of such quantities of fossil fuels, meaning that the CO2 emissions factor of fossil fuel combustion is a constant number based on fuel type. By multiplying this CO2 emissions factor by the fuel consumption, ADAGE can determine emissions levels (typically reported by the model in terms of millions of metric tons of carbon dioxide [equivalent], or MMT CO2eq).

CO2 emissions and fuel consumption data were collected from EIA’s International Energy Statistics (DOE, EIA, 2013). EIA reports annual CO2 emissions from coal, natural gas, and oil for 230 countries/regions from 1980 through 2015. Emissions and fuel consumption by type were aggregated to the eight regions in ADAGE for 2010. The CO2 emissions factor was obtained by dividing this CO2 emissions level by fuel consumption and is shown in Table 5-1. These emissions factors were then multiplied by fuel consumption in the base year to obtain the base-year CO2 emissions. They can also be multiplied by fuel consumption over time to project CO2 emissions pathways.

To enable carbon policy–related analysis, we introduced CO2 emissions from fossil fuels into the fossil fuel retail market. The functional form is Leontief where the elasticity of substitution between fuel and CO2 emissions is zero, reflecting a fixed relationship. Over time, CO2 abatement activity on the producer’s side involves improving energy efficiency (or reducing output) to use less fuel, switching to cleaner energy sources, or installing CO2 control equipment (i.e., carbon capture and storage). Fuel switching is controlled by the model’s CES nesting structure and substitution elasticities or through technology switching in transportation and electricity. Households also can switch fuels, lower overall consumption, and improve their overall energy efficiency.

Table 5-1. CO2 Emissions Factors from Fossil Fuel Combustion (kg CO2/mmBtu)

|  |  |  |  |
| --- | --- | --- | --- |
| Region | Coal | Gas | Oil |
| USA | 95.1 | 64.4 | 72.5 |
| BRA | 114.2 | 72.7 | 97.3 |
| CHN | 128.3 | 69.6 | 86.2 |
| EUR | 101.4 | 64.0 | 76.8 |
| XLM | 135.8 | 75.2 | 87.4 |
| XAS | 115.5 | 75.6 | 88.8 |
| AFR | 132.8 | 74.7 | 81.0 |
| ROW | 126.2 | 60.4 | 70.7 |

Source: Data were retrieved from EIA’s International Energy Statistics (DOE, EIA, 2013) and compiled by the authors.

## CO2 from Land Use Change

Emissions or sequestration of CO2 can occur because of land use change. When land is converted from one type to another, CO2 is released from plants and soil. This process involves immediate and long-term effects, making it difficult to model emissions from land use change, even in a disaggregated biophysical model. Under a much more aggregated CGE framework, we represent land use emissions using a simple approach. When land is converted from one type (*i*) to another (*j*), the net sequestration per ha, , is calculated in Eq. 5.1:

(5.1)

where and are land types and and represent vegetation and soil, respectively; denotes the 20-year land-use change emissions associated with converting from land type ; then is the net sequestration (emissions if negative) from land conversion from land type to ; represents the emissions factor cumulative over a 20-year horizon and represents carbon stocks; and represent the vegetation carbon stock and emissions factor for land type *i*. When is positive, the land conversion leads to an increase in carbon sequestration. However, when is negative, the land conversion leads to net emissions. Our emissions factors are from Timilsina and Mevel (2013).

The vegetation carbon and soil carbon were obtained from an open-source community model—GCAM 3.2, developed by the Joint Global Change Research Institute at PNNL (PNNL 2012). The vegetation biomass carbon and soil carbon (vegc, soilc), separated by 18 agro-ecological zones (AEZs) and 14 regions in GCAM, were then aggregated to the ADAGE regions and land types using weighted areas. Table 5-2 summarizes the carbon stock profile obtained from the GCAM 3.2 input data (PNNL, 2012) where the land acreage from GCAM was used as weight.

Table 5-2. Vegetation and Soil Carbon Stock from GCAM (metric ton CO2eq per ha)

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Region** | **Cropland** | | **Pastureland** | | **Managed Forestland** | | **Natural Forestland** | | **Natural Grassland** | |
| **vegc** | **soilc** | **vegc** | **soilc** | **vegc** | **Soilc** | **vegc** | **soilc** | **vegc** | **soilc** |
| USA | 10 | 299 | 12 | 264 | 209 | 504 | 418 | 579 | 27 | 355 |
| BRA | 11 | 256 | 14 | 286 | 344 | 319 | 687 | 367 | 39 | 382 |
| CHN | 13 | 301 | 13 | 293 | 236 | 379 | 473 | 435 | 28 | 392 |
| EUR | 10 | 317 | 14 | 276 | 199 | 520 | 398 | 598 | 40 | 368 |
| XLM | 11 | 256 | 14 | 286 | 344 | 319 | 687 | 367 | 39 | 382 |
| XAS | 11 | 229 | 13 | 276 | 321 | 315 | 665 | 364 | 41 | 356 |
| AFR | 6 | 209 | 12 | 247 | 332 | 312 | 663 | 359 | 44 | 334 |
| ROW | 8 | 306 | 12 | 263 | 178 | 555 | 302 | 693 | 30 | 351 |

Note: Data are from GCAM 3.2 (PNNL 2012 and raw files were extracted from L212 and L213 in the folder Main\_User\_Workspace \input\aglu\Input Module) and were compiled by RTI. Vegc and soilc refer to biomass carbon and soil carbon, respectively.

Land use emissions factors were collected from the appendix table from Timilsina and Mevel (2013), which is grouped by AEZ for aboveground, belowground, and soil carbon for forest and pastureland. The emissions factor for vegetation carbon is the area-weighted average of emissions factors from aboveground and belowground biomass. We then assumed the emissions factor for cropland by AEZ is equal to the emissions factor of pastureland. In addition, emissions factors for natural forestland and natural grassland were assumed to equal the data’s emissions factor for forestland. Finally, and similarly to carbon stocks, the area and zone mapping in GCAM were then used to convert the emissions factors to ADAGE regions and land types (see Table 5-3).

Table 5-3. Land Use Emissions Factors

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Region | Cropland | | Pastureland | | Managed Forestland | | Natural Forestland | | Natural Grassland | |
| vegc | soilc | vegc | soilc | vegc | Soilc | vegc | soilc | vegc | soilc |
| USA | 0.56 | 0.27 | 0.55 | 0.23 | 0.61 | 0.27 | 0.61 | 0.27 | 0.61 | 0.23 |
| BRA | 0.56 | 0.40 | 0.56 | 0.37 | 0.62 | 0.49 | 0.62 | 0.49 | 0.61 | 0.37 |
| CHN | 0.56 | 0.28 | 0.56 | 0.23 | 0.60 | 0.33 | 0.60 | 0.33 | 0.61 | 0.23 |
| EUR | 0.56 | 0.30 | 0.56 | 0.29 | 0.61 | 0.30 | 0.61 | 0.30 | 0.61 | 0.29 |
| XLM | 0.56 | 0.40 | 0.56 | 0.37 | 0.62 | 0.49 | 0.62 | 0.49 | 0.61 | 0.37 |
| XAS | 0.56 | 0.39 | 0.56 | 0.29 | 0.62 | 0.46 | 0.62 | 0.48 | 0.62 | 0.29 |
| AFR | 0.56 | 0.41 | 0.56 | 0.38 | 0.62 | 0.48 | 0.62 | 0.48 | 0.62 | 0.38 |
| ROW | 0.56 | 0.27 | 0.56 | 0.25 | 0.61 | 0.27 | 0.61 | 0.27 | 0.62 | 0.24 |

Note: Data are from Timilsina and Mevel (2013) and were compiled by RTI. Vegc and soilc refer to biomass carbon (both above- and belowground) and soil carbon, respectively.

## Characterization of GHG Emissions Other than CO2 from Fossil Fuel Combustion and Land Use Change

|  |
| --- |
| Figure 5-1. GHG Emissions |
| Output  Rest Inputs Bundle  (CES functions in Section 3)  GHG  Emissions |

Beyond CO2 emissions from fossil fuel combustion and land use change, there are other sources of GHG emissions, such as CO2 from cement production; CH4 from rice, livestock manure, and landfills; and N2O from coal combustion, agricultural soils, and various waste-related emissions. These sources are discussed in this section because they are introduced into the top nest of the sector-specific production function from which they are produced in ADAGE (see Figure 5-1). Unlike the zero elasticity of substitution between CO2 and fossil fuel combustion, the elasticity of substitution between GHG emissions and the rest of the input bundle was adapted from Ross (2009) and fit to match bottom-up estimates of abatement possibilities. The elasticities of substitution are presented in Table 5-4.

Table 5-4. Reference Values of Elasticities of Substitution for Greenhouse Gases

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Sector | CO2 | CH4 | N2O | HFC | PFC | SF6 |
| Household | 0 | 0.21 |  |  |  |  |
| COL | 0 | 0.40 |  |  |  |  |
| ELE | 0 | 0.11 |  |  | 0.16 |  |
| GAS | 0 | 0.13 |  |  |  |  |
| OIL | 0 | 0.10 |  |  |  |  |
| AG | 0 | 0.05 | 0.07 |  |  |  |
| Eim | 0 | 0.11 | 0.70 | 0.40 | 0.12 | 0.60 |
| Man | 0 | 0.11 |  | 0.40 | 0.14 |  |

Note: Household refers to goods and services directly consumed by households; AG represents all agricultural sectors such as crops, livestock, and forestry.

GHG data in ADAGE come from two primary sources: 1) CO2 emissions from the Emissions Database for Global Atmospheric Research (EDGAR) from the Joint Research Centre (JRC) at the European Commission (JRC, 2013) and 2) non-CO2 emissions from *Global Non-CO2 GHG Emissions: 1990-2030* from EPA (2013). EDGAR version 4.2 provides CO2 emissions for 32 emissions sources in 2010 for more than 230 countries. CO2 emissions sources other than fossil fuel combustion and land conversion were included and mapped to ADAGE regions and sectors. *Global Non-CO2 GHG Emissions: 1990-2030* from EPA provides historical non-CO2 emissions (CH4, N2O, PFCs, HFCs, and SF6) from 1990 through 2010 and projections from 2010 through 2030 from more than 20 emissions sources for approximately 200 countries. Again, these non-CO2 emissions were aggregated to ADAGE regions and sectors. These two data sources were then merged to obtain base-year emissions in CO2 equivalents (CO2eq) and base-year emissions factors (base-year emissions divided by base-year output) in terms of CO2eq per unit of output.

GHG emissions per unit of agricultural output tend to decrease over time through improvement of emissions reduction technologies. The implementation of these emissions reduction technologies over time plays an important role in GHG emissions mitigation. Rather than staying constant, the emissions factors for agriculture decline over time as more emissions reduction technology becomes available. It is a challenging task to estimate the dynamic growth path of GHG emissions factors because sector-specific output projections by country are rarely available. If we were to assume agricultural output grows at the same rate as GDP, emissions factor improvement for agriculture would be overstated because agriculture has tended to grow more slowly than national GDP in recent decades. The World Bank uses historical changes in the share of agriculture as a percentage of GDP by country from 1980 through 2013 to estimate the annual growth rate for agriculture as a share of GDP given the assumption of a constant growth

|  |
| --- |
| Table 5-5. Annual Growth Rate of Agriculture as Share of GDP (%) |
| |  |  | | --- | --- | | Region | Annual Growth Rate (%) | | USA | −0.039 | | BRA | −0.025 | | CHN | −0.041 | | EUR | −0.022 | | XLM | −0.015 | | XAS | −0.005 | | AFR | −0.014 | | ROW | −0.024 | |

rate (World Bank, 2013). From Table 5-5, we can see that agriculture’s output share of GDP has fallen over time for all regions, with the largest decreases seen in China and in the United States. Together with GDP projections from IEO2013 and agriculture-related non-CO2 GHG emissions and projections from EPA (2012), we can capture the agricultural growth trend and quantify emissions factor trends from 2010 through 2050. The emissions reduction factor used in ADAGE was fit to match emissions projections from EPA for the base case.

# Dynamics of the Model

Economic growth over time in ADAGE is influenced by changes in factor endowments, productivity, technical change, and consumer preferences, which encompass the following: 1) changes in the labor endowment resulting from changes in population and labor productivity, 2) capital accumulation through savings and investment, 3) changes in stocks of natural resources, 4) technological change associated with improvements in energy efficiency in energy using sectors, 5) technological improvements in land productivity, 6) technological changes in production costs in some backstop technologies,[[15]](#footnote-16) 7) technological improvements in the efficiency of GHG emissions reductions, and 8) changes in consumers’ preference. The dynamics of changes in the efficiency of GHG emissions reductions are included in Section 5, so they are not discussed here. The remaining seven sources are discussed in each section below.

## Labo**r** Endowment

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. There is an expansive literature on economic growth over the last several decades that offers alternative characterizations of technical progress, including labor saving, capital saving, and factor neutral, with numerous variations based on how technical progress may influence factor demand (Acemoglu, 2009). ADAGE relies on exogenously specified rates of growth to determine how the value of labor endowments changes over time. Using the assumption of Harrod-neutral technical progress (Harrod, 1948),[[16]](#footnote-17) the model tracks the increase in effective units of labor available across the economy, encompassing both population growth and improvements in labor productivity where the combined population and labor productivity growth will align with GDP growth.

**The GDP growth trend was taken from** the IEO2017 (DOE, EIA, 2017a) and mapped to regions in ADAGE. **The United Nations’** World Population Prospects **is listed as one of the baseline population data sources for CGE models suggested by the 2010 GTAP Advisory Board meeting**[[17]](#footnote-18) **and has been used for future labor supply** (EPPA in Paltsev et al. [2005]) as well as in the ADAGE model. The specific set of projections that we used to depict overall population growth are the United Nations’ World Population Prospects: the 2017 Revision from 2010 through 2050 (United Nations, 2017). As shown in Table 6-1, global GDP will grow by 2.54 times by 2050 above the 2010 level. China and Africa have the fastest growth rate and European Regions and Brazil are the slowest growing regions. Global population has a growth of about 42% over four decades where Africa has the highest growth rates, well above the global average throughout the projection period, while all other regions have growth rates less than the global average growth rate. Annual population growth rates are projected to slow over time in every region, even reaching negative values (i.e., periods of population decline) in Europe and China by 2035. The improvement in labor productivity in each region was assumed to ensure labor endowment follows the same trend of the exogenous GDP growth for all regions.

Table 6-1. Regional GDP, Population, Labor Productivity Growth Trend (1 in 2010)

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **2010** | **2015** | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
| *GDP Growth Trend* | | | | | | | | | |
| USA | 1.00 | 1.11 | 1.23 | 1.39 | 1.53 | 1.70 | 1.88 | 2.08 | 2.28 |
| BRA | 1.00 | 1.06 | 1.12 | 1.27 | 1.37 | 1.47 | 1.57 | 1.67 | 1.76 |
| CHN | 1.00 | 1.45 | 1.94 | 2.45 | 3.00 | 3.58 | 4.17 | 4.75 | 5.25 |
| EUR | 1.00 | 1.06 | 1.16 | 1.24 | 1.32 | 1.40 | 1.49 | 1.57 | 1.66 |
| XLM | 1.00 | 0.95 | 1.27 | 1.48 | 1.69 | 1.90 | 2.14 | 2.40 | 2.67 |
| XAS | 1.00 | 1.16 | 1.34 | 1.54 | 1.75 | 1.96 | 2.20 | 2.44 | 2.70 |
| AFR | 1.00 | 1.16 | 1.38 | 1.68 | 2.03 | 2.47 | 3.01 | 3.66 | 4.44 |
| ROW | 1.00 | 1.16 | 1.26 | 1.41 | 1.58 | 1.76 | 1.93 | 2.10 | 2.25 |
| ***World*** | ***1.00*** | ***1.14*** | ***1.31*** | ***1.49*** | ***1.68*** | ***1.88*** | ***2.10*** | ***2.32*** | ***2.54*** |
| *Population Growth Trend* | | | | | | | | | |
| USA | 1.00 | 1.01 | 1.04 | 1.08 | 1.12 | 1.15 | 1.18 | 1.20 | 1.23 |
| BRA | 1.00 | 1.05 | 1.09 | 1.13 | 1.15 | 1.17 | 1.19 | 1.19 | 1.19 |
| CHN | 1.00 | 1.03 | 1.05 | 1.06 | 1.06 | 1.06 | 1.05 | 1.03 | 1.01 |
| EUR | 1.00 | 1.01 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.01 | 1.00 |
| XLM | 1.00 | 1.06 | 1.12 | 1.17 | 1.22 | 1.27 | 1.30 | 1.33 | 1.36 |
| XAS | 1.00 | 1.07 | 1.13 | 1.19 | 1.23 | 1.28 | 1.31 | 1.34 | 1.36 |
| AFR | 1.00 | 1.16 | 1.31 | 1.47 | 1.65 | 1.84 | 2.03 | 2.24 | 2.45 |
| ROW | 1.00 | 1.09 | 1.15 | 1.20 | 1.24 | 1.27 | 1.31 | 1.34 | 1.37 |
| ***World*** | ***1.00*** | ***1.07*** | ***1.13*** | ***1.19*** | ***1.24*** | ***1.29*** | ***1.34*** | ***1.38*** | ***1.42*** |
| *Labor Productivity Growth Trend* | | | | | | | | | |
| USA | 1.00 | 1.11 | 1.19 | 1.31 | 1.41 | 1.55 | 1.71 | 1.88 | 2.05 |
| BRA | 1.00 | 1.00 | 1.02 | 1.14 | 1.22 | 1.29 | 1.38 | 1.48 | 1.57 |
| CHN | 1.00 | 1.42 | 1.88 | 2.39 | 2.94 | 3.52 | 4.12 | 4.72 | 5.24 |
| EUR | 1.00 | 1.05 | 1.14 | 1.22 | 1.30 | 1.38 | 1.47 | 1.56 | 1.66 |
| XLM | 1.00 | 0.88 | 1.15 | 1.31 | 1.46 | 1.64 | 1.84 | 2.07 | 2.32 |
| XAS | 1.00 | 1.09 | 1.21 | 1.36 | 1.51 | 1.69 | 1.89 | 2.11 | 2.34 |

(continued)

Table 6-1. Regional GDP, Population, Labor Productivity Growth Trend (1 in 2010) (continued)

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **2010** | **2015** | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
| *Labor Productivity Growth Trend (continued)* | | | | | | | | | |
| AFR | 1.00 | 1.01 | 1.07 | 1.21 | 1.38 | 1.63 | 1.97 | 2.42 | 3.00 |
| ROW | 1.00 | 1.06 | 1.11 | 1.21 | 1.34 | 1.48 | 1.62 | 1.76 | 1.89 |
| ***World*** | ***1.00*** | ***1.07*** | ***1.18*** | ***1.31*** | ***1.44*** | ***1.59*** | ***1.76*** | ***1.94*** | ***2.12*** |

## Investment and Capital Stocks

The GTAP datasets provide details on the types of goods and services used to produce the investment goods underlying each economy’s initial capital stock. ADAGE uses these data to specify an aggregate investment sector generating the capital needed by the economy. Savings and investment decisions by households and the associated capital formation control many of the behavioral responses required for policy analysis. ADAGE models these decisions using a recursive-dynamic approach in which savings and investment are based only on current-period variables, as opposed to a forward-looking intertemporal optimization model where savings and investment decisions are modeled to take account of all future economic conditions, which are assumed to be known with certainty.

ADAGE adopts the approach described in EPPA4 (Paltsev et al., 2005) for dynamic updating of the capital stock in each region and sector. Capital stock is divided into malleable and nonmalleable capital. The malleable portion of the capital stock in each sector is described by the nested CES production functions previously shown in Section 3 with nonzero substitution elasticities with labor. The nonmalleable portion of the capital stock is Leontief with elasticities of substitution of 0. Savings from previous periods become new capital that is invested in the current period. This new capital starts out in a malleable form at the beginning of each period, and then a proportion of this new capital becomes part of the nonmalleable stock at the end of the period. Malleable capital in period is made up of investment in period plus the stock of capital remaining after depreciation that remains malleable in period *t*. New nonmalleable capital in period is the portion of the nonmalleable stock at time *t* that survives depreciation. A nondecreasing productivity parameter is used to ensure that total capital available is equal to the projected GDP growth rates from IEO2017 (DOE, EIA, 2017a) for all regions.

## 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 quantity and price. Fossil fuel production, consumption, trade, and prices in 2010 were calibrated to WED2010 (see Subsection 4.3), and the amount of resources available for extraction was obtained from International Energy Statistics (DOE, EIA, 2013); however, no projections for the amount of resources available for extraction or the costs associated with extracting them were identified. The resource supply elasticities were taken from Ross (2009), which enabled the inclusion of increasing marginal costs for resource extraction.

The supply elasticities reflect how production costs rise as more resources are extracted, along with the effects of depletion of the fossil fuel resource. By selecting an elasticity of substitution between a resource and other production inputs in these industries, a given resource supply elasticity can be calibrated. The fossil fuel prices from WED2010 and the growth path from IEO2013 forecasts were also matched by adjusting growth rates for the fixed-factor inputs to resource production so that prices in the baseline ADAGE solution were calibrated, as closely as is feasible, to desired forecasts.

## Technical Improvement in Energy Efficiency

Energy consumption per unit of output tends to decrease over time through improvements in production technologies and energy conservation. This may not necessarily be true in developing countries as they move into more energy-intensive and less labor-intensive manufacturing processes; however, the model assumes energy efficiency (energy used per unit of output) improves over time. The energy mix in an industry may also shift as production techniques change. U.S. electricity generation has been shifting rapidly from coal to lower-carbon energy sources: coal-fired generation declined from 45% of national generation in 2010 to about 30% in 2016, while the shares for natural gas and renewable sources rose from 24% to 34% and from 7% to 9%, respectively, during the same period (DOE, EIA, 2017b). When examining environmental policies, it is essential to include these technology shifts in the baseline forecasts.

Like other CGE models, ADAGE captures energy consumption changes through autonomous energy-efficiency improvement (AEEI) parameters. An AEEI index is specified in the model for each fuel type and is calibrated to match energy consumption projected in IEO 2017. 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.

## Technical Improvement on Land Productivity

Land productivity per hectare of agricultural production tends to increase over time due to technological improvement (Ludena et al., 2007). To capture this technological improvement component, ADAGE assumes 1% annual growth in cropland and pastureland productivity. Meanwhile, ADAGE itself can capture land productivity improvement internally from land intensification due to substitution of land with other nonland inputs, as shown in Figure 3-10. As a natural resource, land can be substituted by the materials-energy composite at an elasticity of 0.6. The land-material-energy composites can be further substituted by the capital-labor bundle. In other words, land could become more productive by using more materials (e.g., fertilizer) and/or more capital-labor bundle (e.g., investment on irrigation facility and labor). Thus, land productivity is realized both exogenously through a scaling factor and endogenously through input substitution in the production function.

## Technological Changes in Sectoral Production Cost

Three sets of technologies—second-generation biofuels, AFVs, and some electricity generation technologies such as wind and solar—are either not present in the model base year 2010 or face more significant technological improvement in cost reduction than discussed in Section 3.4. Over time, these technologies can enter the market in later time periods or expand when they become economically competitive relative to existing mature technologies. Competitiveness of these technologies depends on the endogenously determined input prices, which rely on technological improvement, government policy, natural resource abundance, and other forces affecting economic growth.

Specification of these technologies and their technological improvement must rely on other data sources beyond the GTAP v7.1 database. By convention, we set input shares for each technology so that the sum of input shares is equal to 1.0. We then defined a multiplicative markup factor to describe the cost of these technologies relative to the existing mature technology against which it competes in the 2010 base year. The markup factor generally has a downward trend over time to show technological improvement. This markup factor was multiplied by technology-specific inputs to produce the new sector production functions. The introduction of second-generation biofuels into ADAGE is discussed in Section 6.6.1, followed by a discussion of the implementation of alternative fuel technologies in on-road transportation in Section 6.6.2 and the implementation of advanced electricity technologies in Section 6.6.3.

### Second-Generation Biofuels

The five types of second-generation biofuels are absent from the GTAP v7.1 database. ADAGE allows these technologies to enter the market endogenously in the future when technology, economic, or policy forces either bring down their production cost or raise the refined oil price so they can compete with refined oil used in the transportation sectors.

The input cost share data for second-generation biofuels in the base year were collected from various sources: switchgrass from Idaho National Laboratory (2014) for feedstock production, fertilizer usage from Canter et al. (2016), fertilizer cost from USDA, ERS (2017), and biofuel production from Humbird et al. (2011) and Tao et al. (2012);[[18]](#footnote-19) agricultural residue from Aden et al. (2002); and forest wood and residue from the Forest and Agricultural Sector Optimization Model (Beach et al., 2010). Costs for land, machinery, chemicals, storage, transportation and handling, capital investment, labor, and process energy requirements were grouped into corresponding input categories in ADAGE to generate input cost shares for 1 gallon of biofuel production. Second-generation biofuels were assumed to have a 2010 yield of 12 dry ton/ha for switchgrass, 24 dry ton/ha for miscanthus, and 22 dry ton/ha for forest wood products. A conversion rate from switchgrass to ethanol of 70.9 gallon/dry ton was drawn from Tao et al. (2014). In the absence of feedstock-specific data for other cellulosic feedstocks, that conversion rate was applied to all other cellulosic feedstocks as well in the base year. These assumptions for yield and conversion rate were embedded in the model and are reflected in their respective cost shares. Table 6-2 displays the finalized input cost shares for land, labor, capital, intermediate goods, and energy by biofuel type in 2010. These input cost shares were assumed to be the same across all regions. The input cost shares for switchgrass include a negative value for electricity inputs to represent electricity generated as a coproduct to biofuel production using switchgrass.

Table 6-2. Input Cost Shares for Second-Generation Biofuels Production, 2015

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Item | Swge | Msce | ArsE | FrsE | FrwE |
| Land | 0.18 | 0.05 |  |  | 0.02 |
| Capital | 0.30 | 0.53 | 0.40 | 0.45 | 0.41 |
| Labor | 0.18 | 0.14 | 0.08 | 0.09 | 0.09 |
| Eim | 0.27 | 0.08 | 0.30 | 0.32 | 0.32 |
| Srv | 0.07 | 0.06 | 0.03 | 0.04 | 0.04 |

(continued)

Table 6-2. Input Cost Shares for Second-Generation Biofuels Production, 2015 (continued)

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Item | Swge | Msce | ArsE | FrsE | FrwE |
| RodF | 0.05 | 0.07 | 0.15 | 0.07 | 0.09 |
| Ele | −0.06 | 0.03 | 0.01 | 0.01 | 0.01 |
| Gas |  | 0.03 | 0.01 |  |  |
| Oil |  |  |  | 0.01 | 0.01 |
| **Total** | **1.00** | **1.00** | **1.00** | **1.00** | **1.00** |

The advanced biofuel cost assumptions differ by feedstock. Cost data for producing biofuels from switchgrass came from Idaho National Laboratory (2014), and we assumed costs decrease by 1% annually between 2010 and 2050. Costs for all other second-generation biofuels were based on Winchester and Reilly (2015). Their estimates have advanced biofuel costs falling dramatically between 2010 and 2015 because of decreasing costs of enzymes and learning effects and continuing to fall by 2.5% annually (for all but miscanthus) between 2015 and 2030, before becoming flat between 2030 and 2050. Table 6-3 displays the advanced biofuel cost over the time period from 2010 through 2050 in terms of dollars per gallon of oil equivalent.

Table 6-3. Advanced Biofuel Cost Over Time (2010$/gal of Refined Oil Equivalent)

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
| Swge | 6.61 | 3.97 | 3.49 | 3.08 | 2.75 | 2.75 | 2.75 | 2.75 | 2.75 |
| Msce | 4.82 | 2.89 | 2.75 | 2.75 | 2.75 | 2.75 | 2.75 | 2.75 | 2.75 |
| ArsE | 8.20 | 4.80 | 4.23 | 3.73 | 3.28 | 3.28 | 3.28 | 3.28 | 3.28 |
| FrsE | 10.40 | 6.00 | 5.29 | 4.66 | 4.10 | 4.10 | 4.10 | 4.10 | 4.10 |
| FrwE | 10.92 | 6.30 | 5.55 | 4.89 | 4.31 | 4.31 | 4.31 | 4.31 | 4.31 |

The price of refined oil used in the transportation sector (defined in the model as a composite of gasoline and diesel) was about $2.75/gallon in 2010. Ethanol produced from switchgrass could become economically competitive with refined oil if the price of refined oil increases to at least $3.49/gallon by 2020. Ethanol produced from forest residues would begin to become cost competitive with refined oil if the price of refined oil reaches $5.30/gallon by 2020. The markup factor—the ratio of the cost of second-generation biofuels over time relative to the price of refined oil in 2010—was applied to all inputs in the production function other than land. Land is exempt from this calculation because if it were applied the underlying feedstock yield would change along with this markup factor. However, the feedstock yield growth rate should be directly tied to the land. For example, switchgrass and miscanthus yields were assumed to grow at 1% annually, the same rate as applied to all other crops using cropland.

Domestically produced second-generation biofuels are blended with refined oil and first- generation biofuels for use in the domestic on-road transportation sector in ADAGE. There are a few points to note in the representation of second-generation biofuels in ADAGE: 1) imports and exports of second-generation biofuels are not represented in the model and 2) other transportation sectors, such as air and water, are not able to use any biofuels, including second-generation biofuels. These caveats could be addressed in a future model version, for example, to expand biofuel use in airline transportation.

The biofuel consumption structure in ADAGE has some advantages. The blending ratio between first-generation biofuels, second-generation biofuels, and refined oil is flexible, and there is no additional cost tied to the blending ratio, treating biofuels as drop-in fuels. This flexibility to use different ethanol and biodiesel blending ratios in automobiles, trucks, and buses allows for the analysis of specific fuel policy scenarios.

### AFVs in On-Road Transportation

Potential environmental concerns expressed through policies and consumer preferences and potentially higher transportation fuel prices have spurred the development of AFVs with higher fuel economy and/or lower emissions. However, other than the EPPA model (Karplus, Paltsev, and Reilly, 2010; Karplus et al. 2013) and ADAGE, CGE models generally have limited representation of alternative fuel technologies. EPPA disaggregates household transportation from the overall transportation sector and introduces some AFVs within the model. ADAGE includes four categories of AFVs (natural gas [GASV] electric battery [BEV] oil-electric hybrid [HEV],[[19]](#footnote-20) and fuel cell hydrogen [FCEV] drivetrains) for all types of on-road transportation vehicles in the model (light-duty vehicles [LDVs], heavy-duty trucks, and heavy-duty buses, see Table 6-4[[20]](#footnote-21)). The introduction of AFVs in ADAGE allows us to model alternative

Table 6-4. On-Road Vehicle Type for LDVs and HDVs

|  |  |
| --- | --- |
| On-Road Vehicle Type | Definition |
| LDV |  |
| Auto\_OEV | LDV using refined oil and biofuels |
| Auto\_GASV | Natural gas LDV |
| Auto\_BEV | Electric battery LDV |
| Auto\_HEV | Hybrid LDV using refined oil and electricity |
| Auto\_FCEV | Fuel cell hydrogen LDV |
| Heavy-duty truck |  |
| RodF\_OEV | Truck using refined oil and biofuel |
| RodF\_GASV | Natural gas truck |
| RodF\_BEV | Electric battery truck |
| RodF\_HEV | Hybrid truck using refined oil and electricity |
| RodF\_FCEV | Fuel cell hydrogen truck |
| Heavy-duty bus |  |
| RodP\_OEV | Bus using refined oil and biofuel |
| RodP\_GASV | Natural gas bus |
| RodP\_BEV | Electric battery bus |
| RodP\_HEV | Hybrid bus using refined oil and electricity |
| RodP\_FCEV | Fuel cell hydrogen bus |

transportation technologies and build the linkage between monetary units and physical characteristics of alternative fuel technologies in a CGE model. We can explicitly quantify the fuel economy of AFVs in VMT/gallon of oil equivalent for passenger and freight transportations. We can also explore how multiple AFVs compete with conventional technologies and each other under alternative environmental, transportation, and energy-related policies.

Following the approach used for modeling conventional transportation sectors in ADAGE, production and consumption of AFVs are defined as a service. The services provided by these advanced technologies are generated in terms of VMT and not the production and consumption of the actual vehicles themselves. This distinction allows us to build up the operating physical accounts, link them with monetary accounts, and compare accounts across different transportation technologies.

Like second-generation biofuels, input cost shares ($/VMT) for AFVs and markup factors are required for AFVs to build up their production functions and dynamic structure. In addition, fuel economy and VMT are required to build up the linkage between monetary accounts and physical accounts in ADAGE for AFVs. As for conventional transportation technology in GCAM 4.2, AFVs in GCAM 4.2 are defined by vehicle class and size, so the input cost, fuel economy, markup, and other parameters requiring aggregation were calculated as weighted averages from all classes and sizes that fall in that category. The weight used is the simulated VMT in 2010 from the reference case in GCAM 4.2.

First, the load factor, defined as the average number of people traveling in a passenger vehicle by class or the average metric tons of freight traveling in a freight truck for AFVs were assumed to be the same as conventional vehicles for auto, bus, and truck modes and remain unchanged over time (see Table 6-5). The average values varied across ADAGE regions from 1.6 to 3.1 people per LDV vehicle, 16.4 to 47.5 passengers per bus, and 1.3 to 6.5 metric tons of freight hauled per truck.

Second, vehicle fuel economy is available from GCAM 4.2 input data for all regions. Given that the United States is the region that we are especially interested in, the U.S. fuel economy data from AEO2019 (DOE, EIA, 2019) were used to replace the fuel economy from GCAM 4.2 for the United States for all AFVs except FCEVs (because AEO2019 data for FCEVs were insufficient). Table 6-6 displays the fuel economy parameters for conventional vehicles and AFVs for on-road transportation by region in 2010, and Figure 6-1 displays the fuel economy by technology in USA. In general, fuel economy is the highest for BEV, followed by FCEV, HEV, GASV, and OEV and increases from 2010 through 2050 because of energy efficiency improvements.

Third, the fuel efficiency standard for new on-road transportation in the United States is shown in Figure 6-1 as well labeled with “Standard.” The fuel efficiency standard in 2010 is assumed to be the same as OEV’s fuel economy in 2010 shown in Table 6-6. For 2015 through 2025, the fuel efficiency standard is from AEO2019 for light-duty vehicles and the [Phase 2 heavy duty rule](https://nam04.safelinks.protection.outlook.com/?url=https%3A%2F%2Fwww.epa.gov%2Fregulations-emissions-vehicles-and-engines%2Ffinal-rule-phase-2-greenhouse-gas-emissions-standards&data=05%7C01%7Cycai%40rti.org%7C57e866e0bf334c76d8ba08da497c2e86%7C2ffc2ede4d4449948082487341fa43fb%7C0%7C0%7C637903095004603409%7CUnknown%7CTWFpbGZsb3d8eyJWIjoiMC4wLjAwMDAiLCJQIjoiV2luMzIiLCJBTiI6Ik1haWwiLCJXVCI6Mn0%3D%7C3000%7C%7C%7C&sdata=b%2B0nUTAyeydV84imFwOoiuY3xJtLgE%2FOmQ3nD7YTybM%3D&reserved=0) for HDV. The fuel efficiency standard is held constant at the 2025 level for 2030 through 2050. For HDV, we applied the fleetwide percentage improvements from the [Phase 2 heavy duty rule](https://nam04.safelinks.protection.outlook.com/?url=https%3A%2F%2Fwww.epa.gov%2Fregulations-emissions-vehicles-and-engines%2Ffinal-rule-phase-2-greenhouse-gas-emissions-standards&data=05%7C01%7Cycai%40rti.org%7C57e866e0bf334c76d8ba08da497c2e86%7C2ffc2ede4d4449948082487341fa43fb%7C0%7C0%7C637903095004603409%7CUnknown%7CTWFpbGZsb3d8eyJWIjoiMC4wLjAwMDAiLCJQIjoiV2luMzIiLCJBTiI6Ik1haWwiLCJXVCI6Mn0%3D%7C3000%7C%7C%7C&sdata=b%2B0nUTAyeydV84imFwOoiuY3xJtLgE%2FOmQ3nD7YTybM%3D&reserved=0) directly to the truck and bus fuel economy from AEO2019. The fuel efficiency standard will promote the penetration of more efficient technologies and penalize those less efficient technologies.

Table 6-5. Average Number of People/Vehicle (Passenger Transportation) and Tons/Vehicle (Freight Transportation) for On-Road Transportation

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Type of Vehicle** | **Unit** | **USA** | **BRA** | **CHN** | **EUR** | **XLM** | **XAS** | **AFR** | **ROW** |
| Light duty | Number of people/vehicle | 1.6 | 1.8 | 2.6 | 1.7 | 1.8 | 3.1 | 2.4 | 1.9 |
| Freight truck | Tons/vehicle | 2.6 | 6.5 | 1.3 | 7.9 | 5.5 | 1.5 | 3.2 | 3.9 |
| Passenger bus | Number of people/vehicle | 18.4 | 20.7 | 47.5 | 16.4 | 20.7 | 31.6 | 47.5 | 26.9 |

Note: Data are from GCAM 4.2 and were processed by the authors. Values reflect averages across all classes and types. These values were assumed to be constant over time.

Fourth, components of AFVs’ vehicle purchase costs, expenses for charging stations and other facilities, vehicle insurance, and maintenance costs were obtained from GCAM 4.2, supplemented by Annual Energy Outlook 2019 (AEO2019) (DOE, EIA, 2019) for the United States and DOE battery pack and fuel cell stack technology target fuel intensities and costs (DOE, 2015; Nykvist and Nilsson, 2015). These costs were aggregated to materials, capital, and labor in ADAGE and amortized into an annual cost per VMT using an assumed 30-year lifetime. AFVs’ fuel economies, together with fuel price, were used to determine the energy input cost in terms of $/VMT. The input costs from labor, capital, materials, and energy were summed to get the total unit input cost and the corresponding input cost share. Table 6-7 shows the on-road transportation input cost share in 2015 in the United States.

Table 6-6. Fuel Economy for Conventional and AFV On-Road Transportation in 2010

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Type of Vehicle** | **USA** | **AFR** | **BRA** | **CHN** | **EUR** | **XAS** | **XLM** | **ROW** |
| Light-duty vehicle (mile/gallon refined oil equivalent [oil-e]) | | | | | | | | |
| Auto\_OEV | 24.8 | 27.6 | 34.4 | 19.3 | 31.0 | 25.7 | 30.1 | 29.5 |
| Auto\_GasV | 23.6 | 28.2 | 30.4 | 36.4 | 29.7 | 33.5 | 29.3 | 27.5 |
| Auto\_BEV | 76.5 | 98.3 | 114.2 | 117.3 | 141.4 | 123.6 | 129.7 | 118.8 |
| Auto\_HEV | 41.0 | 32.8 | 41.8 | 45.1 | 40.4 | 37.6 | 38.0 | 35.5 |
| Auto\_FCEV | 56.0 | 47.8 | 70.5 | 77.5 | 72.3 | 61.3 | 64.4 | 59.7 |
| Heavy-duty truck (mile/gallon oil-e) | | | | | | | | |
| RodF\_OEV | 8.4 | 5.1 | 6.7 | 21.7 | 16.1 | 11.5 | 5.7 | 6.0 |
| RodF\_GasV | 7.5 | 4.6 | 6.0 | 19.5 | 14.5 | 10.3 | 5.2 | 5.4 |
| RodF\_BEV | 25.1 | 15.2 | 20.0 | 65.2 | 48.3 | 34.4 | 17.2 | 18.1 |
| RodF\_HEV | 10.5 | 6.3 | 8.3 | 27.1 | 20.1 | 14.3 | 7.2 | 7.5 |
| RodF\_FCEV | 16.7 | 10.1 | 13.3 | 43.4 | 32.2 | 22.9 | 11.5 | 12.0 |
| Heavy-duty bus (mile/gallon oil-e) | | | | | | | | |
| RodP\_OEV | 6.5 | 6.6 | 5.7 | 10.2 | 15.4 | 8.3 | 7.5 | 6.5 |
| RodP\_GasV | 5.9 | 5.9 | 5.1 | 9.1 | 13.8 | 7.5 | 6.7 | 5.8 |
| RodP\_BEV | 26.0 | 26.3 | 22.8 | 40.6 | 61.4 | 33.2 | 29.8 | 25.8 |

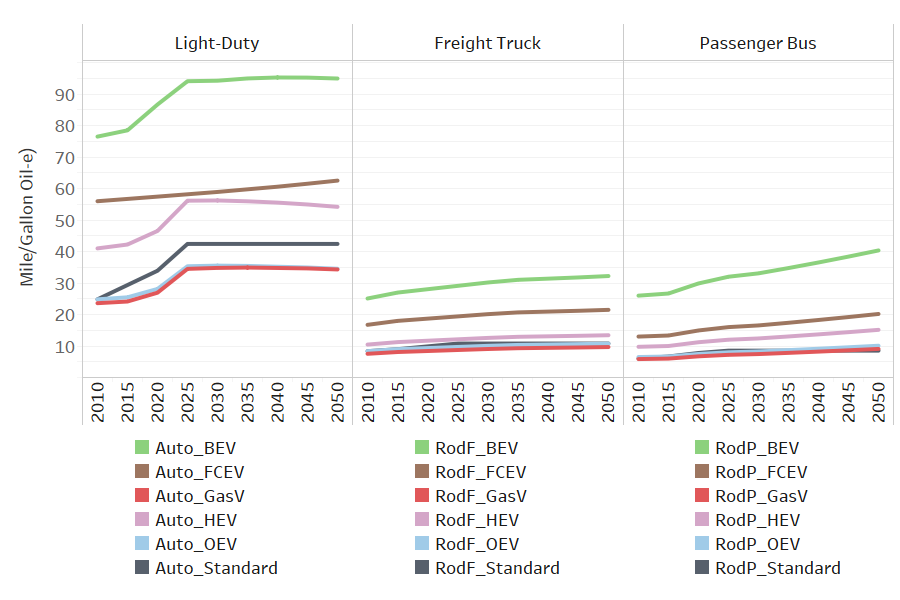
(continued)

Table 6-6. Fuel Economy for Conventional and AFV On-Road Transportation in 2010 (continued)

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Type of Vehicle** | **USA** | **AFR** | **BRA** | **CHN** | **EUR** | **XAS** | **XLM** | **ROW** |
| RodP\_HEV | 9.8 | 9.9 | 8.6 | 15.2 | 23.0 | 12.4 | 11.2 | 9.7 |
| RodP\_FCEV | 13.0 | 13.2 | 11.4 | 20.3 | 30.7 | 16.6 | 14.9 | 12.9 |

Note: Data are from GCAM 4.2 and AEO2019 and processed by the authors. Fuel economy is the average fuel economy from all class and types. Fuel economy grows gradually from 2015 through 2050 as a result of energy efficiency improvements.

Figure 6-1. Fuel Economy by Technology and Efficiency Standard for On-Road Transportation in USA from 2010–2050 (mile/gallon oil-e)



A markup factor is incorporated for AFVs to reflect the relative costs of AFVs over time relative to costs of conventional vehicles in the base year. The AFV total unit production cost from 2015 through 2050 was gathered from the simulated results in the reference case from GCAM 4.2, where VMT in 2015 was again used as the weights for both aggregation and averaging. Figure 6-2 shows the projected total unit production cost of AFVs from 2010 through 2050 for the United States. The unit cost is high in the earlier periods and then declines gradually over time due to projected technological improvements. The cost for FCEV and BEV shows a

Table 6-7. Input Cost Shares of OEVs and AFVs in the United States

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **Energy** | | | | **Materials Bundle (Intermediate Goods)** | | | | **Labor** | **Capital** | **Sum** |
| **Ele** | **Gas** | **Oil** | **Biofa** | **Eim** | **Man** | **Srv** | **Tranb** |
| Light-duty vehicle | | | | | | | | | | | |
| Auto\_OEV |  |  | 0.18 | 0.01 |  |  | 0.37 |  |  | 0.43 | 1.00 |
| Auto\_GasV |  | 0.02 | 0.02 |  |  |  | 0.36 |  |  | 0.61 | 1.00 |
| Auto\_BEV | 0.03 |  |  |  |  |  | 0.27 |  |  | 0.70 | 1.00 |
| Auto\_HEV | 0.02 |  | 0.08 | 0.01 |  |  | 0.39 |  |  | 0.51 | 1.00 |
| Auto\_FCEV | 0.00 | 0.00 |  |  |  |  | 0.17 |  |  | 0.82 | 1.00 |
| Heavy-duty freight truck | | | | | | | | | | | |
| RodF\_OEV |  |  | 0.17 | 0.01 | 0.01 | 0.05 | 0.17 | 0.07 | 0.31 | 0.20 | 1.00 |
| RodF\_GasV |  | 0.02 |  |  | 0.01 | 0.05 | 0.18 | 0.08 | 0.33 | 0.32 | 1.00 |
| RodF\_BEV | 0.03 |  |  |  | 0.01 | 0.04 | 0.14 | 0.06 | 0.28 | 0.43 | 1.00 |
| RodF\_HEV | 0.02 |  | 0.06 | 0.00 | 0.01 | 0.05 | 0.16 | 0.07 | 0.29 | 0.34 | 1.00 |
| RodF\_FCEV | 0.00 | 0.01 |  |  | 0.01 | 0.05 | 0.15 | 0.07 | 0.30 | 0.40 | 1.00 |
| Heavy-duty bus | | | | | | | | | | | |
| RodP\_OEV |  | 0.01 | 0.18 | 0.01 | 0.01 | 0.02 | 0.20 | 0.03 | 0.37 | 0.16 | 1.00 |
| RodP\_GasV |  | 0.02 |  |  | 0.01 | 0.03 | 0.22 | 0.04 | 0.42 | 0.27 | 1.00 |
| RodP\_BEV | 0.02 |  |  |  | 0.00 | 0.02 | 0.12 | 0.02 | 0.26 | 0.55 | 1.00 |
| RodP\_HEV | 0.01 |  | 0.04 | 0.00 | 0.01 | 0.02 | 0.17 | 0.03 | 0.33 | 0.38 | 1.00 |
| RodP\_FCEV | 0.00 | 0.01 |  |  | 0.00 | 0.02 | 0.13 | 0.03 | 0.29 | 0.51 | 1.00 |

a “Biof” in the energy part represents biofuels including corn ethanol.

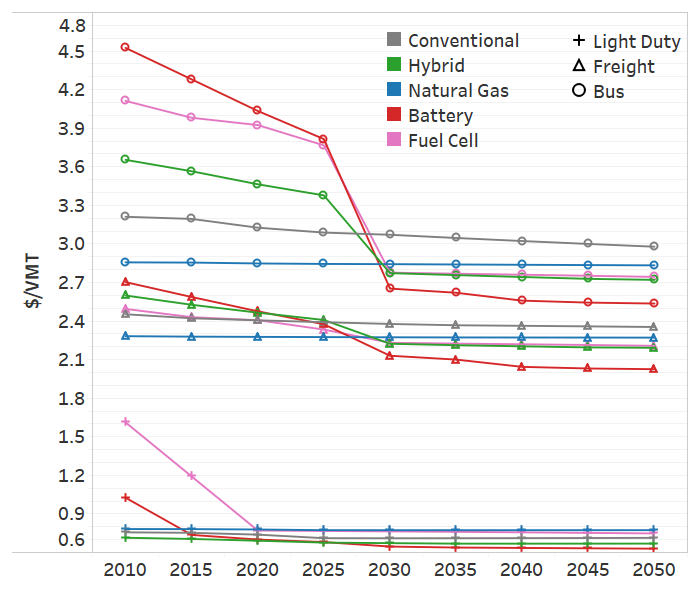
b “Tran” represents total transportation services produced by RalF, RodF, RodP, and Otrn.

Source: Data are from GCAM 4.2; AEO2019; DOE, 2015; and Nykvist and Nilsson, 2015. Input cost shares for other regions are available but not listed here. Table entries with blanks denote values of zero, while those with 0.00 represent small positive numbers that round to 0.00.

rapid reduction from 2010 through 2020 and then declines more slowly thereafter. Battery technology becomes the lowest cost technology after 2030. To preserve the consistency of the fuel economy measure, the markup factor for AFVs was applied to all inputs other than energy inputs. If it is applied to energy inputs, the underlying fuel economy would change over time along with the markup factor, especially in earlier periods. The fuel economy growth rate from 2015 through 2050 was assumed to grow exogenously at the rate used in GCAM 4.2.

ADAGE currently assumes that all non-drivetrain vehicle capital costs are identical for OEVs, BEVs, and FCEVs. As data about the costs of non-drivetrain components become more widely available, this can be updated. But, in the current model, only drivetrain costs differentiate the capital cost of BEV and FCEV relative to OEV capital costs. For BEVs and FCEVs, these drivetrain costs are built up from assumptions about the cost of the battery pack and fuel cell, respectively.

Figure 6-2. On-Road Transportation Service Cost in the United States (2010$/VMT)



Source: Data are from GCAM 4.2; AEO2019; Department of Energy, 2015; and Nykvist and Nilsson, 2015.

Battery pack costs for BEVs are built up from assumptions about the range and fuel intensity of BEVs and the cost of lithium-ion batteries in 2010 dollars per kilowatt hour of capacity. We assumed that lithium-ion battery technology costs $275/kWh in 2015, based on the U.S. DOE Vehicle Technologies Office (VTO) 2015 cost target (DOE, EERE, 2017a). We assumed further that this cost gradually falls to $80/kWh in 2050 as the technology matures, based on VTO’s long-run cost target (DOE, EERE, 2017a).

Similarly, fuel cell costs for FCEVs are built up from assumptions about the range and fuel intensity of FCEVs and the cost of fuel cells in 2010 dollars per kilowatt of capacity. We assumed that fuel cell technology costs $45/kW in 2020, based on U.S. DOE Fuel Cell Technologies Office (FCTO) 2020 cost target (DOE, EERE, 2017b). We assumed further that this cost gradually falls to $15/kWh in 2050 as the technology matures, based on FCTO’s long-run cost target (DOE, EERE, 2017c).

Several factors affect the market penetration of AFVs, such as the development of charging station technology, construction of supporting infrastructure, and fleet turnover. The fixed factor for new vehicles is assumed to be 1% of the total cost per VMT in the AFVs’ CES production function. The endowment of a fixed factor would mimic the availability of these factors to imply the growth of AFVs is not only related to the variable cost of transportation, but also affected by the fixed cost of facilities. In ADAGE, new vehicles’ fixed factor endowment in each period is assumed to be proportional to its service production in the previous period. In addition, the elasticity of substitution between the fixed factor and the rest of the bundle provides the degree of substitution between the fixed factor and the rest of the bundle. The elasticity of substitution in the EPPA model is 0.4 (Cossa, 2004; Paltsev et al., 2005; Karplus, Paltsev, and Reilly, 2010) for Auto\_GasV and 0.5 to 0.76 (Karplus et al., 2013) for Auto\_HEV. However, these values are based on professional judgment of the EPPA modeling team as opposed to empirical data. Because there are no empirical studies identified for the elasticity of substitution for AFVs in LDVs and HDVs, especially by individual AFV type, we conducted a simple econometric estimation using Wards Auto Sales and fuel cost, and GDP per capita to estimate the elasticity of substitution for hybrid and battery vehicles. Based on these results and values assumed in other models, we selected a final elasticity in ADAGE of 0.2 for hybrid and battery and 0.1 for natural gas and fuel cell vehicles to account for the infrastructure hurdle.

The fleet turnover is determined by the characteristics of used vehicles. Vehicle lifetimes are relatively long, they do not depreciate uniformly, and average annual miles driven declines with vehicle age, so it is important for ADAGE to capture these characteristics. The maximum lifetime for light-duty and heavy-duty vehicles in ADAGE is assumed to be 30 years and vehicles are grouped into six age groups, denoted as *i* with a range from 0 to 5, representing vehicle ages 0 to 4 years, 5 to 9 years, ..…, 24 to 29 years. As vehicles age, some are retired from use. In addition, surviving vehicles are typically driven fewer miles per year as they get older. Vehicle survival rate (and average annual VMT were collected from EPA’s Motor Vehicle Emission Simulator (MOVES2014a) and aggregated to six age groups for auto, freight truck, and passenger bus using vehicle sales in 2010 as weights. Table 6-8 shows the vehicle survival rate and VMT schedule by age group where the superscript *n* denotes the vehicle type (i.e., Auto, RodP, RodF). At age 0 to 4 years, all vehicles are considered “new,” and their VMT schedule is normalized to 1. Survival rates for the new vehicle category are assumed to be 1.0 for heavy-duty and 0.987 for light-duty vehicles. Vehicle survival rates and annual VMTs decline as they age. Conventional vehicles and AFVs are assumed to have the same survival rate and VMT schedule. For example, survival rates for Auto\_OEV, Auto\_GasV, Auto\_BEV, Auto\_HEV, and Auto\_FCEV in age group 2 (vehicles 10 to 14 years old) are all equal to 0.727.

**Table 6-8. Vehicle Survival Rate and VMT Schedule Index by Age Group**

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Age**  **Group** | **Survival Rate ()** | | | **VMT Schedule ()** | | | **Average VMT Schedule ()** | | |
| **Auto** | **RodP** | **RodF** | **Auto** | **RodP** | **RodF** | **Auto** | **RodP** | **RodF** |
| 0 | 0.987 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 0.987 | 1.000 | 1.000 |
| 1 | 0.909 | 0.946 | 0.946 | 0.866 | 0.973 | 0.810 | 0.788 | 0.920 | 0.766 |
| 2 | 0.727 | 0.796 | 0.796 | 0.719 | 0.950 | 0.563 | 0.522 | 0.756 | 0.448 |
| 3 | 0.386 | 0.605 | 0.605 | 0.579 | 0.930 | 0.350 | 0.224 | 0.562 | 0.211 |
| 4 | 0.165 | 0.409 | 0.409 | 0.473 | 0.913 | 0.241 | 0.078 | 0.373 | 0.098 |
| 5 | 0.073 | 0.251 | 0.251 | 0.421 | 0.899 | 0.144 | 0.031 | 0.226 | 0.036 |
| >5 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |

Transportation service production for used vehicles (aged 5 to 29 years) for both conventional and alternative fuel technologies uses the same set of energy, capital, labor, and materials inputs as their new counterparts. Used vehicles have no opportunities for substitution among inputs (because they have already been produced), but the relative proportions of their inputs, including their fuel efficiency, are guided by the age structure of vehicles added in prior periods. A vintaged capital stock serves a comparable role to the fixed factor in new vehicles, which is not present for vintaged vehicles. A vehicle survival rate and VMT schedule for vehicles by age (i.e., in annual time steps) inform the weighting of surviving vehicle attributes in the vintage stock. Let define the VMT of vehicle type in period that were produced in period where the number of model periods and , the number of vintaging periods. The initial-period VMT for vehicles of type produced in period is then . Because VMT for a given vintage depends on this initial VMT value, its survival rate (, and VMT schedule (, VMT is defined as:

(6.1)

That is, vehicles produced in period are generating VMT in period equivalent to their initial period VMT () times the period survival rate () and VMT schedule ().

At any given time period *t*, used vehicles are composed of vehicles from age groups from through or Because the stock of conventional vehicles in the first model period represents a mix of historical vintages, we assumed their historical new VMT growth index for vehicles in their first period on the road is equal to ( where ). The initial and zeroth period VMT for vehicles of type produced in period is given in Eqs. 6.2a and 6.2b:

(6.2a)

(6.2b)

The observed VMT for all used vehicles at , defined as , is the sum of vehicles surviving at , shown in Eq. 6.3. We can calculate the oldest surviving stock, and therefore each subsequent stock up to , by combining Eqs. 6.2a, 6.2b, and 6.3, as shown in Eq. 6.4:

(6.3)

(6.4)

Their surviving VMT for the additional four periods will follow Eq. 6.1. Note thatequals zero for all AFVs because they are not present in the 2010 base-year data and enter as backstop technologies. We categorized the inputs to VMT production into labor, capital, materials, and energy. We represent the input costs of labor, capital, energy, and materials as a share of VMT determined in the year of production by and the weighted average input cost share for all used vehicles producing in period as .

(6.5)

where is the VMT share of vintage vehicles producing in period . Note that the benchmark values for are changing over time to represent technological improvement as shown in Figure 6-2 for new vehicle technologies and are further changed by energy-capital substitution behavior simulated within the model period in which it is installed. This weighted average approach allows us to account for the larger role newer vehicles play in the vehicle fleet.

The capital stock for used vehicles type at period *t* is calculated in the same way as VMT. We represent the total used capital stock of type in period as as the sum of surviving capital installed in prior five periods:

(6.6)

Similarly, the initial capital stock for conventional vehicles in their first period is given by:

(6.7)

and can be used to derive .

Using VMT schedule and surviving rate as weights allows ADAGE to capture vehicle physical characteristics and model the behavior of used vehicles, thus providing the foundation of vehicle fleet turnover. Vehicle stocks are defined exogenously for each period in this way, but the actual utilization of those stocks in the period is subject to market conditions, where some stocks may see economic retirements.

### Electricity Technologies

Electricity technologies such as solar and wind experience significant technology advancement. The data required to parameterize electricity technologies come from the NREL ATB database (NREL, 2021). The ATB data consist of generation and cost estimates for nuclear, biomass, renewable, and fossil electricity technologies in the United States with projections through 2050.

The ATB dataset provides cost projections for conventional, renewable, and backstop (i.e., those that are not yet cost competitive in 2010) generation technologies (Figure 6-3). There is a decline in costs for all generation types, reflecting technological improvements. By 2050, solar and wind are the lowest cost renewable options, with solar falling below the cost of combined cycle natural gas by 2050.

The ATB data are used to adjust electricity production costs in future years for new plants. Following the approach used in on-road transportation for used vehicles, we calculated the production cost for existing power plants by technology as an output-weighted average cost based on data from the previous 25 years of capacity additions (30 years is the assumed lifetime of a plant). Unlike transportation service production for used vehicles, where there is declining VMT per vehicle based on the VMT schedule, the capacity factor for existing power plants is assumed to be the same as new plants. A vintaged capital stock in existing power plants continues to serve a comparable role to the fixed factor in new power plants.

**Figure 6-3. Production Cost for Conventional, Renewable, and Advanced Generation Technologies (2010$/mmbtu)**

## Changes in Consumer Consumption over Time

Commodities that are normal goods at low incomes can become inferior goods at higher incomes or may change from income elastic goods to inelastic. For example, light-duty vehicles and air transportation are luxury goods in low levels of incomes but income inelastic in rich countries. It is important for dynamic CGE models to incorporate these types of changes from income, demography, technology, and preferences into their baseline. This is especially important when projecting several decades into the future because profound changes in demography and income can be expected. Because of limited data, the changes in household consumption in ADAGE are only implemented in transportation and agriculture and food commodities.

The change in transportation service demand over time for auto and passenger bus is based on Dargay, Gately, and Sommerdue (2007). This study used pooled time-series (1960–2002) and cross-section data for 45 countries representing 75% of the world’s population to estimate an S-shaped–Gompertz function of the relationship between vehicle ownership and per capita income, urbanization, and population. The functional form for a Gompertz function is:

(6.8)

where

t: time period

Vt: long-run equilibrium level of vehicle ownership (vehicles per 1,000 people)

γ: the saturation level or maximum level of vehicle ownership (measured in vehicles per 1,000 people), which differs by region because of population density and urbanization

θ: the speed of adjustment (0<θ<1) = 0.095

α: negative parameter to define the shape of the Gompertz function = −0.597

β: negative parameter to define the shape of the function, which differs by region

GDPt: per capita income (expressed in real 1995 dollars evaluated at Purchasing Power Parities)

The estimated parameter values along with the latest available vehicle ownership data in 2014 from Nation Master (<https://www.nationmaster.com/country-info/stats/Transport/Road/Motor-vehicles-per-1000-people>) were mapped to ADAGE regions and are shown in Table 6-9. Using GDP per capita data from the International Energy Outlook (DOE, EIA, 2017) and United Nations’ World Population Prospects projections (United Nations, 2017) and data in Table 6-9, we can project vehicle ownership rates for all ADAGE regions over the model horizon. We then used this growth trend for total vehicle ownership to calibrate household demand for light-duty and passenger bus transportation service over time (see Table 6-10). The demand for auto and bus starts at a high level but grows slowly in the United States, while it starts at a low level but grows faster in China and Africa. Overall, household passenger service demand is mainly driven by population growth in the United States with modest per capita VMT growth, whereas both GDP and population growth in China and Africa drive VMT growth rates. The growth trend for household demand for auto and bus is incorporated in the CES utility function and shifts expenditure share over time.

**Table 6-9. Parameter Value from Dargay, Gately, and Sommerdue (2007)**

|  |  |  |  |
| --- | --- | --- | --- |
|  | **β** | **γ** | **V2014** |
| USA | −0.20 | 852 | 797 |
| BRA | −0.17 | 831 | 249 |
| CHN | −0.14 | 807 | 83 |
| EUR | −0.17 | 776 | 537 |
| XLM | −0.15 | 805 | 142 |
| XAS | −0.21 | 687 | 156 |
| AFR | −0.18 | 838 | 42 |
| ROW | −0.17 | 823 | 259 |

**Table 6-10. Vehicle Ownership Growth Trend (1 in 2010)**

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **2010** | **2015** | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
| USA | 1.00 | 1.01 | 1.06 | 1.10 | 1.14 | 1.18 | 1.21 | 1.24 | 1.27 |
| BRA | 1.00 | 1.20 | 1.42 | 1.63 | 1.83 | 2.00 | 2.16 | 2.30 | 2.42 |
| CHN | 1.00 | 1.40 | 1.95 | 2.47 | 2.96 | 3.41 | 3.81 | 4.16 | 4.44 |
| EUR | 1.00 | 1.05 | 1.09 | 1.13 | 1.16 | 1.19 | 1.21 | 1.23 | 1.24 |
| XLM | 1.00 | 1.31 | 1.69 | 2.09 | 2.47 | 2.85 | 3.22 | 3.57 | 3.89 |
| XAS | 1.00 | 1.26 | 1.56 | 1.86 | 2.15 | 2.44 | 2.71 | 2.97 | 3.20 |
| AFR | 1.00 | 1.70 | 2.85 | 4.15 | 5.61 | 7.24 | 9.05 | 11.01 | 13.11 |
| ROW | 1.00 | 1.24 | 1.48 | 1.71 | 1.93 | 2.14 | 2.35 | 2.55 | 2.73 |

The change in agriculture and food demand over time is declining in per capita GDP, which was calibrated based on Lahiri, Babiker, and Eckaus (2000). Consumption shares for agriculture and food in each period were updated as a function of per capita income growth between periods. In ADAGE, we also assumed a 5% lower bound for the share of food and agriculture for all regions.

# 7 References

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# Appendix A

Appendix Table A-1. Region Mapping between GTAP v7.1 and ADAGE

| GTAP | | | ADAGE | |
| --- | --- | --- | --- | --- |
| No. | Country ISO-3 | Definition | Region | Definition |
| 1 | AUS | Australia | XAS | Rest of Asia |
| 2 | NZL | New Zealand | XAS | Rest of Asia |
| 3 | XOC | Rest of Oceania | XAS | Rest of Asia |
| 4 | CHN | China | CHN | China |
| 5 | HKG | Hong Kong | CHN | China |
| 6 | JPN | Japan | XAS | Rest of Asia |
| 7 | KOR | Korea | XAS | Rest of Asia |
| 8 | TWN | Taiwan | XAS | Rest of Asia |
| 9 | XEA | Rest of East Asia | XAS | Rest of Asia |
| 10 | KHM | Cambodia | XAS | Rest of Asia |
| 11 | IDN | Indonesia | XAS | Rest of Asia |
| 12 | LAO | Lao People’s Democratic Republic | XAS | Rest of Asia |
| 13 | MMR\* | Myanmar | XAS | Rest of Asia |
| 14 | MYS | Malaysia | XAS | Rest of Asia |
| 15 | PHL | Philippines | XAS | Rest of Asia |
| 16 | SGP | Singapore | XAS | Rest of Asia |
| 17 | THA | Thailand | XAS | Rest of Asia |
| 18 | VNM | Vietnam | XAS | Rest of Asia |
| 19 | XSE | Rest of Southeast Asia | XAS | Rest of Asia |
| 20 | BGD | Bangladesh | XAS | Rest of Asia |
| 21 | IND | India | XAS | Rest of Asia |
| 22 | PAK | Pakistan | XAS | Rest of Asia |
| 23 | LKA | Sri Lanka | XAS | Rest of Asia |
| 24 | XSA | Rest of South Asia | XAS | Rest of Asia |
| 25 | CAN | Canada | ROW | Rest of World |
| 26 | USA | United States of America | USA | United States |
| 27 | MEX | Mexico | ROW | Rest of World |
| 28 | XNA | Rest of North America | XLM | Rest of South America |
| 29 | ARG | Argentina | XLM | Rest of South America |
| 30 | BOL | Bolivia | XLM | Rest of South America |
| 31 | BRA | Brazil | BRA | Brazil |
| 32 | CHL | Chile | XLM | Rest of South America |
| 33 | COL | Colombia | XLM | Rest of South America |
| 34 | ECU | Ecuador | XLM | Rest of South America |
| 35 | PRY | Paraguay | XLM | Rest of South America |
| 36 | PER | Peru | XLM | Rest of South America |
| 37 | URY | Uruguay | XLM | Rest of South America |
| 38 | VEN | Venezuela | XLM | Rest of South America |
| 39 | XSM | Rest of South America | XLM | Rest of South America |

(continued)

Appendix Table A-1. Region Mapping between GTAP v7.1 and ADAGE (continued)

| GTAP | | | ADAGE | |
| --- | --- | --- | --- | --- |
| No. | Country ISO-3 | Definition | Region | Definition |
| 40 | CRI | Costa Rica | XLM | Rest of South America |
| 41 | GTM | Guatemala | XLM | Rest of South America |
| 42 | NIC | Nicaragua | XLM | Rest of South America |
| 43 | PAN | Panama | XLM | Rest of South America |
| 44 | XCA | Rest of Central America | XLM | Rest of South America |
| 45 | XCB | Caribbean | XLM | Rest of South America |
| 46 | AUT | Austria | EUR | Europe Union 27 |
| 47 | BEL | Belgium | EUR | Europe Union 27 |
| 48 | CYP | Cyprus | EUR | Europe Union 27 |
| 49 | CZE | Czech Republic | EUR | Europe Union 27 |
| 50 | DNK | Denmark | EUR | Europe Union 27 |
| 51 | EST | Estonia | EUR | Europe Union 27 |
| 52 | FIN | Finland | EUR | Europe Union 27 |
| 53 | FRA | France | EUR | Europe Union 27 |
| 54 | DEU | Germany | EUR | Europe Union 27 |
| 55 | GRC | Greece | EUR | Europe Union 27 |
| 56 | HUN | Hungary | EUR | Europe Union 27 |
| 57 | IRL | Ireland | EUR | Europe Union 27 |
| 58 | ITA | Italy | EUR | Europe Union 27 |
| 59 | LVA | Latvia | EUR | Europe Union 27 |
| 60 | LTU | Lithuania | EUR | Europe Union 27 |
| 61 | LUX | Luxembourg | EUR | Europe Union 27 |
| 62 | MLT | Malta | EUR | Europe Union 27 |
| 63 | NLD | Netherlands | EUR | Europe Union 27 |
| 64 | POL | Poland | EUR | Europe Union 27 |
| 65 | PRT | Portugal | EUR | Europe Union 27 |
| 66 | SVK | Slovakia | EUR | Europe Union 27 |
| 67 | SVN | Slovenia | EUR | Europe Union 27 |
| 68 | ESP | Spain | EUR | Europe Union 27 |
| 69 | SWE | Sweden | EUR | Europe Union 27 |
| 70 | GBR | United Kingdom | EUR | Europe Union 27 |
| 71 | CHE | Switzerland | ROW | Rest of World |
| 72 | NOR | Norway | ROW | Rest of World |
| 73 | XEF | Rest of EFTA | ROW | Rest of World |
| 74 | ALB | Albania | ROW | Rest of World |
| 75 | BGR | Bulgaria | EUR | Europe Union 27 |
| 76 | BLR | Belarus | ROW | Rest of World |
| 77 | HRV | Croatia | ROW | Rest of World |
| 78 | ROU | Romania | EUR | Europe Union 27 |
| 79 | RUS | Russian Federation | ROW | Rest of World |

(continued)

Appendix Table A-1. Region Mapping between GTAP v7.1 and ADAGE (continued)

| GTAP | | | ADAGE | |
| --- | --- | --- | --- | --- |
| No. | Country ISO-3 | Definition | Region | Definition |
| 80 | UKR | Ukraine | ROW | Rest of World |
| 81 | XEE | Rest of Eastern Europe | ROW | Rest of World |
| 82 | XER | Rest of Europe | ROW | Rest of World |
| 83 | KAZ | Kazakhstan | ROW | Rest of World |
| 84 | KGZ | Kyrgyzstan | ROW | Rest of World |
| 85 | XSU | Rest of Former Soviet Union | ROW | Rest of World |
| 86 | ARM | Armenia | ROW | Rest of World |
| 87 | AZE | Azerbaijan | ROW | Rest of World |
| 88 | GEO | Georgia | ROW | Rest of World |
| 89 | IRN | Iran, Islamic Republic of | ROW | Rest of World |
| 90 | TUR | Turkey | ROW | Rest of World |
| 91 | XWS | Rest of Western Asia | ROW | Rest of World |
| 92 | EGY | Egypt | AFR | Africa |
| 93 | MAR | Morocco | AFR | Africa |
| 94 | TUN | Tunisia | AFR | Africa |
| 95 | XNF | Rest of North Africa | AFR | Africa |
| 96 | NGA | Nigeria | AFR | Africa |
| 97 | SEN | Senegal | AFR | Africa |
| 98 | XWF | Rest of Western Africa | AFR | Africa |
| 99 | XCF | Rest of Central Africa | AFR | Africa |
| 100 | XAC | Rest of South Central Africa | AFR | Africa |
| 101 | ETH | Ethiopia | AFR | Africa |
| 102 | MDG | Madagascar | AFR | Africa |
| 103 | MWI | Malawi | AFR | Africa |
| 104 | MUS | Mauritius | AFR | Africa |
| 105 | MOZ | Mozambique | AFR | Africa |
| 106 | TZA | Tanzania | AFR | Africa |
| 107 | UGA | Uganda | AFR | Africa |
| 108 | ZMB | Zambia | AFR | Africa |
| 109 | ZWE | Zimbabwe | AFR | Africa |
| 110 | XEC | Rest of Eastern Africa | AFR | Africa |
| 111 | BWA | Botswana | AFR | Africa |
| 112 | ZAF | South Africa | AFR | Africa |
| 113 | XSC | Rest of South African Customs Union | AFR | Africa |

\* Myanmar has some serious data quality issues in GTAP 7 database as found by the GTAP team, so it is removed in the GTAP v7.1.

Appendix Table A-2. Sector Mapping between GTAP v7.1 and ADAGE

| GTAP v7.1 | | | ADAGE |
| --- | --- | --- | --- |
| No. | Code | Description | Sectors |
| 1 | PDR | Paddy rice | Ocr |
| 2 | WHT | Wheat | Wht |
| 3 | GRO | Cereal grains nec | Corn + Gron |
| 4 | V\_F | Vegetables, fruit, nuts | Ocr |
| 5 | OSD | Oil seeds | Soyb + Osdn |
| 6 | C\_B | Sugar cane, sugar beet | Srcn + Srbt |
| 7 | PFB | Plant-based fibers | Ocr |
| 8 | OCR | Crops nec | Ocr |
| 9 | CTL | Bovine cattle, sheep and goats, horses | Liv |
| 10 | OAP | Animal products nec | Liv |
| 11 | RMK | Raw milk | Liv |
| 12 | WOL | Wool, silk-worm cocoons | Liv |
| 13 | FRS | Forestry | Frs |
| 14 | FSH | Fishing | Liv |
| 15 | COA | Coal | Col |
| 16 | OIL | Oil | Oil |
| 17 | GAS | Gas | Gas |
| 18 | OMN | Minerals nec | Man |
| 19 | CMT | Bovine meat products | Mea |
| 20 | OMT | Meat products nec | Mea |
| 21 | VOL | Vegetable oils and fats | Sybd + Rpbd + Plbd + Vol + Omel |
| 22 | MIL | Dairy products | Liv |
| 23 | PCR | Processed rice | Ofd |
| 24 | SGR | Sugar | Ofd |
| 25 | OFD | Food products nec | Ceth + Ddgs + Weth + Ofd |
| 26 | B\_T | Beverages and tobacco products | Ofd |
| 27 | TEX | Textiles | Man |
| 28 | WAP | Wearing apparel | Man |
| 29 | LEA | Leather products | Man |
| 30 | LUM | Wood products | Man |
| 31 | PPP | Paper products, publishing | Man |
| 32 | P\_C | Petroleum, coal products | Cru |
| 33 | CRP | Chemical, rubber, plastic products | Scet + Sbet + Eim |
| 34 | NMM | Mineral products nec | Eim |
| 35 | I\_S | Ferrous metals | Eim |
| 36 | NFM | Metals nec | Eim |
| 37 | FMP | Metal products | Man |
| 38 | MVH | Motor vehicles and parts | Man |
| 39 | OTN | Transport equipment nec | Man |
| 40 | ELE | Electronic equipment | Man |
| 41 | OME | Machinery and equipment nec | Man |

(continued)

Appendix Table A-2. Sector Mapping between GTAP v7.1 and ADAGE (continued)

| GTAP v7.1 | | | ADAGE |
| --- | --- | --- | --- |
| No. | Code | Description | Sectors |
| 42 | OMF | Manufactures nec | Man |
| 43 | ELY | Electricity | Ele |
| 44 | GDT | Gas manufacture, distribution | Gas |
| 45 | WTR | Water | Srv |
| 46 | CNS | Construction | Man |
| 47 | TRD | Trade | Srv |
| 48 | OTP | Transport nec | Ralp + Ralf + Rodf + Rodp + Auto + Otrn |
| 49 | WTP | Water transport | Wtrt |
| 50 | ATP | Air transport | Airp |
| 51 | CMN | Communication | Srv |
| 52 | OFI | Financial services nec | Srv |
| 53 | ISR | Insurance | Srv |
| 54 | OBS | Business services nec | Srv |
| 55 | ROS | Recreational and other services | Srv |
| 56 | OSG | Public Administration, Defense, Education, Health | Srv |
| 57 | DWE | Dwellings | House |

1. The recursive-dynamic ADAGE has two versions: the 8-region version and the 27-region version. The 8-region version is our main focus in this document. [↑](#footnote-ref-2)
2. ADAGE currently uses the GTAP v7.1 database. See <https://www.gtap.agecon.purdue.edu/databases/v7/default.asp> for more information. [↑](#footnote-ref-3)
3. Each foreign country also contains all the linkages among households, firms, and government shown in the figure. [↑](#footnote-ref-4)
4. In the terminology used by I/O models, direct effects are experienced by a specific industry. Indirect effects capture how direct effects spill over into other industries in the direct industry’s supply chain, and induced effects cover how income changes from direct/indirect effects affect the economy when the incomes are spent. [↑](#footnote-ref-5)
5. Oil palms and rapeseed are not broken out as individual crops but grouped into the rest of oilseed category (Osdn) in ADAGE, so their biodiesel feedstocks are both from Osdn instead. [↑](#footnote-ref-6)
6. See <http://www.esru.strath.ac.uk/EandE/Web_sites/02-03/biofuels/quant_biodiesel.htm> for rapeseed yield and rapeseed biodiesel assumption; see <https://en.wikipedia.org/wiki/Biodiesel> for palm oil yield and biodiesel yield. [↑](#footnote-ref-7)
7. Electricity is generally introduced as an energy input in biofuel production (for miscanthus, agriculture residue, forest residue, and forest wood products feedstocks) but incorporated as a by-product in switchgrass biofuel in accordance with a study (Larson, Jin, and Celik, 2009) that showed the extra electricity generated is more than enough to offset the electricity used in the conversion process from switchgrass to a final fuel. [↑](#footnote-ref-8)
8. Fujimori et al. (2014) compared the CET function and logit function in land use change modeling in the Asia-Pacific Integrated Model CGE model (Fujimori, Hasegawa, and Masui, 2017) and found that agricultural goods production and land use were similar with CET and logit functions. The area balance violation generated by CET was large and heterogeneous across regions but was small for the aggregated world total. [↑](#footnote-ref-9)
9. There is also a land category “other land” that is kept constant over time and does not interact with these five land types. [↑](#footnote-ref-10)
10. Refer to <https://www.gtap.agecon.purdue.edu/databases/v7/default.asp> for more detailed information about the database and assumptions. [↑](#footnote-ref-11)
11. Unsurprisingly, actual economic growth between 2004 and 2010 differed from perfectly balanced expansion in all factors at the rate of GDP growth. [↑](#footnote-ref-12)
12. “Nec” is the abbreviation of “not elsewhere classified.” [↑](#footnote-ref-13)
13. To the extent that additional data become available for non-U.S. regions, we anticipate updating this characterization of transportation in those regions in future model updates. [↑](#footnote-ref-14)
14. One reason for deviations between these data sources is that FAOSTAT reports harvested area, whereas TEM reports planted area. These values will differ because of crop failures (i.e., a crop may be planted but not harvested) and multicropping (i.e., crops are grown on the same land during multiple growing seasons of the same year). [↑](#footnote-ref-15)
15. Technological change in ADAGE is specified as exogenous improvement in energy efficiency and land productivity. Technological change that may reduce labor and capital inputs is not included in ADAGE. [↑](#footnote-ref-16)
16. Harrod-neutral technical progress refers to growth with a constant capital/output ratio and profit rate. The assumption of a constant capital/output ratio implies that capital stock and labor force grow at the same rate. [↑](#footnote-ref-17)
17. See <https://www.gtap.agecon.purdue.edu/models/Dynamic/Baseline/default.asp> for more information. [↑](#footnote-ref-18)
18. Miscanthus yield was assumed to be twice the switchgrass yield. Production cost per hectare and conversion cost to fuel per gallon were assumed to be the same for switchgrass and miscanthus. [↑](#footnote-ref-19)
19. Oil-electric HEV includes all types of hybrid vehicles that can use both petroleum and electricity to run their motor, including plug-in hybrids. Production cost, input cost, and fuel economy (miles per gallon) and other input assumptions for HEVs were calculated as weighted averages from all types of hybrids in 2010. According to AEO2015 data (DOE, EIA, 2015), hybrids that use gasoline as their primary energy source dominated the market for HEVs from 2010 through 2015. [↑](#footnote-ref-20)
20. From now on, we use the abbreviation OEV to represent conventional vehicles that use gasoline and biofuels and BEV, HEV, and FCEV for advanced vehicles for auto (Auto), bus (RodP), and truck (RodF). [↑](#footnote-ref-21)