MIT Joint Program on the Science and Policy of Global Change

The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Version 4

Sergey Paltsev, John M. Reilly, Henry D. Jacoby, Richard S. Eckaus, James McFarland, Marcus Sarofim, Malcolm Asadoorian and Mustafa Babiker

Report No. 125
August 2005

The MIT Joint Program on the Science and Policy of Global Change is an organization for research, independent policy analysis, and public education in global environmental change. It seeks to provide leadership in understanding scientific, economic, and ecological aspects of this difficult issue, and combining them into policy assessments that serve the needs of ongoing national and international discussions. To this end, the Program brings together an interdisciplinary group from two established research centers at MIT: the Center for Global Change Science (CGCS) and the Center for Energy and Environmental Policy Research (CEEPR). These two centers bridge many key areas of the needed intellectual work, and additional essential areas are covered by other MIT departments, by collaboration with the Ecosystems Center of the Marine Biology Laboratory (MBL) at Woods Hole, and by short- and long-term visitors to the Program. The Program involves sponsorship and active participation by industry, government, and non-profit organizations.

To inform processes of policy development and implementation, climate change research needs to focus on improving the prediction of those variables that are most relevant to economic, social, and environmental effects. In turn, the greenhouse gas and atmospheric aerosol assumptions underlying climate analysis need to be related to the economic, technological, and political forces that drive emissions, and to the results of international agreements and mitigation. Further, assessments of possible societal and ecosystem impacts, and analysis of mitigation strategies, need to be based on realistic evaluation of the uncertainties of climate science.

This report is one of a series intended to communicate research results and improve public understanding of climate issues, thereby contributing to informed debate about the climate issue, the uncertainties, and the economic and social implications of policy alternatives. Titles in the Report Series to date are listed on the inside back cover.

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Abstract

The Emissions Prediction and Policy Analysis (EPPA) model is the part of the MIT Integrated Global Systems Model (IGSM) that represents the human systems. EPPA is a recursive-dynamic multi-regional general equilibrium model of the world economy, which is built on the GTAP dataset and additional data for the greenhouse gas and urban gas emissions. It is designed to develop projections of economic growth and anthropogenic emissions of greenhouse related gases and aerosols. The main purpose of this report is to provide documentation of a new version of EPPA, EPPA version 4. In comparison with EPPA3, it includes greater regional and sectoral detail, a wider range of advanced energy supply technologies, improved capability to represent a variety of different and more realistic climate policies, and enhanced treatment of physical stocks and flows of energy, emissions, and land use to facilitate linkage with the earth system components of the IGSM. Reconsideration of important parameters and assumptions led to some revisions in reference projections of GDP and greenhouse gas emissions. In EPPA4 the global economy grows by 12.5 times from 2000 to 2100 (2.5%/yr) compared with an increase of 10.7 times (2.4%/yr) in EPPA3. This is one of the important revisions that led to an increase in CO_2 emissions to 25.7 GtC in 2100, up from 23 GtC in 2100 projected by EPPA3. There is considerable uncertainty in such projections because of uncertainty in various driving forces. To illustrate this uncertainty we consider scenarios where the global GDP grows 0.5% faster (slower) than the reference rate, and these scenarios result in CO_2 emissions in 2100 of 34 (17) GtC. A sample greenhouse gas policy scenario that puts the world economy on a path toward stabilization of atmospheric CO_2 at 550 ppmv is also simulated to illustrate the response of EPPA4 to a policy constraint.

Contents

1. INTRODUCTION

The MIT Emissions Predictions and Policy Analysis (EPPA) model is a recursive-dynamic multi-regional general equilibrium model of the world economy, which is built on the GTAP dataset and additional data for the greenhouse gas (GHG) and urban gas emissions. The version of EPPA described here (EPPA4) has been updated in a number of ways from the model described in Babiker *et al.* (2001). Compared with the previous EPPA version, EPPA4 includes the following changes:

- Greater regional and sectoral disaggregation;
- The addition of new advanced technology options (natural gas combined cycle, natural gas combined cycle with carbon capture and sequestration, integrated gas combined cycle with carbon capture and sequestration);
- Explicit representation of renewable electricity (solar and wind, biomass);
- Liquid fuel from biomass;
- Updating of the economic base data to the GTAP 5 data set (Dimaranan and McDougall, 2002) including newly updated input-output tables for Japan, the US, and the EU countries, and rebasing of the data to 1997;
- Disaggregation of hydroelectric power from electricity sector;
- Disaggregation of household transportation into purchased and own-supplied transport;
- Updating of the demographic data and future projections (UN, 2000, 2001);
- Different options for international trade in natural gas (globally homogenous, regional trade, and Armington specification);
- Introduction of sector-specific constraints on greenhouse gases;

In addition, the model has received a general revision of projected economic growth and inventories of non-CO_2 greenhouse gases and urban pollutants.

The EPPA model can be used as a stand-alone model of the global economy for the study of greenhouse gas emissions and environmental policy. It also is a component of the MIT Integrated Global Systems Model or IGSM (Sokolov *et al.*, 2005) illustrated in **Figure 1**. Some of these improved features were developed in versions of EPPA subsequent to the version described in Babiker *et al.* (2001). EPPA4 brings all of these advances together, and the cumulative effect of these improvements and additions is to provide consistency between economic and key physical flows critical for integrating and dynamically linking EPPA with other components of the IGSM, such as with land use and in the effects of urban air pollution on human health and the economy.

EPPA4 is a flexible framework that can be applied to a variety of climate-energy-environment issues. The underlying GTAP data set provides a disaggregation of political units and economic sectors beyond that applied in the standard EPPA4 application. Examples of the use of this

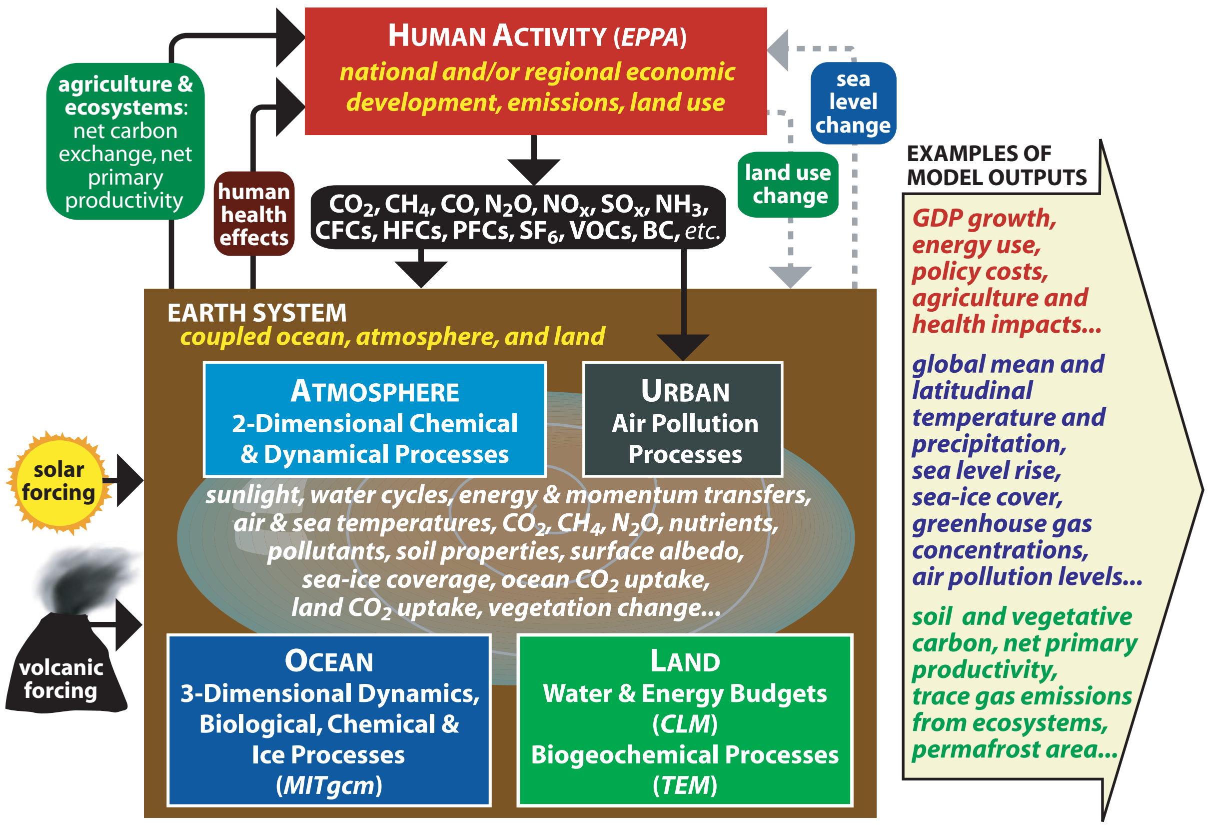

Figure 1. MIT Integrated Global System Model. Feedbacks between the component models that are currently included, or under development, are shown as solid and dashed lines, respectively.

capability for extensions of the standard model are EPPA4-EURO where the EU-25 countries are disaggregated into thirteen separate regions, and EPPA4-AGRI where the agricultural sector is broken out into crops, livestock and forestry. To consider the impacts of air pollution on human health and subsequent feedback on the economy we have also developed a specialized EPPA-HE (Health Effects) version of the model that reformulates the household sector to include demand for air pollution-related health services and treatment of household labor and leisure.

This report documents Version 4 of the EPPA model, focusing on the level of sectoral and regional detail in the standard version of the model. Modifications to accomplish the special versions above are described in other papers to be at http://mit.edu/globalchange/. Also, we present the reference values of the key model parameters. We recognize that these values are uncertain among and across regions and through time, and we consider these uncertainties in applications of the model (*e.g.*, Webster *et al.*, 2002). To introduce CGE-type models and the particular features needed for application to analysis of climate change we begin in Section 2 with an overview of the EPPA model. There we summarize the key features of the model and the components required to link a model based on economic variables to the physical quantities (*e.g.*, CO_2, energy consumption, land use) to an analysis of human-climate interaction. We also discuss how constraints on GHG emissions are imposed on solution and the options for representing GHG policies. Section 3 then presents the structure of the model with its representation of production, consumption and trade, and Section 4 discusses the various dynamic processes that influence model outcomes—such as evolution of the capital stock, population and labor force change, various aspects of productivity and technical change, and the influence of limited natural resources. New technologies play an important role in the model, in both its structure and its behavior over time, and their representation is described in Section 5. Section 6 presents the methods and data applied to estimation of the various emissions that are relevant to the climate issue. In Section 7 we describe efforts to calibrate EPPA for recent economic performance and the further post-processing of projected outputs to facilitate linkage to other components of the IGSM. In Section 8 we present results from the reference case of the model, including comparison with the model as documented by Babiker *et al*. (2001) for EPPA3, and illustrate application of the model to a sample emissions mitigation policy. Section 9 concludes with a discussion of ongoing work on the EPPA structure and its parameters. References are provided in Section 10.

2. THE EPPA MODEL: OVERVIEW

2.1 Purpose and Applications

The EPPA model simulates the world economy through time to produce scenarios of greenhouse gases, aerosols, other air pollutants and their precursors, emitted by human activities. These emissions scenarios are input into a coupled model of atmospheric chemistry, climate and terrestrial ecosystems to produce scenarios of anthropogenic climate change and changes in atmospheric composition. The requirements of the IGSM dictate a number of the features of its EPPA component:

- A long simulation horizon (through the year 2100);
- Comprehensive treatment of emissions of major greenhouse gases—carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6);
- Projections of emissions of substances with direct climatic impact such as aerosols from sulfates (SO_x), black carbon (BC), and organic carbon (OC);
- Similar treatment of other substances—nitrogen oxides (NO_x), carbon monoxide (CO), ammonia (NH_3), and non-methane volatile organic compounds (NMVOCs) that are important for the atmospheric chemistry of greenhouse gases;
- Spatial disaggregation for those gases that are not rapidly mixed in the atmosphere; and sectoral disaggregation sufficient to identify activities that emit GHGs.

Questions evaluated in applications of EPPA as part of the IGSM include, for example, uncertainty in forecasts of future climate change, effects on future climate of proposed greenhouse gas emissions policies, economic and policy implications of various atmospheric stabilization goals, and the validity of Global Warming Potential (GWP) indices as currently prescribed under the Kyoto Protocol.

The EPPA model is also designed to evaluate the economic impacts of emissions mitigation policies. Different versions of the EPPA model have been used for many such applications, including:

- Study of the interaction of climate policies and other economic policies (Jacoby *et al.*, 1997);
- Exploration of the implications of assumptions about malleability of capital (Jacoby and Sue Wing, 1999);
- The cost implications of controlling multiple trace gases (Reilly *et al.*, 1999);
- Elaboration of issues of design of carbon emissions trading (Ellerman and Sue Wing, 2000);
- Analysis of the interaction of nuclear electric sector and climate change policy in Japan (Babiker *et al.*, 2000a);
- Study of the impacts of the Kyoto Protocol on the US economy (Babiker *et al.*, 2000b), developing countries (Babiker *et al.*, 2000c) and the European Union (Viguier *et al.*, 2003);
- Preparation of information on uncertainty in emissions projections for use in climate models (Webster *et al.*, 2002);
- Uncertainty analysis of climate change and policy response (Webster *et al.*, 2003);
- Demonstration of the effects of non-CO_2 greenhouse gases and carbon sinks on climate control policy (Reilly *et al.*, 2002);
- Calculation of the environmental and economic implications of the Marrakech agreement (Babiker *et al.*, 2002);
- Study of alternative Kyoto targets (Babiker and Eckaus, 2002);
- Analysis of carbon capture and sequestration (McFarland *et al.*, 2004);
- Assessment of Russia's role in the Kyoto Protocol (Bernard *et al.*, 2003);
- Assessment of the US Climate Stewardship Act of 2003 (Paltsev *et al.*, 2003);
- Studies of approaches to modeling technology and technical change (Jacoby *et al.*, 2004);
- Estimation of the cost of the Kyoto Protocol targets for Japan (Paltsev *et al.*, 2004b);
- Calculation of air pollution health effects (Yang *et al.*, 2005);
- Assessment of the role of non-CO_2 gases in climate policy (Reilly *et al.*, 2005); and
- Exploration of the role of the existing fuel taxes in climate policy (Paltsev *et al.*, 2005).

For many of these studies EPPA is run in stand-alone mode, without the full IGSM.

Assessment of the costs, equity implications, and welfare impacts of different policies, especially under alternative technological assumptions, requires that particular features be included in EPPA. A general requirement is a comprehensive economic foundation for the model so that meaningful and complete estimates of costs can be made. Also needed is a level of regional disaggregation sufficient to represent major countries and regional blocs, and explicit representation of critical sectors (particularly energy resource and supply sectors) along with key technological alternatives. Inevitably, the availability of data and parameters for which there is an empirical basis places limits on the structure and level of detail of the model. Also, there are tradeoffs between realistic detail for individual technologies and sectors and the computational demands of solving a complex model such as EPPA.

2.2 The Structure of CGE Models

EPPA belongs to a class of economic simulation models known as computable general equilibrium (CGE) models. CGE models represent the circular flow of goods and services in the economy, as illustrated in **Figure 2**. Starting at the top of the cartoon of an economy, the model represents the supply of factor inputs (labor and capital services) to the producing sectors of the economy and provides a consistent analysis of the supply of goods and services from these producing sectors to final consumers (households), who in turn control the supply of capital and labor services. Corresponding to this flow of goods and services is a reverse flow of payments. Households receive payments for the services from the producing sectors of the economy for the labor and capital services they provide. They then use the income they receive to pay producing sectors for the goods and services consumed.

Personal and business savings as well as taxes provide the funds for investment and government purchases. EPPA also contains a full set of inter-industry transaction (not shown in Figure 2). Much of the gross production of some industries is used as intermediate inputs in other

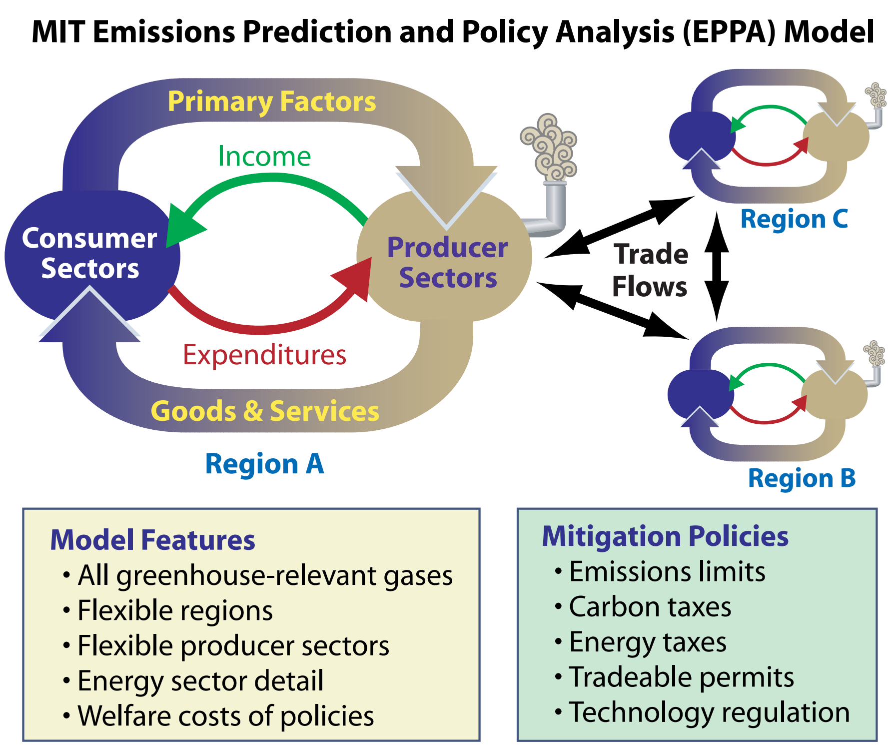

Figure 2. The circular flow of goods and resources in EPPA.

industries. The government is modeled as a passive entity that simply collects taxes and distributes the full value of the proceeds to the households. EPPA does not endogenously model international trade in factors such as capital and labor. The international capital flows that compensate for commodity trade imbalances in the base year are assumed to disappear gradually, and thus current account imbalances that exist in the base year disappear.

The closed nature of an economic system means that all the revenues from the production of goods must be allocated either to households (as returns to labor or capital), to other industries as payments for intermediate output, or to government as taxes. Prices of goods must also reflect the cost of all of the inputs, wages and the return on capital. EPPA also separately identifies natural resource capital as fixed factors in agriculture (arable land) and in the oil, coal, and natural gas industries (fossil fuel resources). These assets are owned by households, and their returns (associated with their rental values to producers) accrue to households as income. The value of these assets thus reflects the annual flow of returns to the economy.

The critical data that determine the structure of a CGE model are contained in Social Accounting Matrices (SAMs), which represent a snapshot of the economy of each region in the model for the base year of 1997. SAMs are developed from systems of national income and product accounts and the input-output tables that quantify the inter-industry flows of goods and services (Pyatt and Round, 1985). In addition, EPPA keeps track through time of the physical flows of carbon-based fuels and resources in the economy, their different calorific values, and also their greenhouse gas emissions in order to identify the specific sectors that are most affected as a result of policies.

Production functions for each sector describe the ways in which capital, labor, energy and intermediate inputs can be used to produce output. Consumption is modeled as if there were a representative consumer maximizing utility by the choice among goods. A fundamental feature of EPPA's modeling is its representation of the ability of individuals to make tradeoffs among the inputs to both production and consumption. For producers this reflects the underlying technology—the extent to which labor, capital and energy can be substituted for each other. The technical ability or willingness to make such tradeoffs is summarized by elasticities of substitution, which are key parameters in production and utility functions. In the EPPA model elasticities of substitution are important determinants of the estimates of the cost of policies to control greenhouse gaes. If a carbon restriction increases the price of carbon-based fuels, the cost of production of goods will rise depending on the energy share, its carbon content and the ability of the industry to substitute other inputs for energy. Similarly, consumers' ability to shift away from the use of energy and to substitute away from goods that are relatively more energy intensive depends on the elasticity of substitution and how prices for each of the goods changes. The importance of the circular flow concept intrinsic to CGE models becomes apparent here. If consumers (or producers) can substitute other goods (or inputs), but the latter are intensive in carbon-based energy as well, then a carbon restriction will increase both the price of energy faced by producers and consumers and the price of goods (or inputs) that use energy intensively in their production. In this way, the quantity of carbon (and the associated costs of policies that restrict carbon emissions) that is embodied in commodities is reflected in economic decisions about what inputs to use and what goods to consume.

As illustrated in Figure 2, EPPA also models trade flows for all goods among regions. Some goods (*e.g.*, crude oil, emissions permits) are treated as perfect substitutes in global trade. For most goods, however, the model embodies the Armington convention widely used in modeling international trade (Armington, 1969) whereby a domestically produced good is treated as a different commodity from an imported good produced by the same industry. Thus, for example, imported energy-intensive goods are not perfect substitutes for domestically produced energy-intensive goods. The degree to which domestic and imported goods differ is controlled by the elasticity of substitution between them. One can think of a firm producing a composite good that is an aggregate of domestic- and foreign-produced goods. Changes in the relative shares of foreign and domestic goods in the composite are determined by changes in the relative prices of these goods at home and abroad, given the Armington substitution elasticity and the initial shares of these goods in the benchmark SAM.

The Armington elasticity is a key parameter in determining the "leakage" rate of carbon and other greenhouse gases in response to climate policy. A carbon constraint placed on a subset of countries (for example, the Annex B nations) will raise the cost of producing energy intensive goods in those countries. Producers will respond by increasing the share of imported energy-intensive goods in the composite, while reducing the share of domestically produced goods. In turn, foreign producers that face no carbon constraints will expand production. Thus, the domestic carbon constraint is met in part by a contraction of domestic energy intensive industries. Other features in EPPA also affect leakage such as effects on income abroad of changes in import and export demand and the effect of policies on international energy prices.

Another important aspect of CGE models is the degree to which they capture the dynamics of the economy through time, particularly their representation of savings-investment decisions. In this regard, EPPA falls into a class of models known as *recursive dynamic*. Savings and investment are based only on current period variables, as opposed to a forward-looking inter-temporal optimization model. In this latter approach savings and investment decisions are modeled to take account of all future economic conditions, which are assumed to be known with certainty.[1] Saving in each period is equal to investment, which both compensates for current-period depreciation and contributes to the next period's stock of capital.

In addition to capital accumulation, technological change is an important source of growth of the economy. EPPA models technical change in three ways (Jacoby *et al.*, 2004). First, there is an exogenous augmentation of the supplies of labor and natural resources. Second, energy use per

[1] As noted in Section 9, a forward-looking version of the EPPA structure is in preparation.

unit output decreases exogenously through time (the so-called autonomous energy efficiency improvement index, or AEEI). The AEEI is a heuristic representation of non-price driven changes in energy use over time. For developed countries there has been an observed improvement in energy intensity of the economy that is not easily explained by fuel prices. While this improvement is sometimes considered due to technical change, it can also result from changes in the structure of the economy. And third, included in EPPA are energy technologies that are currently unused (or only at very small scale), but which come into play as supplies of conventional energy resources deplete causing their prices to rise or as policies penalize the GHG emissions of conventional fossil technologies. Their time of entry in a simulation depends on their costs relative to those of current fuels, as they endogenously change in a forward simulation of EPPA.

The algorithm used to solve the EPPA models finds a solution that maximizes consumer welfare and producer profits subject to the technologies of production and consumption, consumer endowments of primary factors (capital, labor, natural resources, and other fixed factors), and existing taxes and distortions. A convenient way to represent carbon policies in these models is to introduce an additional constraint that holds carbon emissions from aggregate fossil fuel to a specified limit. In the model's solution there is a shadow value on carbon associated with such a constraint, much as the fixed endowments of capital, labor, natural resources, and other fixed factors in each period result in a shadow value of capital, the wage rate, and a rental price for natural resources. Because of this similarity, the shadow price of carbon is readily interpretable as the price at which carbon permits would trade if such a permit system were implemented. In EPPA the carbon price behaves identically to a tax, and is therefore conceptually similar to other prices in the model. A binding emissions constraint has economic value, which, like a tax, generates a stream of revenue that must be allocated somewhere in the economy. Revenue collected from the imposition of carbon constraint is treated like other taxes and its full value is transferred to the representative agent.

The shadow price or tax on each physical unit of greenhouse gas emissions is one indicator of the cost of a control policy, and these will exhibit increasing marginal cost such that the tighter the constraint the higher the shadow price. This facilitates the creation of reduced-form representations of model responses to policy constraints. One way to summarize the EPPA model response is to plot the relationship between imposed taxes on carbon and the levels of emissions reduction that result. This relationship is known as a marginal abatement cost curve (or MAC) and has been used to assess the impacts of emissions trading and other policy questions (Ellerman and Decaux, 1998). Note, however, that in the presence of distortions in the economy the MAC curve solution can give results inconsistent with a conventional welfare analysis (Paltsev *et al.*, 2004b).

Besides calculating the shadow price of carbon, CGE models also facilitate the computation of measures of the total cost of policies simulated within their structure. These take into account multiple feedbacks on production, income and demand across the full range of industries in an economy. One such measure, common in economic analysis, is the change in economic welfare measured as equivalent variation. Conceptually, this is the amount of income needed to compensate the representative agent for welfare losses suffered as a result of the policy. In most EPPA applications this is measured by the change in aggregate consumption, which because of the structure of the standard EPPA is a measure of welfare in equivalent variation**.** Additional outputs of EPPA simulations are the prices and quantities necessary to calculate other indices of economic well-being that are sometimes of interest in assessing the effects of policies. These include gross domestic product (GDP), sectoral output, commodity and factor prices, and the terms of trade.

2.3 The Linkage to Physical Quantities

CGE models are based on a rich underpinning of economic theory and have been widely used to evaluate economic issues. A goal of the MIT IGSM, however, is to study the earth as an interacting system, which requires the formulation of links between an economic model such as EPPA and other components that go beyond the traditional focus of CGE models. As already discussed, EPPA includes projections of emissions of key climate related emissions and associated quantities such as the level of fuel burning. The accounting of these physical flows has been expanded in EPPA4. A brief introduction to the issues associated with creating physical flows that are consistent with the economic data base provides an idea of the advances in this regard in EPPA4, and why EPPA is in a sense a hybrid economic and physical accounting model.

The economic data that are the foundation of CGE models are the National Income and Product Accounts (NIPAs) of countries and these data underlie the GTAP data set. The NIPA data follow a long-standing tradition in economics of using total expenditure or sales as a measure of the quantity of inputs and outputs in the economy. That is, these data do not report quantities in tons of wheat, coal, iron ore, or steel produced or the hectares of land, hours of labor, or exajoules of energy used to produce them. Instead they report the total expenditure on energy or labor, rental payments to land and capital, and the total sales or purchases of goods and services.

Measuring inputs and outputs in terms of expenditure or of the total value of sales greatly facilitates aggregation. The economic theory underlying this practice holds that the prices of goods reflect their marginal value as inputs into production or of consumption.[2] Different prices for varying grades of a particular commodity thus reflect their differential value as a production input or for consumption. One might ideally desire a fine disaggregation of inputs and outputs, but of course there are different varieties and grades of even such basic commodities as, for example, apples, wheat, coal or crude oil. Similarly, the labor force is composed of individuals with widely varying skills, and land has a wide range of characteristics that are more or less

[2] Problems of aggregation are eliminated in a base year, but they resurface when comparisons of real economic growth are to be made over time. One then must worry about the quality (and implicitly) the mix of products of different qualities in any aggregation. Much economic work has been devoted to creating prices indices that capture accurately the changing mix, but there remain difficult problems of changing quality that bedevil efforts to identify real growth and changes in the price level. To solve these problems requires going back to more fundamental and disaggregated observations.

useful for different purposes. In manufacturing and services, product differentiation is the rule rather than the exception, and no one would believe it made much sense to measure hair cuts and financial services in their natural units and add them together.

In economic models the problem of adding together apples and oranges (or different varieties of apples) is solved by using price weights. For example, consider a land owner with three different parcels of land: parcel #1 is 300 hectares and rents for $75 per hectare, parcel #2 is 150 hectares and rents for $150 per hectare, and parcel #3 is 75 hectares and rents for $300 hectare. Most people would sum together the hectares and conclude that the total land owned is 525 hectares. Economists are interested, however, in the contribution this land makes to the economy, and they would thus observe that parcel #2 is twice as valuable per hectare as parcel #1, and parcel #3 twice as valuable as parcel #2. They use the rental value as an appropriate weight to sum these together. Parcel 1's annual value to the economy is $75 x 300 = $22,500; parcel 2 is $150 x 150 = $22,500, and parcel 3 is $300 x 75 = $22,500. The example here is constructed so that when weighted by price, the three parcels are equal in size in terms of their input into the economy, which is a very different conclusion than using hectares directly which would indicate that parcel #1 is four times bigger than parcel #3.

The approach of weighting inputs and products by their marginal value allows agricultural or steel production or energy input to be aggregated in an economically meaningful manner. Agriculture output is composed of commodities like corn, wheat, beef, lamb, apples, oranges, raspberries, and asparagus. It would be nonsensical to add together total tons because that would mean that fruit and vegetable production is a minor component of agriculture when in value terms it is as important as grain crops. Output of the iron and steel industry includes specialty alloy products, cast iron, and more common sheet or bar products. Similarly, an exajoule of coal is of less value to the economy than an exajoule of oil, gas, or electricity.

Formally, a CGE model such as EPPA measures all inputs and outputs in the economy in billions of dollars. Given the use of value as the quantity measure, all prices are unit-less (= 1.0) in the base year and so when multiplied times the input quantity one then gets back expenditure or income as a monetary measure.[3] Simulating the model forward, or in a counterfactual case, is a process of finding prices that clear the markets given some exogenous change or limitation on how the economy can use its resources. Market-clearing prices in these simulations will typically vary from 1.0. If, for example, the labor force is estimated to increase by 20% from $10 billion this will be simulated as a labor input of $12 billion. The base year wage rate is defined as 1.0 and so wage income (and the wage bill for employers in the economy) is $10 billion in the base year. But in the future year if the market clearing wage rate falls to 0.95 relative to the numeraire good then labor income will have increased by 0.95 x $12 billion = $11.4 or only 14% but we still measure the "physical" increase in labor to be the 20% increase from $10 to $12 billion.

[3] For an introduction to the analytic procedures underlying CGE models see Sue Wing (2004).

If the focus is on purely economic results over the short- and medium-term, this approach to economic modeling has proven useful without further extension. Changes in physical inputs are implied by economic modeling but need not be explicitly tracked. The limitation of this approach for earth system and longer-term economic modeling is that there is no straightforward way to keep track of important physical flows such as emissions of pollutants, depletion of resources, changes in land use, and the efficiency of physical processes such as conversion of fuels to electricity. This feature further limits the use of engineering data on new technologies. For example, the electric sector data includes multiple fuels, capital, labor, and intermediate inputs that lead to the fossil-based production and transmission of electricity, but also includes technologies such as nuclear and hydroelectric power that do not use fossil fuels. Engineering cost data for new electricity technologies such as wind, natural gas combined cycle, or integrated coal gasification with sequestration typically focus on generation cost rather than the broader costs of running an electric utility company and transmitting and distributing the product. Moreover, an aggregate electricity sector that includes both fossil sources and hydro, nuclear, and other renewable sources cannot be evaluated directly to determine the efficiency of energy conversion. Engineering estimates of future efficiency of conversion and the technological costs of key options as they depend on resource availability and quality is useful information that can help constrain and inform longer run economic-energy forecasts. Finally, environmental feedbacks on the economy, through changes in the productivity of crops and forests and impacts on the human population, will be mediated through impacts on physical systems. For all of these reasons it is essential in climate analysis to link the changes in the physical and biological environment of the earth system to the underlying economic variables.

This need to link physical and economic changes has driven key developments in EPPA toward what is now a hybrid model—one that operates as a conventional computable general equilibrium model but includes supplemental accounting of the physical and biological variables. Earlier EPPA versions contained such supplemental tables for physical energy use, as they were necessary for accounting of carbon dioxide emissions. They also included accounting of key pollutant emissions. Physical energy use allowed tracking of physical depletion of energy resources. Key developments in this domain in EPPA4 are:

- Elaboration of the relationship between agricultural emissions and output and the emissions of other substances as further described in Sarofim *et al.* (2005);
- An explicit treatment of demography and labor force;
- Elaboration and disaggregation of the electric utility sector (*e.g.*, McFarland *et al*., 2004); and
- Further disaggregation of agriculture to explicitly treat land use and feedbacks impacts on vegetation (Felzer *et al.*, 2005; Reilly *et al.*, 2004).

A key to these developments is disaggregation to a level where it can be assumed that changes in economic variables can be related to changes in physical values. One always faces the problem that a persistent trend within the economy toward higher or lower quality (changing mix of products) means that there will be a divergence between the economic measure and the physical measure. We have invested considerable effort to examining this relationship, and where we believe there is a persistent trend below the level of aggregation in EPPA, we have introduced adjustments in the relationship between the physical variable and the economic measure (see Sarofim *et al.*, 2005). Each of these efforts represents a contribution to the development of supplemental physical accounts that provides links from the economic data to the physical and biological system components of an earth system model. And in general these developments have two components, linking a physical data set to the economic data set in the base year, and parameterizing the evolution of the relationship of the physical and economic variables over time.

3. EQUILIBRIUM STRUCTURE, PARAMETERS, AND POLICY CONSTRAINTS

The basic income and product data in the EPPA model come from a comprehensive dataset GTAP 5 (Hertel, 1997; Dimaranan and McDougall, 2002) that accommodates detailed accounts of regional production, consumption, and bilateral trade flows in addition to a consistent representation of energy markets in physical units. The standard programming language for GTAP data and modeling work is GEMPACK (Harrison and Pearson, 1996). We convert and rearrange the data into the General Algebraic Modeling System (GAMS) format using GTAPinGAMS (Rutherford and Paltsev, 2000). The model is calibrated on this dataset to generate a benchmark equilibrium in 1997 as a base year. From 2000 onward, it is solved recursively at 5-year intervals.

EPPA4 aggregates the GTAP dataset into 16 regions shown in **Table 1** and to the production and household sectors presented in **Table 2**. A mapping of the GTAP regions and sectors into the EPPA format is provided in Appendix 1. To better focus on climate policy, the model is disaggregated beyond that provided in the GTAP data set for energy supply technologies and for transportation, and a number of supply technologies are included that were not in use in 1997 but could take market share in the future under some energy price or climate policy conditions. All production sectors and final consumption are modeled using nested Constant Elasticity of Substitution (CES) production functions (or Cobb-Douglas and Leontief forms, which are special cases of the CES). The model is solved using the MPSGE modeling language (Rutherford, 1999).

In comparison to EPPA3, the regional disaggregation of EPPA4 includes a breakout of Canada from Australia/New Zealand, and a breakout of Mexico to better focus on North America. Developing country regional groupings were altered to create groups that were geographically contiguous. New sectoral disaggregation includes a breakout of services (SERV) and transportation (TRAN) sectors. These were previously aggregated with other industries (OTHR). This further disaggregation allows a more careful study of the potential growth of these sectors over time, and the implications for an economy’s energy intensity. In addition, the sub-

Table 1. Countries and Regions in the EPPA Model.

Regions in Earlier Versions	Regions in EPPA4	Europe Detail for Special Studies
Annex B		
United States (USA)	United States (USA)	
European Union (EEC)	European Union[a] (EUR)	Great Britain
Eastern Europe (EET)	Eastern Europe[b] (EET)	Finland
Japan (JPN)	Japan (JPN)	France
Former Soviet Union (FSU)	Former Soviet Union[c] (FSU)	Germany
Other OECD (OOE)	Australia & New Zealand (ANZ)	Hungary
	Canada (CAN)	Italy
Non-Annex B		Netherlands
China (CHN)	China (CHN)	Poland
India (IND)	India (IND)	Spain
Dynamic Asian Economies (DAE)	Higher Income East Asia[d] (ASI)	Sweden
Energy Exporting LDCs (EEX)	Middle East (MES)	EFTA (Switzerland, Norway, Iceland)
Brazil (BRA)	Indonesia (IDZ)	Other
Rest of the World (ROW)	Mexico (MEX)	
	Central & South America (LAM)	
	Africa (AFR)	
	Rest of World[e] (ROW)	

[a] The European Union (EU-15) plus countries of the European Free Trade Area (Norway, Switzerland, Iceland)
[b] Hungary, Poland, Bulgaria, Czech Republic, Romania, Slovakia, Slovenia
[c] Russia and Ukraine, Latvia, Lithuania and Estonia (which are included in Annex B) and Azerbaijan, Armenia, Belarus, Georgia, Kyrgyzstan, Kazakhstan, Moldova, Tajikistan, Turkmenistan, and Uzbekistan (which are not)
[d] South Korea, Malaysia, Philippines, Singapore, Taiwan, Thailand
[e] All countries not included elsewhere: Turkey, and mostly Asian countries

model of final consumption was restructured to include a household transportation sector. This household activity provides transportation services for the household, either by purchasing them from TRAN or by producing them with purchases of vehicles from OTHR, fuel from ROIL, and insurance, repairs, financing, parking, and other inputs from SERV. While the necessary data disaggregation for TRAN is included in GTAP5, the creation of a household transportation sector required augmentation of the GTAP data as described in Paltsev *et al*. (2004a).

3.1 Equilibrium Structure

EPPA is formulated and solved as a mixed complementarity problem (MCP) (Mathiesen, 1985; Rutherford, 1995), where three inequalities should be satisfied: the zero profit, market clearance, and income balance conditions. Using the MCP approach, a set of three non-negative variables is involved: prices, quantities, and income levels.

The zero profit condition requires that any activity operated at a positive intensity must earn zero profit (*i.e.*, value of inputs must be equal or greater than value of outputs). Activity levels y for constant returns to scale production sectors are the associated variables with this condition. It means that either $y > 0$ (a positive amount of y is produced) and profit is zero, or profit is negative and $y = 0$ (no production activity takes place). Specifically, the following condition should be satisfied for every sector in an economy[4]:

$$profit \geq 0,\ y \geq 0,\ output^T\,(-profit) = 0. \tag{1}$$

[4] An expression written as $x^T y = 0$ (when $x \geq 0$ and $y \geq 0$) means $x_i y_i = 0$, for all $i = 1, ..., n$. The variables x_i and y_i are called a complementary pair and are said to be complements to each other.

Table 2. Sectoral Breakdown and Resource Factors in the EPPA Model.

Sectors in Earlier Versions	Sectors in EPPA4	Production Sectors
Non-Energy		
Agriculture	Agriculture (AGRI)	***Agriculture for Special Studies***
Energy Intensive	Energy Intensive (EINT)	Crops
Other Industries & Services	Transportation (TRAN)	Livestock
	Other Industry (OTHR)	Forestry
	Services (SERV)	
Energy		
Electricity *(detail not shown here)*	Electricity (ELEC)	***Electric Generation Technology***
Crude Oil	Conventional Crude Oil (OIL)	Coal
Oil from Shale	Oil from Shale (SOIL)	Gas
Refined Oil	Liquid Fuel from Biomass (BOIL)	Refined Oil
Coal	Refined Oil (ROIL)	Hydro
Natural Gas	Coal (COAL)	Nuclear
Gas from Coal	Natural Gas (GAS)	NGCC[a]
	Gas from Coal (SGAS)	NGCC-CCS[b]
		IGCC-CCS[c]
		Wind & Solar
Household		Biomass
Household Consumption	Own-Supplied Transport	
	Purchased Transport	
	Other Goods & Services	

Primary Input Factors in EPPA 4: *For Each Region*	*For Energy Resource Sectors*
Capital	Crude Oil
Labor	Shale Oil
Land	Natural Gas
	Coal
	Hydro
	Nuclear
	Wind & Solar

[a] Natural Gas Combined Cycle
[b] Natural Gas Combined Cycle with Carbon Capture and Sequestration
[c] Integrated Gas Combined Cycle with Carbon Capture and Sequestration

The market clearance condition requires that any good with a positive price must have a balance between supply and demand and any good in excess supply must have a zero price. Price vector p (which includes prices of final goods, intermediate goods and factors of production) is the associated variable. Using the MCP approach, the following condition should be satisfied for every good and every factor of production:

$$supply - demand \geq 0,\ p \geq 0,\ p^T(supply - demand) = 0. \tag{2}$$

The income balance condition requires that for each agent (including any government entities) the value of income must equal the value of factor endowments and tax revenue:

$$income = endowment + tax\ revenue. \tag{3}$$

A characteristic of the CES production and consumption structures that are used throughout EPPA is that all inputs (consumption goods) are necessary inputs. Thus, for most markets the above conditions are satisfied with prices, output, income, and consumption of all goods strictly greater than zero, and with supply strictly equal to demand. Falling demand for an input or consumption good will simply mean that the price will fall very low. The exceptions are for those goods that enter as perfect substitutes—such as many of the backstop technologies modeled in EPPA. Their prices and output levels are zero until they are economically competitive. Note also that the zero profit condition is a standard condition for equilibrium in economics. The definition of profits in economics differs, however, from that used in common parlance. What would be considered "profits" in more common discussions are, in a CGE model like EPPA, reflected in the rental price of a "fixed factor." For example, for a given time period, the capital stock for each vintage of capital is fixed. If demand for the output of that sector rises (or falls) significantly the rental rate for the fixed vintages of capital will rise (or fall) and will not reflect the original cost of installing that capital or a replacement cost of the capital. Common parlance would tend to refer to a rise in the rental value above a rate reflecting installation cost as profits (or a fall as a loss). Other fixed factors (land, resources, and specialized fixed factor inputs for new technologies as discussed in Section 5) are not "produced" at all and these also generate rents. In common parlance changes in these rents also often would be counted toward a change in profit for a firm.

In simple form, a corresponding optimizing problem in the EPPA model may be summarized as follows.

Behavior of Firms

In each region (indexed by the subscript *r*) and for each sector (indexed interchangeably by *i* or *j*), a representative firm chooses a level of output *y*, quantities of primary factors *k* (indexed by *f*) and intermediate inputs *x* from other sectors *j* to maximize profits subject to the constraint of its production technology. The firm's problem is then:

$$\max_{y_{ri},\, x_{rji},\, k_{rfi}} \pi_{ri} = p_{ri} y_{ri} - C_{ri}(p_{ri}, w_{rf}, y_{ri}) \quad \text{such that} \quad y_{ri} = \varphi_{ri}(x_{rji}, k_{rfi}), \tag{4}$$

where π and C denote the profit and cost functions, respectively; and p and w are the prices of goods and factors, respectively.

In EPPA we assume that production is represented by constant elasticity of substitution (CES) technologies that exhibit constant returns to scale (CRTS). These assumptions greatly simplify the firm's problem in Eq. 4. First, the linear homogeneity of the cost function implied by duality theory enables us to re-express Eq. 4 in terms of the unit cost and unit profit functions. Second, CRTS implies that in equilibrium firms make zero economic profits. Hence, the firm's optimizing behavior implies the equilibrium condition:

$$p_{ri} = c_{ri}(p_{rj}, w_{rf}), \tag{5}$$

where c is the unit cost function.

By Shephard's Lemma, in sector i the intermediate demand for good j is:

$$x_{rji} = y_{ri} \frac{\partial c_{ri}}{\partial p_{rj}}, \tag{6}$$

and the demand for factor *f* is:

$$k_{rfi} = y_{ri} \frac{\partial c_{ri}}{\partial w_{rf}}. \tag{7}$$

Household Behavior

In each region, a representative agent is endowed with the supplies of the factors of production, the services of which may be sold or leased to firms. In each period, the representative agent chooses consumption and saving to maximize a welfare function subject to a budget constraint given by the level of income *M*:

$$\max_{d_{ri},\, s_r} W_{ri}(d_{ri}, s_r) \quad \text{such that} \quad M_r = \sum_f w_{rf} K_{rf} = p_{rs} s_r + \sum_i p_{ri} d_{ri}, \tag{8}$$

where *s* is saving, *d* is the final demand for commodities, *K* is the aggregate factor endowment of the representative agent in region *r*.

Like production, preferences are represented by a CES utility function. By duality and the property of linear homogeneity, for each region there exists a unit expenditure function or welfare price index that corresponds to the configuration in Equation 8, given by:

$$p_{rw} = E_r(p_{ri}, p_{rs}). \tag{9}$$

By Shephard's Lemma, the compensated final demand for goods is given by

$$d_{ri} = \overline{m}_r \frac{\partial E_r}{\partial p_{ri}}, \tag{10}$$

and that for savings is:

$$s_r = \overline{m}_r \frac{\partial E_r}{\partial p_{rs}}, \tag{11}$$

where $\overline{m}_r$ is the initial level of expenditure in each region.

The system is closed with a set of market clearance equations that determine the equilibrium prices in the different goods and factor markets. Suppressing for simplicity the final demand categories investment, government and foreign trade, these equations are:

$$y_{ri} = \sum_j y_{rj} \frac{\partial C_{rj}}{\partial p_{ri}} + \overline{m}_r \frac{\partial E_r}{\partial p_{ri}}, \tag{12}$$

and

$$K_{rf} = \sum_j y_{rj} \frac{\partial C_{rj}}{\partial w_{rf}}. \tag{13}$$

The following sections elaborate on the practical implementation of the abstract production and demand structures shown here.

3.2 Production

Production technologies are described using nested CES functions. The nesting structures for most sectors remain unchanged in EPPA4 from EPPA3, except as they incorporate further disaggregation and as noted below. Greater sector disaggregation itself can improve the representation of energy substitution possibilities. For example, disaggregating transportation, where ROIL is the primary fuel used, has the effect of essentially eliminating direct substitution of gas or electricity for ROIL in the provision of transportation services, a more realistic representation of transport technology in the household. The nesting structure was designed to allow flexibility in setting elasticities of substitution particularly with regard to fuels and electricity, and those elasticities to which emission and abatement costs are especially sensitive. Extensive testing of the sensitivity of key results to elasticity values has been done with EPPA3 (Webster *et al*., 2002) and with early versions of EPPA4 (Cossa, 2004). Elasticities of substitution were re-evaluated and updated based on the review of the literature and expert elicitation conducted by Cossa (2004). Key elasticities of substitution used in reference runs of the model are given in **Table 3**, and the nest structure for sectors is given in **Figure 3**.

Table 3. Reference Values of Production Sector Substitution Elasticities.

σ_j	Description	Value	Comments
	Energy Substitution Elasticities		
σ_{EVA}	Energy-Value Added	0.4 – 0.5	Applies in most sectors, 0.5 in EINT, OTHR
σ_{ENOE}	Electricity-Fuels aggregate	0.5	All sectors
σ_{EN}	Among fuels	1.0	All sectors except ELEC
σ_{EVRA}	Energy/Materials/Land-Value Added	0.7	Applies only to AGRI
σ_{ER}	Energy/Materials-Land	0.6	Applies only to AGRI
σ_{AE}	Energy-Materials	0.3	Applies only to AGRI
σ_{CO}	Coal-Oil	0.3	Applies only to ELEC
σ_{COG}	Coal/Oil-Gas	1.0	Applies only to ELEC
	Other Production Elasticities		
σ_{VA}	Labor-Capital	1.0	All sectors
σ_{GR}	Resource-All other inputs	0.6	Applies to OIL, COAL, GAS sectors, calibrated to match medium run supply elasticity
σ_{NGR}	Nuclear Resource-Value added	0.04 – 0.4	Varies by region
	Armington Trade Elasticities		
σ_{DM}	Domestic-Imports	2.0 – 3.0	Varies by good
		0.3	Electricity
σ_{MM}	Among Imports from different regions	5.0	Non-Energy goods
		4.0	Gas, Coal
		6.0	ROIL
		0.5	Electricity

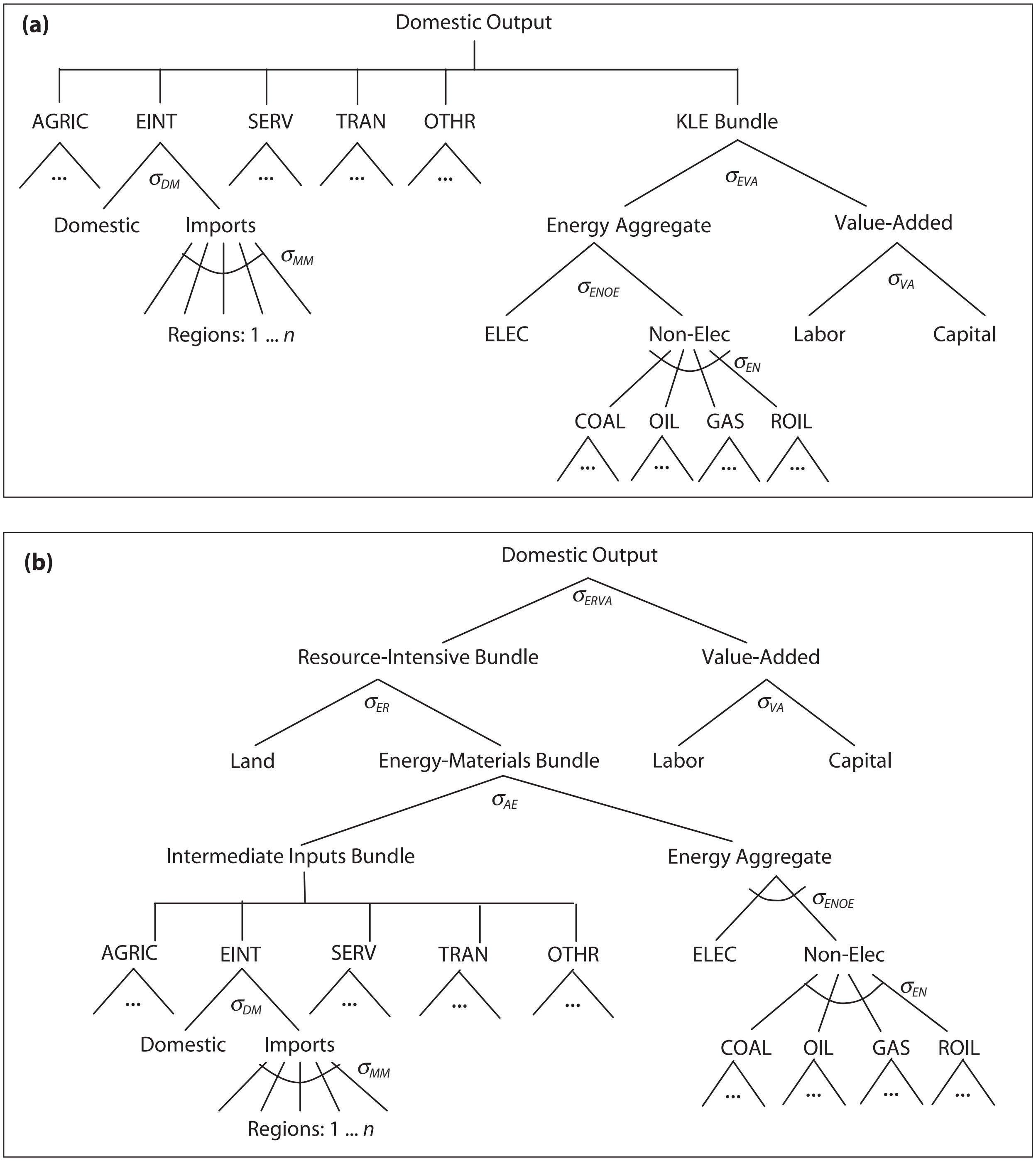

Figure 3. Structure of Production Sectors: **(a)** Services, Industrial Transportation, Energy Intensive and Other Industries, **(b)** Agriculture. Vertical lines in the input nest signify a Leontief or fixed coefficient production structure where the elasticity of substitution is zero. Terminal nests with… indicate the same aggregation structure for imported goods as shown in detail for the EINT sector. OIL(crude oil) is modeled as an internationally homogenous good ($\sigma_{DM} = \sigma_{MM} = \infty$). [*Figure continues on following page.*]

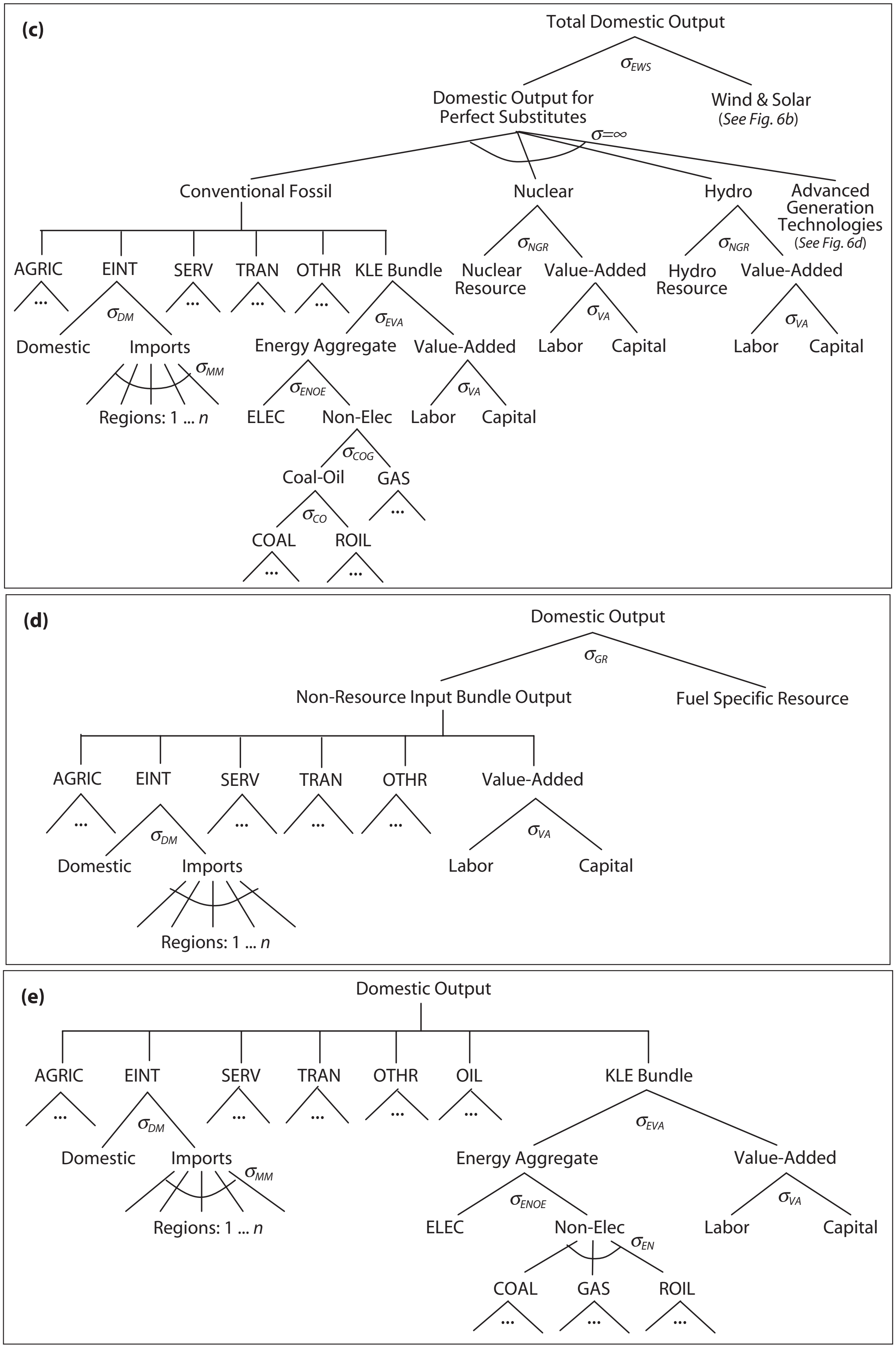

Fig. 3 (*continued*). Structure of Production Sectors: **(c)** Electricity, **(d)** Primary Energy Sectors (COAL, OIL, GAS), **(e)** the ROIL sector.

A common nest structure exists for the Services, Transportation, Energy Intensive, and Other industries (Figure 3a). Intermediate inputs enter in a Leontief structure with the Capital-Labor-Energy (KLE) bundle, which consists of an energy and value-added bundle. The single nest for fuels that includes coal, oil, gas, and refined oil would appear to limit flexibility in setting separate elasticities for individual fuel pairs. In practice this limitation is not significant. While OIL is retained in this nest for completeness, crude oil is not used directly in any sector except in the refined oil (ROIL) sector. In addition, among these sectors coal use is significant only in EINT in most countries, with negligible use in other sectors in a few regions of the world. China is an exception, and has been dealt with as a special case of calibration as described in Section 7.2. Thus for most of the sectors represented by this nest structure the interfuel substitution elasticity, σ_{EN}, is only important in determining substitution between ROIL and GAS, and thus there is substantial flexibility to set this elasticity at whatever level is deemed appropriate. In the transportation sector, where most of the energy use is a petroleum product that is part of ROIL, the critical elasticity is between the energy aggregate and value added, σ_{EVA}, reflecting the fact that there is little direct substitution between electricity, gas, and petroleum products. Another aspect of the nest structure worth note is that for imported goods. They are first combined by region of origin as Armington goods (*i.e.*, $\sigma_{MM} < \infty$), with the value of σ_{MM} describing the ability of a country to substitute among, for example, EINT goods from different regions. Imported goods as a bundle are then further aggregated to create an Armington good composed of the domestic good and imports. The input of, for example, the EINT good into OTHR is thus a composite of the domestically produced EINT and imported EINT goods.

Disaggregation of transport is a new feature of EPPA4, and is discussed in detail in Paltsev *et al.* (2004a). It is represented by two activities: an industry transportation sector (aggregating the modal splits in the base GTAP5 data) represented in Figure 3a and the household transportation sector that is treated explicitly in household consumption. Its representation there is discussed further in Section 3.4. The industry transportation (TRAN) sector supplies transport services (both passenger and freight) to other sectors of the economy and to households. The values for elasticities in the industry transportation sector are provided in Table 3. The data for the modeling of this sector come directly from the GTAP data set and include, following the nomenclature of the GTAP data set, OTP (other transport), ATP (air transport), and WTP (water transport).

The structure of the agriculture sector (Figure 3b) differs from that of the other sectors. The nesting structure includes land explicitly, and represents a tradeoff between land and an energy-materials bundle. This resource-intensive bundle enters at the top nest with the value-added bundle. Because the land input is critically unique in agriculture, the nest structure for agriculture provides flexibility in representing substitution between land and other inputs.

The production structure for electricity is the most detailed among the sectors (Figure 3c). The top level nests allow treatment of different generation technologies. These include generation technologies that exist in the base year data (conventional fossil, nuclear, and hydro) and advanced technologies that did not exist in the base year data. The structures of the advanced technologies are discussed in Section 5. Here we show that most of these advanced technologies enter as perfect substitutes for existing technologies, signified by $\sigma = \infty$ at this nest level. The exception is the Wind & Solar technology that enters at the very top of the nest, and substitutes for other electric technologies as controlled by σ_{EWS}. Treatment of these as imperfect substitutes represents the unique aspects of these renewable technologies. While they can be well-suited to some remote locations, they also suffer from intermittency that can add to their cost if they were to provide a large share of electricity production. The σ_{EWS} parameter allows gradual penetration only as the prices of other generation technologies continue to rise, and tends to limit the share of electricity that can be generated by Wind & Solar. Other approaches to characterizing these resources that explicitly treats intermittency through construction of back-up capacity or storage were investigated by Cheng (2005). This is an area of continuing investigation as we seek better ways to represent the complex aspect of utilizing these intermittent sources in an electricity grid.

The lower nests in Figure 3c represent the structure within particular generation technologies. Note, however, that conventional fossil does not separately represent coal, oil, and gas generation technologies, but instead treats these via direct substitution among the fuels. This has the advantage of limiting substitution among fuels, thus representing their unique value for peaking, intermediate, or base load. For example, even if gas generation becomes much more expensive than coal or nuclear, this structure will preserve its use, as realistically would be the case because building capacity of nuclear and coal for peak demand would mean large amounts of capital would be idle much of the time. Note also that we have a more elaborate fuel nest structure for electricity than in other sectors to allow greater flexibility to set substitution elasticities for individual fuel pairs.

Nuclear and hydro have much simpler structures, focusing on the relevant resource and capital and labor. For both of these the resource is a fixed factor endowment specific to the technology and region. Changes in the resource over time are controlled exogenously. More discussion of the basis for these exogenous assumptions are found in Section 4.4.

Primary energy sectors (coal, oil, and gas) have a structure similar to that of most other sectors of the economy with two exceptions (Figure 3d). An important difference is that these include at the top nest a fuel specific resource, with σ_{GR} controlling the short run supply (*i.e.*, the rate of production from the resource). The sectors also do not explicitly use fuels or electricity, a simplification driven by limits of the data.

The refined oil sector is unique in that it uses OIL as a “feedstock” to produce refined oil products. OIL thus enters not as part of the energy nest but as a Leontief intermediate input (Figure 3e). A major improvement in EPPA4 is that energy use in ROIL production is now explicitly represented whereas in EPPA3 the ROIL sector was modeled similarly to the primary energy sectors. This reflects improvements in the GTAP energy accounting and allows proper treatment of sector emissions policies directed toward the refinery sector.

3.3 International Trade

In general, we maintain the same trade structure as previous EPPA versions. Crude oil is imported and exported as a homogeneous product, subject to tariffs, export taxes, and international transport margins. Given the transportation costs and different products/grades involved we treat coal, gas, and refined oil as Armington goods. The Armington good assumption is perhaps least justified in the case of gas. Historically, markets for gas were national/regional because of limits to transportation via pipeline, and thus prices in different markets could diverge. Increasingly, transport of liquefied natural gas (LNG) via ship provides the flexibility to direct gas to regional markets on the basis of highest return. We have thus developed three versions of EPPA: (1) gas as an Armington good, (2) gas as a globally homogenous good, and (3) gas as an homogenous good within composite regions of EPPA4 but as an Armington good among these composite regions. Results reported in Section 8 are based on the full Armington model.

All goods in the model are traded in world markets. Electricity trade is represented but very little trade occurs in the base data, and it only occurs among regionally contiguous regions. The share-preserving nature of the CES function tends to limit expansion of electricity trade, and, realistically given difficulty of transmission, prevents trade from ever occurring among two regions if it is not in the base data. For example, trade in electricity between Japan, Europe, and the US is not possible. More trade occurs among, for example, individual EU member states, and for the EPPA-EU, a disaggregated version of EPPA, this trade can be important. In such cases, the Armington specification may overly limit the expansion of trade. The Armington goods specification allows an explicit representation of bilateral trade flows, calibrated to the base year, 1997, such that regions are both exporters and importers of a particular good. Bilateral trade flows involve export taxes, import tariffs, and international transport margins, all of which are explicitly represented in the model.

3.4 Consumption

The EPPA model uses a nested CES structure to describe preferences as well as production, as this specification is compatible with the MPSGE solver. The representation of consumption in EPPA4 is considerably elaborated compared with EPPA3. **Figure 4** illustrates the new household sector. Savings enters directly into the utility function as previously, which generates the demand for savings and makes the consumption-investment decision endogenous. For welfare accounting, however, we report changes in aggregate consumption (excluding savings) rather than utility value inclusive of savings. This avoids double counting over time of changes in savings, once in the current period and then in later periods through its effects on investment and hence production and consumption. Instead, we report as our measure of welfare change the change in consumption in each period, and thus observe directly the impact of changes in savings on future consumption in those future periods. As structured in the standard version of EPPA this

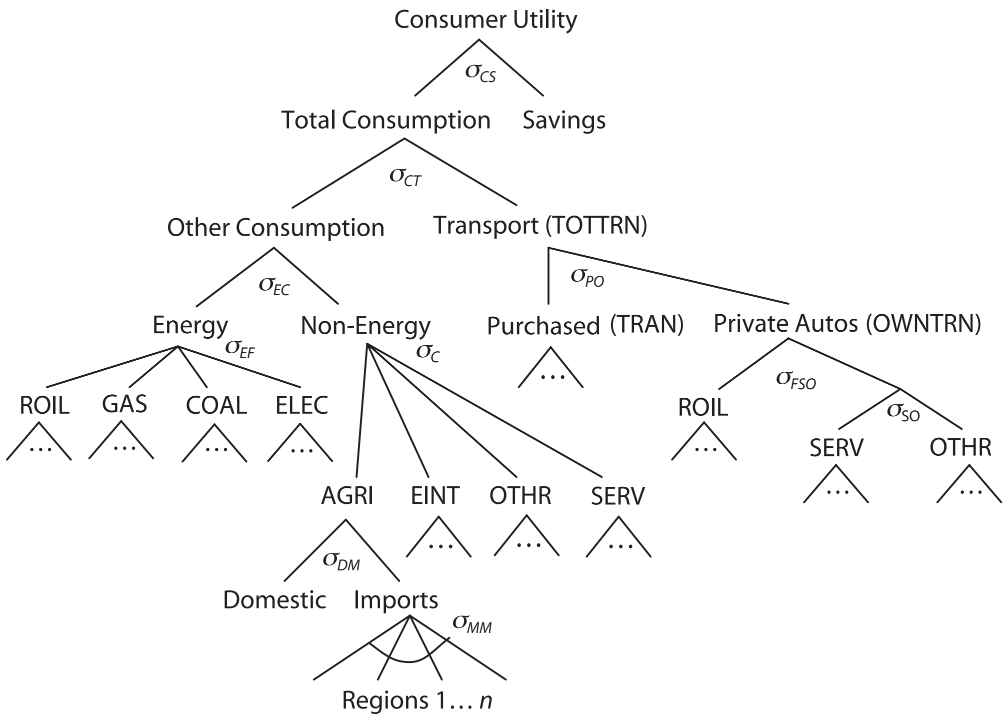

Figure 4. Structure of the Household Sector. Terminal nests with … indicate the aggregation structure for imported goods, shown in detail for the AGRI sector.

measure of consumption is also an equivalent variation measure of welfare in each period. In special versions of EPPA (*e.g.*, EPPA-HE), we have included leisure entering into the consumption bundle. In these special versions, our measure of welfare includes market consumption plus the value of leisure.

Whereas in EPPA3, all goods entered in a single nest with substitution controlled by a single elasticity parameter, in EPPA4 the elaborated nesting structure includes an energy nest and a nest that captures household transportation. The energy nest excludes purchases of transport fuels by households, which are now treated explicitly in the transport nest. Households consume both own-supplied (*i.e*., private cars) and purchased transport. Purchased transport comes from the industry transportation (air travel, water travel, rail service, trucks, *etc.*) sector described above. Own-supplied transportation services are provided using inputs from the other industries products (purchases of vehicles), services (maintenance, insurance, parking, *etc*.) and refined oil (fuel) sectors. For more detail and discussion see Paltsev *et al.* (2004a; 2005).

The reference values for elasticities in the household sector are provided in **Table 4**. The elasticity between non-energy inputs to consumption over time periods is a function of per capita income growth between periods and thus varies by region and time period. Consumption shares in each period are also updated as a function of per capita income growth between periods. (Details on this approach as used in EPPA3 are reported in Lahiri *et al*., 2000.) Data for the past hundred years show that the shares of output of the different sectors have changed significantly in all countries. For example, over the period 1900-1990 the share of agricultural output in

Table 4. Reference Values for Final Demand Elasticities.

	Final Demand Elasticities for Energy		
σ_{EC}	Energy-Other Consumption	0.25	
σ_{EF}	Among Fuels and Electricity	0.4	
σ_{FSO}	ROIL-Services/Other	0.3	Increases over time
	Other Final Demand Elasticities		
σ_{CS}	Consumption-Savings	0.0	
σ_{C}	Among Non-Energy goods	0.25 - 0.65	Base year values that among countries, and increase with per capita income
σ_{CT}	Transportation – Other Consumption	1.0	
σ_{PO}	Purchased-Own Transportation	0.2	
σ_{SO}	Services-Other	0.5	In the OWNTRN bundle

national income declined from about 17% to around 2% in the United States and from 34% to 3% in Japan. This type of structural change is not easily captured in the EPPA framework. For example, the CES consumption function used in EPPA is homogenous of degree one, which implies that if total consumption doubles, the share of each good in total consumption remains unchanged, other things equal. Such response is not consistent with long-term trends such as that noted above or with cross-country evidence. In fact, most conventional demand estimates use consumer demand functions that are non-homogeneous, that is, where the income elasticities of some goods (luxuries like private automobiles) are greater than one and other goods (basic necessities like food) are less than one. Adjustments to consumption shares and elasticities in EPPA as described in Lahiri *et al.* (2000) were designed to mirror demand relationships originally proposed by Frisch (1959) where the substitution elasticity also depends on income. More recently, the AIDADS (An Implicit Direct Additive Demand System) has been developed that includes the property of not only having an income elasticity different from 1, but that itself changes with per capita income (Rimmer and Powell, 1996).

Homogeneity (constant returns to scale) in EPPA is convenient because it simplifies solution of the model in the MPSGE algorithm. To overcome the limits of CRTS consumption we adopt an approach that makes the elasticity and share parameters a function of income between periods, but not within a period. This maintains homogeneity within a period and is consistent with the MPSGE but captures the evolution of consumption with income over time. The relationships were estimated using weighted least squares regression on cross-section data for the components of consumption from the GTAP database. We are continuing to investigate and develop approaches to incorporate an improved representation of consumption to capture these effects. As shown in Lahiri *et al*. (2000) this change had a surprisingly small effect on energy use in EPPA3. However, in EPPA3 most household consumption was of OTHR, particularly in developed countries (output of EINT and AGRI mostly is used as intermediate inputs not in final consumption). Greater disaggregation of the output into multiple sectors means that there is more scope for impacts of changing consumption shares. Preliminary investigation of comparing results with AIDADS results of Yu *et al.* (2000), particularly with regard to disaggregating the agriculture sector, are reported in Wang (2005).

3.5 Policy Constraints

EPPA4 incorporates a variety of options for specifying emissions control policies. Taxes and subsidies for fuels or other inputs can be represented, and the tax rates can be set to represent the carbon content of different fuels (*e.g.,* Kasahara *et al.*, 2005). Explicit constraints on emissions, for which the MPSGE solver computes the shadow price, are most easily solved, and major additions to EPPA4 involve increasing the flexibility to represent separate constraints by region, sector, and GHG. As in EPPA3, an economy-wide cap can be independently set for each region, and the model can be solved to find an autarkic price in each region or, allowing for international trade, a global price. In a trading case, exports and imports of permits are accounted along with other trade flows, and permit trade thus enters as part of the trade balance and is subject to capital account closure assumptions. Surpluses associated with inframarginal sales of permits enter into the exporting economy and are automatically calculated in the welfare measure.

New additions to EPPA4 include the ability to set separate constraints on each sector and each GHG and then solve for a sector/GHG-specific price. Emissions of non-CO_2 GHGs are modeled separately and reported in tons of CH_4, N_2O, SF_6, HFCs (using HFC-134a as a marker), and PFCs (using CF_4 as a marker).[5] Control prices resulting from a solution of the model with constraints on these gases are thus reported per ton of the relevant gas (rather than as a carbon-equivalent price). When trading among the gases is allowed a trading rate must be specified. The default is the 100-year GWP for the gases. With this option the carbon-equivalent price is the reported price for the carbon constraint. Sector-specific constraints can also be specified, and these constraints can be met with or without emissions trading among a sub-group of sectors. This feature has proved useful in simulating the impacts of the European Trading Scheme (ETS) as was done by See (2005) or other hypothetical sector policies such as by Paltsev *et al.* (2004b).

These new capabilities allow simulation of a wide variety of policies representing sector-, gas-, region-specific policies, global emissions trading, or hybrid policies where some sectors, regions, and gases enter into an emissions trading system that operates across a country or among countries while others have no constraint on emissions or have a constraint but cannot take advantage of emissions trading. This capability has proved useful in examining the benefits of emissions trading when there are pre-existing distortions such as energy taxes that vary across regions or sectors (see, for example, Babiker *et al.*, 2003a, 2004; Paltsev *et al.*, 2005).

An additional feature of EPPA4 is the ability to endogenously represent a carbon or greenhouse gas constraint with a limit on the carbon price, a so-called "safety valve" policy (see Jacoby and Ellerman, 2004, for a discussion of this policy instrument). Technically the safety valve is implemented via endogenous scaling of the constraint on emissions such that the emissions limits remain constant if the carbon price is less than the user-specified safety valve

[5] There are multiple species of HFCs and PFCs. We include emissions of all of them in the base year, but use GWP weights for the subspecies to convert them to an equivalent of HFC-134a or CF_4.

price but relaxed sufficiently to keep the carbon price constant when it reaches the level of the safety valve price. This feature allows representation of the safety valve instrument, which has been widely discussed, and automatically calculates the additional permits required to be sold/allocated to prevent the price from exceeding the safety valve level.

4. THE DYNAMIC PROCESS

There are six particularly critical features of EPPA that govern the evolution of the economy and its energy-using characteristics over time. These are: (1) the rate of capital accumulation, (2) population and labor force growth, (3) changes in the productivity of labor and energy, (4) structural change in consumption, (5) fossil fuel resource depletion, and (6) the availability of initially unused "backstop" energy-supply technologies. We discuss each of these features below.

4.1 The Capital Stock and Its Evolution

The evolution of capital stock over time is unchanged in EPPA4 from that of EPPA3. The GTAP dataset includes an explicit set of accounts that detail the demand for investment by sector in each region for the 1997 base year. Using these data we specify an investment sector that produces an aggregate investment good equal to the level of savings determined by the representative agent's utility function. The accumulation of capital is calculated as investment net of depreciation according to the standard perpetual inventory assumption.

As a practical matter, capital stock accounting is often problematic because of empirical measurement issues. The base year regional data on capital stocks and output provided in the GTAP5 release give rise to capital-output ratios that diverge significantly from the range of 2 to 4 that is generally observed. It was therefore necessary to calibrate the initial capital stocks. In doing so we accepted as being more accurate the initial regional investment flows, and these were used to determine scale factors that yielded more plausible initial capital-output ratios and rates of return for the EPPA regions[6]. Given these initial capital stock estimates we were able to specify the dynamic process of capital evolution, which is described more formally below.

An important feature carried over from previous versions of EPPA is distinction between malleable and non-malleable capital. The malleable portion of the capital stock in each sector is described by the nested CES production functions shown in Figures 3a-e (*i.e.*, with non-zero substitution elasticities). The non-malleable portion of the capital stock is Leontief (*i.e.*, all elasticities of substitution are 0). Input share parameters for the Leontief production functions for each vintage of capital are the actual input shares for the period when the capital was put in place. These reflect the substitution possibilities as described by the CES production functions and the relative prices in that period. This formulation means that EPPA exhibits a short-run and a long-run response to changes in relative input prices. The substitution response in a single

[6] The rate of return is defined as the sum of the rates of interest and depreciation, equal to the ratio of the flow capital services K_0^S to the underlying capital stock K_0:$r + \delta = K_0^S/K_0$. Adjusting K_0 to be consistent with observed rates of return gives the required scale factor for the capital stock estimates in GTAP.

period to a change in prices in that period is a combination of the long-run substitution possibilities (weighted by output produced by malleable capital) and no substitution (weighted by the output produced with vintaged capital). Even if all other things remained unchanged, one would observe further substitution in subsequent periods as the non-malleable capital depreciated and was replaced by new vintages of capital that reflected the changed relative prices. In general, the larger the share of sectoral output originating in the non-malleable portion of the production structure, the less the substitution possibilities in that period.

The dynamic updating of the capital stock in each region and sector is determined by the capital vintaging procedure. In each period a fraction of the malleable capital is frozen to become part of the non-malleable portion. Letting K^m represent the malleable portion of capital and K^r the rigid portion, the procedure can be described as follows. New capital installed at the beginning of each period starts out in a malleable form. At the end of the period a fraction φ of this capital becomes non-malleable and frozen into the prevailing techniques of production. The fraction $(1 - \varphi)$ can be thought of as that proportion of previously-installed malleable capital that is able to have its input proportions adjust to new input prices, and take advantage of intervening improvements in energy efficiency driven by the AEEI. It can also be reallocated to other sectors of the economy, although in a growing economy and absent strong shocks that would cause rapid collapse of an industry this is rarely an issue because the capital stock in each sector is always growing, or at least not falling more rapidly than deprecation.

As the model steps forward in time it preserves v vintages of rigid capital, each retaining the coefficients of factor demand fixed at the levels that prevailed when it was installed. EPPA specifies $v = 1, \ldots, 4$, implemented in all industrial sectors and in the electricity sector including advanced technologies. Each of the sector specific vintages is tracked through time as a separate capital stock. The evolution of capital over time is implemented in a set of dynamic equations, as follows. Malleable capital in period $t + 1$ is made up of investment, plus the stock of capital remaining after depreciation that also remains malleable:

$$K_{t+1}^{m} = I_t + (1-\varphi)(1-\delta)K_t^m \,. \tag{14}$$

Malleable capital is indistinguishable from new investment, in that there is flexibility defined by the nested CES production function to adjust the proportions of capital, labor, energy and other inputs given prevailing relative prices.

In period $t + 1$, the first vintage of non-malleable capital is the portion φ of the malleable stock at time t in sector i that survives depreciation, but remains in the sector in which it was installed with its factor proportions frozen in place:

$$K_{i,t+1,v}^{r} = \varphi(1-\delta)K_{i,t}^{m} \quad \text{for } v = 1. \tag{15}$$

Production in $t + 1$ that uses a vintage of non-malleable capital is subject to a fixed-coefficient transformation process in which the quantity shares of capital, labor and energy by fuel type are set to be identical to those in period t. The coefficients of this production function remain unchanged over the lifetime of the capital stock of each vintage. None of the stocks of rigid capital is subject to improvements in energy efficiency via the AEEI.

In each sector, the quantity of capital in each of the remaining vintages (2 through 4) is simply the amount of each vintage that remains after depreciation:

$$K^{r}_{i,t+1,v+1} = (1-\delta)K^{r}_{i,t,v} \quad \text{for } v = 2, 3, 4. \tag{16}$$

We assume that rigid capital cannot be reallocated among different sectors, so that in each sector vintage v in period t becomes vintage v +1 in period t +1. Because there are only four vintages and the model's time step is five years, the vintaged capital has a maximum life of 25 years, the first five years of which its input coefficients are identical to malleable capital, and the following 20 years as non-malleable, vintaged capital.

4.2 Population, Productivity and Labor Supply

A number of key variables within the EPPA model are determined by algebraic relationships among outputs of the model in per capita terms. This requires that the model keep track of the population in each region over the simulation horizon. Regional population in EPPA4 is specified as an exogenous long-run trend based on United Nations data (UN, 2000, 2001).

In a change from EPPA3, EPPA4 separately tracks changes in labor force size and changes in productivity growth per worker. Labor productivity is modeled as factor-augmenting, thus it makes no difference in terms of the effect on labor supply whether augmentation is due to more workers or more productivity per worker, but distinguishing augmentation due to labor force growth and productivity provides the ability to identify the separate effects of population growth (on labor force) and pure productivity growth. Labor force growth is thus computed based on the population projection and this is combined with labor productivity growth to compute the labor augmentation factor. Specifically, for region r and time t the supply of labor is scaled from its base-year value $L_{r,0}$ by an augmentation parameter whose rate of growth, $g_{r,t}$, represents the combined effect of increased labor input in natural units and chained rates of increase of labor productivity:

$$L_{r,t+1} = L_{r,0}(1+g_{r,t})^{t}\,. \tag{17}$$

The augmentation rate, $g_{r,t}$, is now composed of the $g^{L}_{r,t}$, the growth of labor force, and $g^{P}_{r,t}$, the growth of productivity. The productivity component is specified as in EPPA3, requiring an exogenous initial rate at t = 0 and a terminal rate at t = T, with rates for intervening periods determined by a logistic function:

$$g^{P}_{r,t} = (g^{P}_{r,0} - g^{P}_{r,T})\frac{1+\alpha}{1+\alpha^{\beta t}} + g_{t,T}\,. \tag{18}$$

The values of the logistic parameters α and β are set at 0.1 and 0.07, respectively. This representation means productivity augmentation adjusts from the initial rate to the final rate in an S-shaped fashion. This growth for the first two periods (1997-2000, and 2000-2005) is over-ridden by specifying an augmentation factor so that simulated GDP growth matches the historical rate over these periods based on IMF data.

4.3 AEEI

One of the stylized facts of economic development is that countries tend to use first more, then less energy per unit of GDP as their economies expand from very low to high levels of activity (Schmalensee *et al.*, 1998). In simulations used to analyze energy or climate policy it is customary to model these dynamics by means of exogenous time-trends in the input coefficients for energy or fossil fuels. We employ such trends in the EPPA model to control the evolution of demand reduction factors that scale production sectors' use of energy per unit of output. The rate of growth of these factors is called the autonomous energy efficiency improvement (AEEI), which is a reduced-form parameterization of the evolution of non-price induced, technologically-driven changes in energy demand. EPPA4 differentiates the rate of AEEI among regions, between non-energy and energy sectors of the economy.

The evolution of the AEEI for the non-energy sectors of the economy by region is shown in **Figure 5**. Rates of increase are the same across developed regions and for China, whose gradual emergence from non-market systems of production has seen rising efficiency of resource allocation and a very rapid fall in the use of energy per unit output. This pattern is different for other developing countries that have shown little reduction in energy intensity or even increases. To follow the historic pattern for developing economies we assume a gradual decrease in AEEI through the next few decades and energy efficiency improvement later in the century. The actual

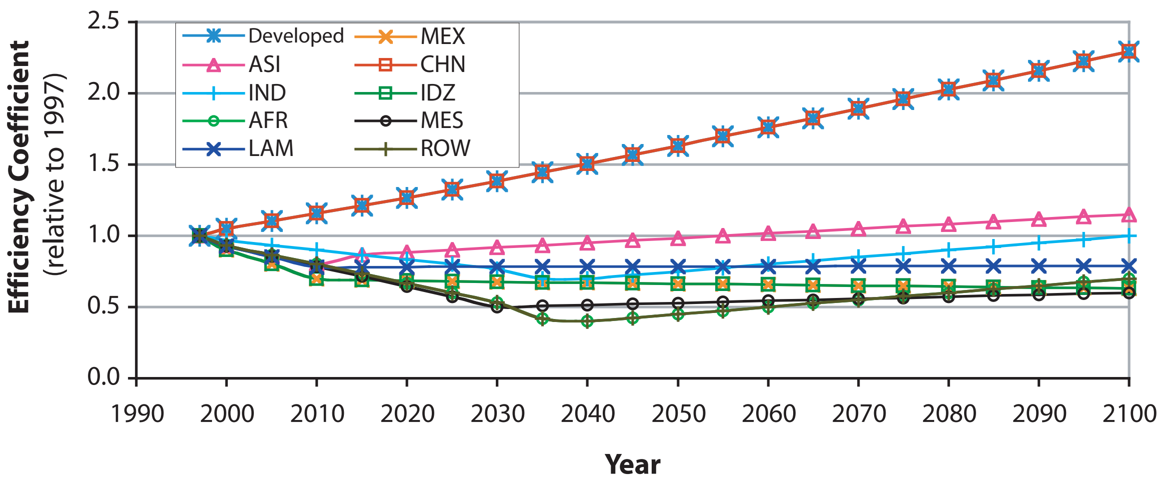

Figure 5. Trends in the Efficiency Coefficient on Energy Input to Non-Primary Energy Sectors (relative to 1997).

path of energy use per unit output that results from the model simulation depends on energy prices and other structural changes. The resulting energy intensity of GDP for a reference case is discussed in Section 8.1. As discussed in Section 3.2, energy is not an explicit input in the COAL, OIL, and GAS sectors. We assume no AEEI trend in ROIL. In the ELEC sector we assume a rate of AEEI improvement that leads to an efficiency of conversion of fuels to electricity that approaches 0.5 in the reference. The global trend in electric utility efficiency (including substitution effects do to rising energy prices) is shown in Section 8.

4.4 Natural Resource Inputs

All fossil energy resources are modeled in EPPA4 as graded resources whose cost of production rises continuously as they are depleted. The basic production structure for fossil energy production sectors given in Figure 3d, plus the depletion model and representations of backstop technologies, completely describe fossil fuel production. The resource grade structure is reflected by the elasticity of substitution between the resource and the capital-labor-materials bundle in the production function. The elasticity was estimated based on the distribution of discrete resource grades for the median estimate of resources reported in Edmonds *et al.* (1986), by fitting a long-run constant-elasticity supply curve through the midpoints of each of the discrete grade categories in that study.

In the fossil fuel production sectors, elasticities of substitution were then chosen that would generate elasticities of supply that matched the fitted value in the respective supply curves, according to the method developed in Rutherford (1998). Production in any one period is limited by substitution and the value share of the resource, *i.e.*, the technical coefficient on the fixed factor in the energy sector production functions. The resource value shares were determined to represent key differences among regions and fuels. For example, the cost of capital, labor and materials in Middle East crude oil production is quite low relative to the market price, implying a relatively high value share for the oil resource. By contrast, regions with less accessible resources have higher production costs for the same world oil price and similar technology—implying that the value share of resources is lower. For coal, the bulk of the cost of production in most regions is made up of labor, capital and materials, indicating that the cost share of resources in this industry is relatively small.

Over time, energy resources R in sector e are subject to depletion based on physical production of fuel F in the previous period. Because EPPA solves on a five-year time-step we approximate depletion in intervening years by multiplying the output of each fuel sector by a factor of five. Thus, in period t:

$$R_{e,t} = R_{e,\,t\text{-}1} - 5\,F_{e,\,t\text{-}1}\ . \tag{20}$$

This specification captures the major long-run dynamics of resource prices. EPPA4 also has an option allowing the model user to exogenously specify fuel prices. In policy cases the resource quantity in value terms is constrained to follow the same path as in the reference scenario, while leaving the price of *R* endogenous. This convention implies that across states of the world (in the present context the reference scenario and cases where different policies are imposed) differences in demand give rise to different resource price paths, but these are all consistent with the fundamental value of the resource that obtained in the reference.

In EPPA4, the improving technological capability to produce resources is reflected in estimates of the total energy content of resources available in 1997 (**Table 5**). These resource estimates in **Tables 6** through **8**, include estimates of additional recoveries beyond those currently considered economically and technologically feasible. Included, for example, are estimates of in-place resources that would not be recovered with current technology: heavy oils, gas in tight gas formations, and deep-water offshore resources. For oil, we include tar sand resources as part of the resource base. For coal, we similarly include both currently recoverable and speculative resources.

Also included in EPPA are the shale oil resources given in **Table 9**. Production of fuel from this resource is at present limited to demonstration projects (*e.g.*, Youngquist, 1998). While oil shale resources are distributed widely across the world (Edmonds *et al.*, 1986; Rogner, 1997) the resource quality varies in grade. We thus make shale oil available in the four regions (USA, ANZ, FSU, AFR) where the resources are most promising (see Table 9). While it is possible for poorer grades of this resource to be developed in other regions, the quantity of high grades of this resource in the four regions where we make the technology available is very large. Limiting the technology to these regions reflects our assumption that, at least through 2100, shale oil resource availability in these regions would allow them to dominate world production. We treat shale oil as a separate production technology, rather than include the resource along with conventional oil as in the case of tar sands, because of the carbon emissions difference for shale oil production. Details on the assumption underlying shale oil output are included in the following section on new technologies.

Table 9. Resource Estimates for Shale Oil.

Region	**Resource Supply** (EJ)
AFR	40000
ANZ	122000
FSU	200000
USA	275000

5. NEW TECHNOLOGIES

Several new advanced energy supply options have been specified in EPPA4. These technologies endogenously enter if and when they become economically competitive with existing technologies. Competitiveness of different technologies depends on the endogenously determined prices for all inputs, as those prices depend on depletion of resources, climate policy, and other forces driving economic growth such as the savings, investment, and the productivity

Table 5. World Total Fossil Resources (in exajoules).

	Total Oil (EJ)	Total Gas (EJ)	Total Coal (EJ)
USA	**1,128.5**	**1,112.0**	**24,962.9**
CAN	**3,357.3**	**178.1**	**656.8**
MEX	**547.4**	**156.9**	**60.3**
EUR	**773.8**	**1,093.6**	**9,696.9**
Denmark	16.2	20.4	5.1
France	3.6	30.8	8,928.6
Germany	7.1	47.8	4.6
Italy	9.5	62.3	67.2
Netherlands	10.1	185.9	89.3
Spain	0.9	26.3	0.1
UK	321.9	205.8	202.9
Rest of EU	0.0	0.4	398.9
EFTA (Norway)	404.5	513.8	0.1
EET	**57.7**	**75.7**	**2,380.7**
Poland	3.6	13.4	1572.4
Hungary	4.2	13.5	77.8
Rest of EET	49.9	48.8	730.4
RUS+UKR	**7,583.3**	**5,410.5**	**91,965.2**
Russia	7,534.9	5,299.1	75,534.8
Ukraine	48.4	111.4	16,430.4
JPN	**0.0**	**0.0**	**55.9**
ASI	**104.0**	**341.5**	**75.4**
IDZ	**196.5**	**440.6**	**240.7**
CHN	**558.0**	**228.1**	**13,595.0**
IND	**144.6**	**110.4**	**2,491.0**
AFR	**2,100.0**	**994.4**	**5,303.0**
South Africa	0.4	2.2	4,762.9
North Africa	888.6	523.8	5.9
Rest of Africa	1,211.0	468.3	534.2
Morocco	0.0	0.1	0.0
MES	**9,784.6**	**5,994.3**	**58.0**
LAM	**7,497.1**	**1,261.6**	**1,082.7**
Brazil	638.0	310.4	593.8
Venezuela	6,311.2	491.8	23.8
Colombia	132.9	61.3	330.9
Rest of LAM	415.0	398.1	134.2
ANZ	**92.5**	**430.1**	**5,974.1**
ROW	**1,300.7**	**1,128.5**	**20,360.3**
Baltic	0.0	0.0	0.0
Leftover FSU	725.7	799.8	18,671.8
RROW	77.6	241.9	1,171.2
Turkey	11.1	1.6	499.1
Greenland	486.2	85.2	18.3
TOTAL	**35,225.9**	**18,956.2**	**178,959.0**

Table 6. Oil Resources.

		Remaining Reserves (MMBO)	**Conventional Reserve growth** (MMBO)	**Undiscovered** (MMBO)	**Total reserves + undiscovered** (MMBO)	**Total reserves + undiscovered** (EJ)	**Tar sands** (EJ)	**Total including Tar sands** (EJ)	**Readjust coefficient**	**Readjust Total** (EJ)
USA		**32,000**	**76,000**	**83,000**	**191,000**	**1,128.5**		**1,128.5**	**1.00**	**1,128.5**
CAN		**4,871**	**3,470**	**2,774**	**11,115**	**65.7**	**1700**	**1,765.7**	**1.90**	**3,357.3**
MEX		**22,273**	**15,869**	**20,569**	**58,711**	**346.9**		**346.9**	**1.58**	**547.4**
EUR		**24,865**	**17,715**	**26,385**	**68,965**	**407.5**		**407.5**	**1.90**	**773.8**
	Denmark	790	563	95	1,448	8.6		8.6	1.90	16.2
	France	0	0	323	323	1.9		1.9	1.90	3.6
	Germany	281	200	156	637	3.8		3.8	1.90	7.1
	Italy	280	199	371	850	5.0		5.0	1.90	9.5
	Netherlands	339	242	319	900	5.3		5.3	1.90	10.1
	Spain	0	0	78	78	0.5		0.5	1.90	0.9
	UK	9,648	6,874	12,162	28,684	169.5		169.5	1.90	321.9
	ROEU	0	0	0	0	0.0		0.0	1.90	0.0
	EFTA (Norway)	13,527	9,637	12,881	36,045	213.0		213.0	1.90	404.5
EET		**2,153**	**1,534**	**1,453**	**5,140**	**30.4**		**30.4**	**1.90**	**57.7**
	Poland	66	47	206	319	1.9		1.9	1.90	3.6
	Hungary	133	95	146	374	2.2		2.2	1.90	4.2
	Rest of EET	1,954	1,392	1,101	4,447	26.3		26.3	1.90	49.9
RUS + UKR		**131,242**	**93,504**	**78,722**	**303,468**	**1,793.0**	**2200**	**3,993.0**	**1.90**	**7,583.3**
	Russia	129,507	92,268	77,382	299,157	1,767.5	2200	3,967.5	1.90	7,534.9
	Ukraine	1,735	1,236	1,340	4,311	25.5		25.5	1.90	48.4
JPN		**0**	**0**	**0**	**0**	**0.0**		**0.0**	**n/a**	**0.0**
ASI		**4,003**	**2,852**	**3,228**	**10,083**	**59.6**		**59.6**	**1.75**	**104.0**
IDZ		**7,968**	**5,677**	**7,435**	**21,080**	**124.5**		**124.5**	**1.58**	**196.5**
CHN		**24,519**	**17,469**	**12,115**	**54,103**	**319.7**		**319.7**	**1.75**	**558.0**
IND		**6,693**	**4,768**	**2,556**	**14,017**	**82.8**		**82.8**	**1.75**	**144.6**
AFR		**63,929**	**45,547**	**94,148**	**203,624**	**1,203.1**		**1,203.1**	**1.75**	**2,100.0**
	South Africa	0	0	35	35	0.2		0.2	1.75	0.4
	North Africa	37,876	26,985	21,302	86,163	509.1		509.1	1.75	888.6
	Rest of Africa	26,053	18,562	72,807	117,422	693.8		693.8	1.75	1,211.0
	Morocco	0	0	4	4	0.0		0.0	1.75	0.0
MES		**490,525**	**349,478**	**209,426**	**1,049,429**	**6,200.4**		**6,200.4**	**1.58**	**9,784.6**
LAM		**50,275**	**35,819**	**99,262**	**185,356**	**1,095.1**	**3200**	**4,295.1**	**1.75**	**7,497.1**
	Brazil	8,826	6,288	46,746	61,860	365.5		365.5	1.75	638.0
	Venezuela	29,605	21,092	19,664	70,361	415.7	3200	3,615.7	1.75	6,311.2
	Colombia	4,538	3,233	5,120	12,891	76.2		76.2	1.75	132.9
	Rest of LAM	7,306	5,205	27,732	40,243	237.8		237.8	1.75	415.0
ANZ		**1,869**	**1,332**	**5,032**	**8,233**	**48.6**		**48.6**	**1.90**	**92.5**
ROW		**23,705**	**16,889**	**85,527**	**126,121**	**745.2**		**745.2**	**1.75**	**1,300.7**
	Baltic	0	0	0	0	0.0		0.0	1.75	0.0
	Leftover FSU	21,018	14,974	34,376	70,368	415.8		415.8	1.75	725.7
	RROW	2,494	1,777	3,254	7,525	44.5		44.5	1.75	77.6
	Turkey	193	138	749	1,080	6.4		6.4	1.75	11.1
	Greenland	0	0	47,148	47,148	278.6		278.6	1.75	486.2
TOTAL		**890,890**	**687,922**	**731,632**	**2,310,444**	**13,650.8**	**7,100**	**20,750.8**	**n/a**	**35,225.9**

Table 7. Gas Resources.

		Remaining Reserves (BCFG)	**Conventional Reserve growth** (BCFG)	**Undiscovered** (BCFG)	**Total reserves + undiscovered** (BCFG)	**Total reserves + undiscovered** (EJ)	**Readjust coefficient**	**Readjust Total** (EJ)
USA		**172,000**	**355,000**	**527,000**	**1,054,000**	**1,112.03**	**1.00**	**1,112.03**
CAN		**51,302**	**36,692**	**24,519**	**112,513**	**118.71**	**1.50**	**178.06**
MEX		**33,213**	**23,754**	**49,272**	**106,239**	**112.09**	**1.40**	**156.92**
EUR		**250,470**	**179,139**	**311,316**	**740,925**	**781.72**	**1.40**	**1,093.55**
	Denmark	7,616	5,447	777	13,840	14.60	1.40	20.43
	France	0	0	20,861	20,861	22.01	1.40	30.79
	Germany	11,320	8,096	12,993	32,409	34.19	1.40	47.83
	Italy	8,720	6,237	27,272	42,229	44.55	1.40	62.33
	Netherlands	68,455	48,960	8,554	125,969	132.90	1.40	185.92
	Spain	0	0	17,795	17,795	18.77	1.40	26.26
	UK	57,985	41,472	39,958	139,415	147.09	1.40	205.77
	ROEU	115	82	70	267	0.28	1.40	0.39
	EFTA (Norway)	96,259	68,846	183,036	348,141	367.31	1.40	513.83
EET		**21,125**	**15,109**	**11,574**	**47,808**	**50.44**	**1.50**	**75.66**
	Poland	3,286	2,350	2,822	8,458	8.92	1.50	13.39
	Hungary	3,510	2,510	2,508	8,528	9.00	1.50	13.50
	Rest of EET	14,329	10,248	6,244	30,821	32.52	1.50	48.78
RUS+UKR		**1,438,135**	**1,028,573**	**1,196,271**	**3,662,979**	**3,864.65**	**1.40**	**5,410.51**
	Russia	1,410,212	1,008,602	1,168,735	3,587,549	3,785.07	1.40	5,299.09
	Ukraine	27,923	19,971	27,536	75,430	79.58	1.40	111.42
JPN		**0**	**0**	**0**	**0**	**0.00**	**n/a**	**0.00**
ASI		**92,621**	**66,244**	**56,939**	**215,804**	**227.69**	**1.50**	**341.53**
IDZ		**111,098**	**79,459**	**107,710**	**298,267**	**314.69**	**1.40**	**440.56**
CHN		**34,001**	**24,318**	**85,786**	**144,105**	**152.04**	**1.50**	**228.06**
IND		**23,035**	**16,475**	**30,279**	**69,789**	**73.63**	**1.50**	**110.45**
AFR		**339,921**	**243,116**	**359,481**	**942,518**	**994.41**	**1.00**	**994.41**
	South Africa	15	11	2,085	2,111	2.23	1.00	2.23
	North Africa	232,489	166,279	97,667	496,435	523.77	1.00	523.77
	Rest of Africa	107,417	76,826	259,623	443,866	468.30	1.00	468.30
	Morocco	0	0	106	106	0.11	1.00	0.11
MES		**1,615,780**	**1,155,627**	**1,286,790**	**4,058,197**	**4,281.63**	**1.40**	**5,994.28**
LAM		**223,610**	**159,929**	**470,576**	**854,115**	**901.14**	**1.40**	**1,261.59**
	Brazil	9,173	6,561	194,408	210,142	221.71	1.40	310.40
	Venezuela	135,079	96,610	101,240	332,929	351.26	1.40	491.76
	Colombia	18,323	13,105	10,101	41,529	43.82	1.40	61.34
	Rest of LAM	61,035	43,653	164,827	269,515	284.35	1.40	398.09
ANZ		**92,013**	**65,809**	**113,954**	**271,776**	**286.74**	**1.50**	**430.11**
ROW		**294,195**	**210,412**	**565,021**	**1,069,628**	**1,128.52**	**1.00**	**1,128.52**
	Baltic	0	0	0	0	0.00	1.00	0.00
	Leftover FSU	230,685	164,989	362,434	758,108	799.85	1.00	799.85
	RROW	63,062	45,103	121,129	229,294	241.92	1.00	241.92
	Turkey	448	320	749	1,517	1.60	1.00	1.60
	Greenland	0	0	80,709	80,709	85.15	1.00	85.15
TOTAL		**4,792,519**	**3,659,656**	**5,196,488**	**13,648,663**	**14,400.10**	**n/a**	**18,956.23**

Table 8. Coal Resources.

	Reserve Coal (MT)	**Reserve coal** (EJ)	**Aggregate UNDP region**	**Share in aggregated region** (%)	**Coal resources** (EJ) **of aggregated region**	**Coal resource** (EJ)
USA	**249,994**	**6,462.06**	**1**	**97**	**25,638**	**24,962.89**
CAN	**6,578**	**170.03**	**1**	**3**	**25,638**	**656.84**
MEX	**1,211**	**31.30**	**2**	**5**	**1,143**	**60.28**
EUR	**71,680**	**1,852.85**	**3**	**95**	**10,196**	**9,696.95**
France	38	0.98	3	0	10,196	5.14
Germany	66,000	1,706.03	3	88	10,196	8,928.55
Italy	34	0.88	3	0	10,196	4.60
Netherlands	497	12.85	3	1	10,196	67.23
Spain	660	17.06	3	1	10,196	89.29
Sweden	1	0.03	3	0	10,196	0.14
United Kingdom	1,500	38.77	3	2	10,196	202.92
Rest of EU	2,949	76.23	3	4	10,196	398.94
AFTA	1	0.03	3	0	10,196	0.14
EET	**33,550**	**867.23**	**4**	**68**	**3,516**	**2,380.66**
Poland	22,160	572.81	4	45	3,516	1,572.44
Hungary	1,097	28.36	4	2	3,516	77.84
Rest of EET	10,293	266.06	4	21	3,516	730.38
RUS+UKR	**191,163**	**4,941.35**	**5**	**83**	**110,637**	**91,965.22**
Russian Fed.	157,010	4,058.53	5	68	110,637	75,534.80
Ukraine	34,153	882.82	5	15	110,637	16,430.42
JPN	**773**	**19.98**	**11**	**1**	**6,030**	**55.87**
ASI	**1,683**	**43.50**	**8**	**21**	**352**	**75.44**
IDZ	**5,370**	**138.81**	**8**	**68**	**352**	**240.70**
CHN	**114,500**	**2,959.70**	**10**	**100**	**13,595**	**13,595.00**
IND	**84,396**	**2,181.54**	**9**	**100**	**2,491**	**2,491.00**
AFR	**55,367**	**1,431.17**	**7**	**100**	**5,303**	**5,303.00**
South Africa	49,728	1,285.41	7	90	5,303	4,762.90
North Africa	62	1.60	7	0	5,303	5.94
Rest of Africa	5,577	144.16	7	10	5,303	534.16
Morocco		0.00	7	0	5,303	0.00
MES	**1,710**	**44.20**	**6**	**100**	**58**	**58.00**
LAM	**21,752**	**562.26**	**2**	**95**	**1,143**	**1,082.72**
Brazil	11,929	308.35	2	52	1,143	593.77
Venezuela	479	12.38	2	2	1,143	23.84
Colombia	6,648	171.84	2	29	1,143	330.91
Rest of LAM	2,696	69.69	2	12	1,143	134.20
ANZ	**82,662**	**2,136.72**	**11**	**99**	**6,030**	**5,974.13**
ROW	**62,064**	**1,604.28**	**n/a**			**20,360.28**
Baltic		0.00	5	0	110,637	0.00
Leftover FSU	38,812	1,003.25	5	17	110,637	18,671.78
RROW	19,380	500.95	8 and 4	10,19 (8) and 32,29 (4)	352	1,171.17
Turkey	3,689	95.36	3	5	10,196	499.05
Greenland	183	4.73	1	0	25,638	18.27
TOTAL	**984,453**	**25,447.00**	**N/a**	**n/a**	**n/a**	**178,958.98**

of labor. These advanced technology options are summarized in **Table 10**. Three technologies produce substitutes for conventional fossil fuels (gas from coal, a crude oil product from shale oil, and a refined fuel from biomass). The remaining five are electricity generation technologies (biomass, wind and solar, natural gas combined cycle with and without carbon capture and sequestration, and integrated coal gasification combined cycle with carbon capture and sequestration). The unique attributes of these technologies are captured through parameters of nested CES functions. The basic approach is similar to the specification of other sectors of the economy as described in Section 3.2. The production structure for each of these technologies is shown in **Figure 6**. Shale oil and bio-oil have a similar production structure, with the key difference being that resources for shale oil are the estimated oil content of shale reserves whereas the resource input for bio-oil is land (Figure 6a). Moreover, shale oil resources are depletable, although estimated to be very large as described in Section 4.4, whereas land is modeled as a non-depletable resource whose productivity is augmented exogenously. Agriculture (AGRI), as previously discussed, and bio-electricity (Figure 6b) also compete for land. Both shale oil and bio-oil use capital, labor, and intermediate inputs from OTHR. For oil from shale, the emissions of carbon during the extraction process are estimated to be 20% of the carbon per unit of oil produced.[7] The carbon content of the ROIL produced from shale is assumed to be the same as ROIL from conventional crude. Thus, carbon emissions from production are 20% of the carbon in the oil product. The oil product is assumed homogeneous with crude oil and carbon emitted from combustion is accounted at the point of consumption of ROIL produced from the crude oil.

Table 10. Summary of New Technologies in EPPA.

	Technology	Description
1	Coal Gasification	Converts coal into a perfect substitute for natural gas.
2	Shale Oil	Extracts and upgrades bitumen from shale into a perfect substitute for oil
3	Biomass Oil	Converts biomass into a perfect substitute for refined oil.
4	Biomass Electricity	Converts biomass into a perfect substitute for electricity.
5	Wind and Solar	Converts intermittent wind and solar energy into an imperfect substitute for electricity.
6	Advanced Gas	Based on natural gas combined cycle (NGCC) electricity generation technology that converts natural gas into electricity.
7	Advanced Gas with Carbon Capture and Sequestration	Natural gas combined cycle technology that captures 90% or more of the CO_2 produced in generating electricity.
8	Advanced Coal with Carbon Capture and Sequestration	Integrated coal gasification combined cycle (IGCC) that capture 90% or more of the CO_2 produced in generating electricity.

[7] This figure is based on a recent estimate that the process energy for extracting crude oil from shale is 16% of the energy content of the extracted resource (Müller-Wenk, 1998).

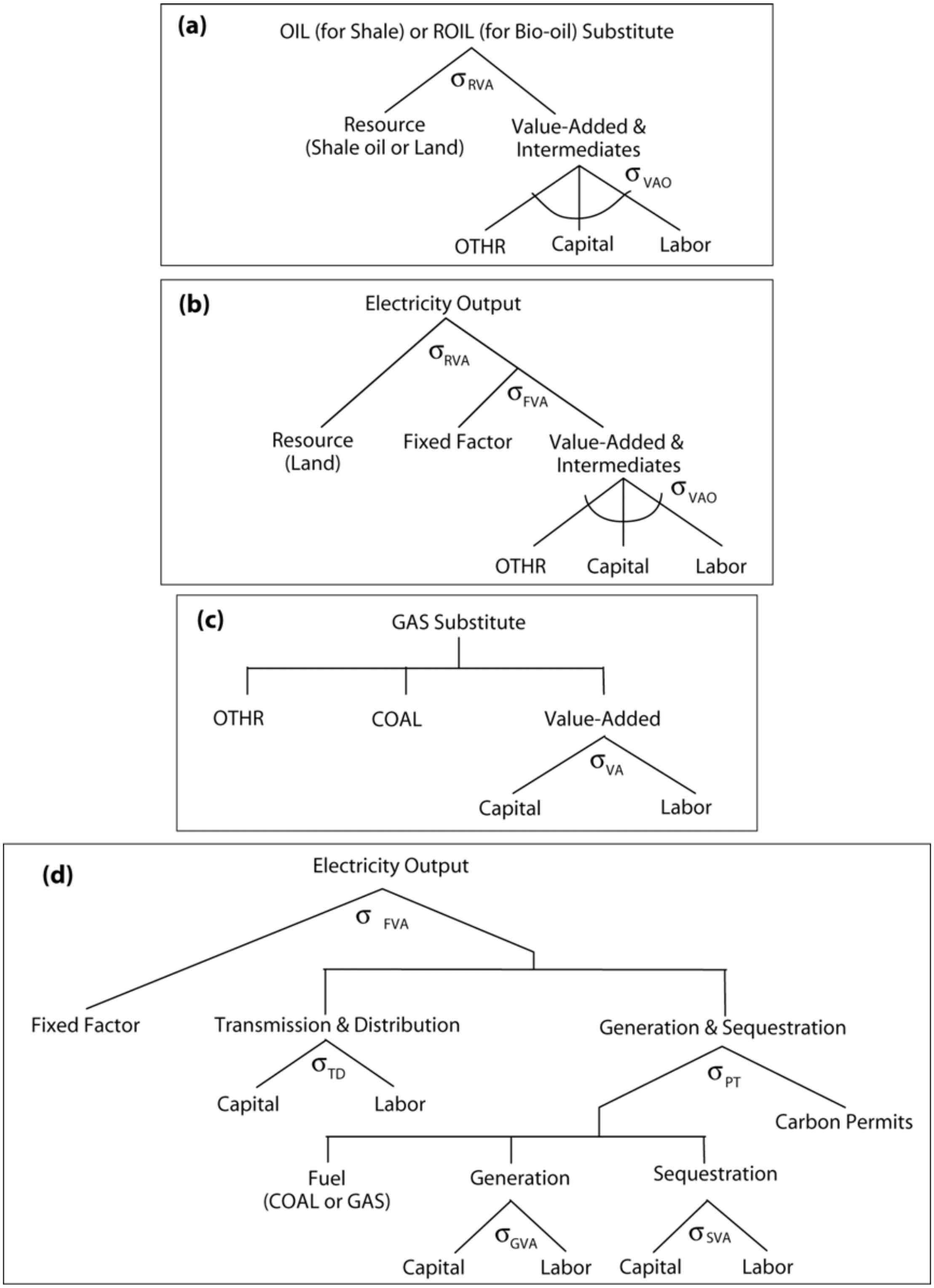

Figure 6. Structure of Production for Advanced Technologies: **(a)** Shale and Bio-oil, **(b)** Bio-electric and Wind & Solar, **(c)** Coal Gasification, and **(d)** Advanced Fossil Electricity. Vertical lines in the input nest signify a Leontief or fixed coefficient production structure where the elasticity of substitution is zero. Intermediate inputs are a combination of domestic and imports as in other sectors as shown in Figure 3.

Bio-electric and Wind & Solar have a very similar production structure, except that they include an additional fixed factor to slow initial penetration of the technologies as described in more detail below and in McFarland *et al.* (2004). Both use land and a combination of OTHR, capital, and labor. Note that for the biomass technologies, the production of the biomass and the conversion of the biomass to fuel or electricity is collapsed into this simple nest (*i.e.*, the capital and labor needed for both growing and converting the biomass to a final fuel are combined). These are parameterized to represent a conversion efficiency of 40% from biomass to the final energy product. This conversion efficiency also assumes that process energy needed for bio-fuel production is biomass. Our main interest in including bio-fuels is to represent a low carbon emissions option. Current biomass production (*e.g.*, ethanol from corn) often uses coal in the distillation process and fossil energy in the production of corn, thus releasing as much or more CO_2 as is offset when the ethanol is used to replace gasoline. There is little reason to represent such a technology option in a climate policy scenario where carbon is priced because its cost would escalate with the carbon price just as would the price of conventional ROIL, and thus it would never be competitive.

The coal gasification technology includes intermediates in the top nest as Leontief inputs (Figure 6c). The coal input enters at this level, and these are combined with the value added bundle. We assume that the energy conversion efficiency of coal to natural gas is 50% and that the resulting fuel has the same carbon coefficient as natural gas. The efficiency factor, when combined with the differences in carbon emissions per exajoule of gas and coal implies that 73% of the carbon in the coal is emitted in the gasification process and 27% remains in the synthesis gas.

The three advanced fossil electric generation technologies have a similar structure to one another, but one that is more elaborated than the other advanced technologies (Figure 6d). These technologies represent: (1) a natural gas combined cycle technology (advanced gas) *without* carbon capture and sequestration, (2) a natural gas combined cycle technology *with* carbon capture and sequestration (gas CCS), and (3) an integrated coal gasification technology *with* carbon capture and sequestration (coal CCS). The elaborated production structures for these technologies include separate nests that describe the cost of transmission & distribution (T&D), generation, and sequestration. For the other advanced electric technologies (bio-electricity and wind & solar) the costs of transmission and distribution are implicitly included in the capital, labor, and OTHR bundle. Separate identification of these components creates greater flexibility in the structure. An important difference from other sectors is that carbon permits enter in a CES nest with generation. This is benchmarked so that at entry, the technology captures 90% of carbon dioxide from combustion. This percentage increases as the price of carbon permits increase relative to the cost of generation. While current performance goals for these technologies are to capture 90% of emissions, testing of the model with a fixed 90% capture rate showed switching from gas to coal and back to gas as the carbon price rose, reflecting the fact that the capture efficiency of 90% eventually led coal CCS to be uneconomic with very high carbon prices. It is more realistic to represent the capture rate as variable: at higher carbon prices, it becomes economic to capture a higher percentage of the carbon. The nest structure we use means that to increase the capture rate, more of all of the generation and sequestration inputs are used as the carbon price rises. These technologies also include an additional fixed factor at the top of the nest that slows initial penetration.

Specification of advanced technologies must rely on data beyond that contained in National Income and Product Account (NIPA) data because these technologies are not currently used (or used on a very small scale) and thus the production inputs are not identified in standard input-output tables in the 1997 benchmark year. By convention, we set input shares in each technology so that they sum to 1.0. We then separately identify a multiplicative mark-up factor that describes the cost of the advanced technology relative to the existing technology against which it competes in the base year. This markup is multiplied by all of the inputs. For example, the mark-up of the coal gasification technology in the USA region is 3.5, implying that this technology would be economically competitive at a gas price that is 3.5 times that in the reference year (1997) *if* there were no changes in the price of inputs used either in natural gas production or in production of gas from coal. As with conventional technologies, the ability to substitute between inputs in response to changes in relative prices is controlled by the elasticities of substitution. These key parameters are given in **Tables 11** through **13**.

The estimates of factors shares and markups for shale oil and synthetic gas from coal are unchanged from EPPA3, with details on these provided in Babiker *et al*. (2001). For biomass energy, we considered early estimates of global resource potential and economics (Edmonds and Reilly, 1985) and recent reviews of potential (Moreira, 2004; Berndes *et al.*, 2003) and the economics of liquid fuels (Hamelinck *et al.*, 2005) and bio-electricity (International Energy Agency, 1997). Regarding cost, Hamelinck *et al.* (2005), estimate costs of lignocellusic conversion of ethanol of 8.7 to 13 €/GJ compared with 8 to 12 and eventually 5 to 7 €/GJ for methanol production from biomass. They compare these to before tax costs of gasoline production of 4 to 6 €/GJ. Our estimated mark-up of 2.1 is thus consistent with the lower end of the near- and mid-term costs for ethanol or methanol. The range of the estimated global biomass production potential is very wide, depending on assumptions of yield, available land that would

Table 11. Mark-ups and Input Shares for Coal Gas, Shale Oil, Bio-oil, Bio-electric, and Wind & Solar.

Supply Technology	Mark-up Factor	Input Shares				
		Resource	OTHR	Capital	Labor	Fixed Factor
Coal gas	3.5-4.0	0.40	0.10	0.30	0.20	--
Shale oil	2.5-2.8	0.10	0.27	0.36	0.27	--
Bio-oil	2.1	0.10	0.18	0.58	0.14	--
Bio-electric	1.4-2.0	0.19	0.18	0.44	0.14	0.05
Wind & Solar	1.0-4.0	0.05	0.25	0.40	0.25	0.05

Table 12. Mark-ups and Input Shares for Advanced Gas and Coal Electric Generation Technologies.

			Input Shares						
Supply Technology	**Mark-up Factor**	**Fixed Factor**	**Capital, Generation**	**Labor, Generation**	**Capital, T&D**	**Labor, T&D**	**Capital, Seq.**	**Labor, Seq.**	**Fuel**
Advanced Gas	0.94	0.01	0.24	0.05	0.31	0.19	0	0	0.23
Advanced Gas with CCS	1.16	0.01	0.29	0.07	0.26	0.16	0.05	0.00	0.16
Advanced Coal with CCS	1.19	0.01	0.39	0.12	0.21	0.13	0.08	0.01	0.07

Note: Mark-ups for Advanced Gas and Coal w/sequestration are higher in MEX, FSU, ASI, IDZ, AFR, MES, LAM, and ROW due to differences in the structure of these economies.

Table 13. Reference Values for Elasticities in Advanced Technologies.

		Resource and Fixed Factor Elasticities	
σ_{RVA}	Resource-Value Added/Other	0.5	Shale oil
		0.3	Bio-Electric
		0.1	Bio-oil
		0.02 - 0.06	Wind & Solar—range across regions
σ_{FVA}	Fixed Factor-Value Added/Other	0.4	Bio-Electricity
		0.6	Wind & Solar
		0.1	NGCC, NGCC & IGCC w/sequestration
		Value Added and Intermediate Input Elasticities	
σ_{VAO}	Labor-Capital-OTHR	0.2	Shale
		1.0	Bio-oil & Electricity, Wind & Solar
σ_{VA}	Capital-Labor	0.5	Applies to Coal Gasification
$\sigma_{GVA, SVA, TD}$	Capital-Labor	0.8	Generation, Transmission, and Sequestration
		Elasticity Governing Variable Rate of Carbon Capture	
σ_{PT}	Permits-Generation	1.0	NGCC & IGCC w/sequestration

be allowed to be converted to a biomass crop, and competition with agriculture. Our estimated contribution in reference and policy runs based on the parameterization of biomass production fits within that range. We continue to investigate the specification of biomass and expect to integrate the results in the version of EPPA with agriculture disaggregated into crops, livestock, and forestry as discussed in Wang (2005). Improved representation of agriculture and land use will provide an increased capability to explicitly evaluate biomass yield, land use, and feedbacks on biomass production as climate changes. The current specification does not include climate feedbacks.

Data for Wind & Solar electricity is based primarily on estimates of wind electricity potential taken from the International Energy Agency (2000) and evaluated further in light of results reported from the International Energy Agency (2004). Because wind enters as an imperfect substitute and is not explicitly represented in the 1997 data set, it is necessary to exogenously introduce wind with a positive share of electricity. IEA (2000) provided estimated forecasts of wind penetration by 2010, and we benchmarked the exogenous penetration of wind to these forecasts. We based estimates of cost on data from US DOE (1997) and developed regional cost factors based on regional assessment of wind potential by wind grade provided in International Energy Agency (2000). These provided the basis for the region specific mark-up factors. As discussed in IEA (2004), integration of wind into the grid and providing back-up capacity can add substantially to the cost of wind power. IEA (2004) estimates the cost of electricity generated from gas and coal in the range of $32 to $42 per MWh. In contrast they estimate wind costs of $45 per MWh at good sites and at $55 per MWh at moderate sites. They estimate the extra costs related to back-up and grid connection to add between $7.5 and $14 per MWh. Given our approach we assume a relatively low cost of wind, on the basis that the initial exogenously driven share is for high quality sites that can be easily integrated into the grid. Treatment of wind as an imperfect substitute implies that increases in the share require an ever higher relative price of conventional electricity to elicit further increases in the share of wind. Thus, the markup we specify is a minimum or entry-level cost. We assume that wind can maintain the initial exogenous share even as total electricity production generally increases in reference projections because expansion of the power sector will mean expansion of the grid and access to more high quality wind sites, and that other issues such as the need for back-up depend on the size of the total electricity market. Choice of the substitution elasticity creates an implicit supply elasticity of wind in terms of the share of electricity supplied by the technology. The value chosen for this elasticity results in relatively inelastic supply in terms of wind share, with it reaching at most 15 to 20% of electricity supply in any region, even under relatively tight constraints on carbon that lead to increased cost of generating electricity from fossil energy sources. We implicitly assume that this technology includes some deployment of solar electricity as well. Cheng (2005) investigated more complex treatments of wind, and we anticipate making use of this work to improve the representation of wind in future versions of EPPA.

Finally, the three advanced fossil electricity generation technologies have been extensively evaluated as discussed in McFarland *et al*. (2004). The basis for these costs is the work of Herzog (2000).

As noted above, for several of the new technologies we specify a fixed factor input that is technology-specific. As noted by Jacoby *et al.* (2004) observations on penetration rates for new technology typically show a gradual penetration, for which there are numerous contributing factors. EPPA4 replicates the penetration behavior that is typically observed by endowing the representative agent with a small amount of a specialized resource. The endowment of this resource grows as a function of output in the previous period. Capacity expansion is thus constrained in any period by the amount of this fixed factor resource and the ability to substitute other inputs for it. As output expands over time the endowment is increased, and it eventually is not a significant limitation on capacity expansion. The basic approach posits:

$$FF_{t+1} = f\left(Y_t, FF_t, FF_0\right), \tag{21}$$

where FF is the quantity of fixed factor and Y is the output from the technology at time t. FF_0 is the exogenous initial endowment. This follows the basic idea that adjustment costs occur when there is a desire to rapidly expand an industry, and these adjustments cost limit expansion in any given period.

The intuition behind this specification is as follows: at the start-up of a new industry there is limited trained engineering capacity to build plants with the new technology. With significant demand for capacity expansion, engineering firms with this capacity earn rents (or in the normal parlance, profits). There is not an absolute limit on capacity expansion as there is an ability to substitute other inputs for this fixed factor. Essentially, engineering firms can be employed with less of the specialized capability in the technology (or these firms can hire on more staff that are not as well trained) but that will mean higher real costs of installation—more capital, labor and other materials. These new firms gain experience (or the newly hired staff gain experience) and this expands the endowment of the fixed factor for future periods. Thus, over time the rents associated with this fixed factor mostly disappear. Parameterization of this adjustment cost process is based on observations of the ability of nuclear power to expand over from its introduction to the mid 1980s. The advanced fossil electric generation technologies are also vintaged as are other sectors (see Section 4.1). A more complete discussion of the process of specifying a new technology that is consistent with the existing specification of production technologies in the CGE data base is given in McFarland *et al.* (2004).

6. GREENHOUSE GAS AND URBAN GAS EMISSIONS

EPPA projects emissions of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), perfluorocarbons (PFCs), hydrofluorocarbons (HFCs), and sulfur hexafluoride (SF_6), gases that have direct radiative forcing effects in the atmosphere. It also projects sulfur dioxide (SO_2) emissions—a major source of aerosols that are thought to have a cooling effect, and CO, NO_x, non-methane volatile organic compounds (NMVOCs), ammonia (NH_3), black carbon (BC), and organic carbon (OC) that are all important for the climate and chemistry components of the IGSM. Babiker *et al.* (2001) included extensive tables of 1995 emissions inventories for each substance and a description of the evolution of emissions time trends. **Tables 14** and **15** report the substances we cover, their source, and the EPPA sector we model as the source. The approach for developing a reference case level of emissions of these substances remains unchanged in EPPA4. All of these inventories were updated to be consistent with the 1997 benchmark year and with revised data on them. These revisions are extensively documented in Sarofim *et al.* (2005).

A significant difference in modeling the non-CO_2 gases involves a revised approach by which we endogenously estimate the cost of abatement of these gases. This facility was not included in the version of EPPA3 described in Babiker *et al.* (2001) but was introduced in later versions of EPPA3. The approach has been extensively reviewed and evaluated, and has been widely

Table 14. Gas sources and EPPA Activities for Gases Listed in the Kyoto Protocol.

GAS AND SOURCE	EPPA ACTIVITY
CO_2	
Coal, oil, and natural gas combustion	Coal, refined oil, and natural gas consumption in all sectors, and coal gasification
Cement production	Energy intensive industry production
Deforestation, biomass burning	Agriculture production
CH_4	
Coal seams	Coal production
Petroleum production	Oil production
Transmissions and distribution losses	Gas consumption
Landfill, wastewater gas	Household consumption
Industrial sewage, paper and chemicals	Energy intensive industry production
Industrial sewage, food processing	Other industry production
Rice, enteric fermentation, manure management, agricultural waste, savannah, and deforestation burning	Agriculture production
N_2O	
Adipic and nitric acid production	Energy intensive industry
Refined oil products combustion	Refined oil consumption in all sectors
Coal combustion	Coal consumption in all sectors
Agricultural soils, manure management, agricultural waste, savannah, and deforestation burning	Agriculture production
HFCs	
Air conditioning, foam blowing, other	Other industry production
PFCs	
Semi-conductor production, solvent use, other	Other industry production
Aluminum smelting	Energy intensive industry production
SF_6	
Electrical switchgear,	Electricity production
Magnesium production	Energy intensive industry production

Table 15. Gas Sources and EPPA Activities for Other IGSM Gases Not Listed in the Kyoto Protocol.

Gas and Source	EPPA Activity
SO_2	
Coal, oil, and natural gas combustion	Coal, refined oil, and natural gas consumption in all sectors
Non-ferrous metals, iron and steel, chemicals, and cement	Energy intensive industry production
Refinery processes	Refined oil production
Agricultural waste, savannah, deforestation, biofuels, and uncontrolled waste burning	Agricultural production
Biofuel use in households	Household consumption
NMVOCs	
Coal, petroleum products in transportation, and natural gas combustion	Coal, refined oil, and natural gas consumption in all sectors
Refinery processes	Refined oil production
Natural gas production processes	Natural gas production
Oil production processes	Oil production
Solvents, other industrial processes	Other industry production
Iron & steel, chemicals	Energy intensive industry production
Biofuel use in households	Household consumption

[*Table continues on following page.*]

Table 15 [*continued*]. Gas Sources and EPPA Activities for Other IGSM Gases Not in the Kyoto Protocol.

Gas and Source	EPPA Activity
NMVOCs (*continued*)	
Agricultural waste, savannah, deforestation, biofuels, and uncontrolled waste burning	Agricultural production
NO_x	
Coal, oil, and natural gas combustion	Coal, refined oil, and natural gas consumption in all sectors
Cement, chemical, iron & steel manufacture	Energy intensive industry production
Refinery processes	Refined oil production
Biofuel use in households	Household consumption
Agricultural waste, savannah, deforestation, biofuels, and uncontrolled waste burning	Agricultural production
CO	
Coal, oil, and natural gas combustion	Coal, refined oil, and natural gas consumption
Chemical, iron & steel manufacture	Energy intensive industry production
Refinery processes	Refined oil production
Other industrial processes	Other industry production
Biofuel use in households	Household consumption
Agricultural waste, savannah, deforestation, biofuels, and uncontrolled waste burning	Agricultural production
Black Carbon and Organic Carbon	
Coal, oil, and natural gas combustion	Coal, refined oil, and natural gas consumption
Biomass and waste burning in agriculture	Agricultural production
Biomass burning in households	Household consumption
NH_3	
Manure management and fertilizer use	Agricultural production
Sewage	Household consumption

adopted by others. Originally developed by Hyman (2001) the approach and implications for methane abatement are extensively documented in Hyman *et al.* (2003), and the broader policy implications of such a treatment of all greenhouse gases are found in Babiker *et al.* (2002), Paltsev *et al.* (2003), Reilly *et al.* (2003) and Reilly *et al.* (2005).

The approach is to introduce emissions of each greenhouse gas into sectors of the economy responsible for them. These are introduced into the nest structure of each production sector. CO_2 generally is introduced as a Leontief input associated with fuel with a zero elasticity of substitution reflecting the reality that abatement involves using less of the fuel (except in the case of separation and sequestration as discussed in Section 5). In most other cases, we introduce the greenhouse gases into a top nest. Process emissions of CO_2 from coal gasification and from shale oil production are introduced as a Leontief input in such a top nest for these sectors, indicating that emissions of CO_2 from these processes are fixed in relation to total production of coal gas or shale oil. Most other substances enter as a CES input, and the elasticities of substitution are fit to match bottom-up estimates of abatement possibilities (Hyman, 2001; Hyman *et al.*, 2003). The elasticties of substitution are given in **Table 16**.

Table 16. Reference Values for Elasticities Governing Abatement of Greenhouse Gases.

Resource and Fixed Factor Elasticities			
σ_{CH4}	Gas consumption	0.15	Estimates for agriculture are based on separately identified abatement opportunities for rice, enteric fermentation from livestock, manure handling, and biomass burning. Regional differences reflect different shares of these sources in emissions from each region
	Oil production	0.15	
	Coal production	0.3	
	Other Industries, Final demand	0.11	
	Agriculture	0.02 – 0.08	
σ_{N2O}	Coal	0.0	Developed countries (OECD regions, FSU, and EET) agriculture are 0.04, developing regions are 0.02
	Roil	0.0	
	EINT	1.0	
	Agriculture	0.02-0.04	
σ_{PFC}	EINT	0.3	
	OTHR	0.3	
σ_{SF6}	EINT	0.3	
	ELEC	0.3	
σ_{HFC}	OTHR	0.15	

7. CALIBRATION AND OUTPUT PROCESSING FOR LINKING WITH THE IGSM

7.1 Calibration to Actual 1997-2005 Data

Several years have already elapsed from the EPPA4 base year 1997. We do not imagine that we can forecast business cycle behavior of economies, however, we have observed data for growth from 1997 to present. This actual behavior can have important implications for nearer-term emissions. Since EPPA is often used to estimate nearer-term policy costs, we have adjusted parameters so that EPPA projections through 2005 approximately match historical data. For this purpose, we use IMF data on growth, adjusting labor and capital growth to match GDP growth rates as reported in **Table 17**. The IMF growth rates in Table 17 are part actual data, and part short-term forecasts because final data on GDP growth were not available through 2005.

Table 17. Annual Real GDP Growth Rates for 1997-2005.

	1997-2000	**2000-2005**
USA	4.23	2.53
CAN	4.89	2.98
MEX	5.32	2.13
JPN	0.62	0.71
ANZ	4.13	3.57
EUR	3.14	1.74
EET	3.26	3.44
FSU	3.12	4.79
ASI	2.4	3.64
CHN	7.34	7.91
IND	6.33	5.77
IDZ	–2.7	4.01
AFR	2.81	4.22
MES	3.41	3.26
LAM	1.18	1.96
ROW	3.35	3.91

In addition to calibrating economic growth to actual data, we have adjusted parameters in EPPA to match historical energy production and consumption data for the year 2000 in China and India, regions that exhibited important disparities. Using energy balance data from the International Energy Agency (2005), and following the aggregation procedures used in GTAP (Dimaranan and McDougall, 2002) and EPPA4, we calculated energy consumption for refined oil, gas, and coal by sector for the year 2000. Based on these data, we parameterized EPPA to match industrial and household consumption and total fossil production.

7.2 Preparing EPPA Outputs for Linking with Other IGSM Components

A key linkage between EPPA's emissions output and the Integrated Global System Model's climate-chemistry model is the emissions postprocessor. It serves to spatially distribute emissions generated by EPPA, predicts emissions of some species that are not handled in EPPA, and includes emissions from some natural sources that are not otherwise incorporated into the earth system portion of the IGSM.

EPPA categorizes all emissions as either agricultural or non-agricultural. While the economics model works with five-year time-steps and a regional geographic scale, the earth systems model requires daily emissions on a four degree latitudinal scale. Therefore, the postprocessor first distributes emissions on a 1º by 1º degree grid, with non-agricultural emissions distributed based on a population map derived from the Columbia University's dataset (CIESIN, 2000) and agricultural emissions for each gas distributed based on EDGAR 2.0 emissions inventories for 1990. Any 1º x 1º latitude-longitude area that has NO_x emissions above 5 $kgN/day/km^2$ is considered to be an urban area for purposes of the chemistry component of the earth systems model. The 1º x 1º emissions are then integrated to yield the latitudinal data. Yearly emissions are linearly interpolated between the five-year EPPA time-steps, and then evenly distributed over the days of the year.

The following natural emissions are included in the postprocessor: 370 Tg of CO (20 Tg from oceans and the remainder from vegetation), 21 Tg of NO (lightning and other processes), 40 Tg of CH_4 (termites and ocean and other emissions; Prather *et al.*, 2001), and 26 Tg of SO_2 (marine and terrestrial biospheres; Spiro *et al.*, 1992).

Historical CFC11 and CFC12 emissions are based on the Global Emissions Inventory Activity (GEIA) data (McCulloch *et al.*, 2001, 2003) through 2000 and assumed to decline to zero by 2005 (though research by Fraser and Montzka (2003) indicates that there is a slow release from foam mechanism for CFC11, which leads to continued emissions for 20 years after production). HCFCs are not included in the model at this time.

The postprocessor also does some carbon balancing: because all CH_4 and CO emitted from organic sources (*e.g.*, the agricultural sector) originate from CO_2 that has been sequestered by the ecosystem in the recent past, the postprocessor subtracts the carbon from these sources from CO_2 emitted in that time period. Oxidation in the earth systems model will eventually turn the CO or CH_4 back into CO_2, completing the cycle.

Currently the postprocessor operates as a back-end to EPPA. Work is ongoing to integrate the postprocessor more fully, which will eventually allow period-by-period integration of EPPA with the earth systems component of the IGSM (see Figure 1). This project will also implement a population map that will evolve over time, which is important for the model's ability to realistically project urban regions in the future.

8. REFERENCE SCENARIO AND POLICY ILLUSTRATION

8.1 A Reference Case

The model structure and parameters reported in the previous sections give rise to a reference set of projections of GNP and energy growth, changes in relative prices and the economic structure of nations or multi-nation regions, and greenhouse-relevant emissions. Here we present a reference case based on plausible assumptions about labor productivity growth, exogenous changes in energy efficiency, technology costs and other key parameters. Naturally, projections of economic and technical change over many decades are subject to great uncertainty, and reasonable cases can be made for other projections that vary considerably from that shown here, as illustrated below. However, base case or reference scenarios often are an important input to estimates of the seriousness of the climate threat and the costs of greenhouse gas emissions targets, and it is useful to present a picture of the underlying behavior of the EPPA model. In addition, we show how the reference GHG projections vary from those of the previous Version 3 of the model.

Population and GDP Growth. In this reference case we apply a United Nations forecast of population (UN, 2000, 2001). As shown in **Table 18**, under this projection global population grows by about 60% over the 21st century. The aggregate pattern is the result of contrasting rates of change in different parts of the world. With the exception of the US, Canada and Australia/

Table 18. UN Population Forecast (in millions).

	2000	2025	2050	2075	2100
USA	283.4	347.1	397.4	395.6	392.9
CHN	1,282.0	1,479.5	1,471.7	1,379.9	1,334.3
IND	1,008.9	1,351.8	1,572.1	1,633.5	1,643.3
AFR	792.9	1,357.2	1999.4	2,344.7	2,499.8
JPN	127.1	123.8	109.2	117.0	119.5
CAN	30.8	36.7	40.4	40.2	39.9
MEX	98.9	130.2	146.7	155.3	159.0
EUR	389.6	384.8	352.0	307.5	288.5
EET	96.6	89.6	78.2	68.2	63.9
FSU	290.9	274.1	248.4	235.8	229.8
ASI	211.4	272.9	304.9	326.5	333.6
IDZ	212.8	274.1	312.7	334.9	342.2
MES	174.1	298.3	430.3	460.8	470.8
LAM	419.3	563.7	657.8	696.5	713.4
ANZ	22.9	27.8	30.9	32.4	32.9
ROW	615.1	925.1	1,170.1	1,247.9	1,273.1
World	**6,056.7**	**7,936.7**	**9,322.3**	**9,776.7**	**9,936.9**

New Zealand whose patterns are influenced to some degree by in-migration, the OECD countries and Economies in Transition lose population over this period. This reduction in developed countries is overwhelmed, however, by the projected growth in developing countries with particularly large increases in India, Africa and Latin America. Growth rates in the developing countries slow over time, and the rate of growth in most regions is near zero for the last 25 years.

Figure 7 shows annual GDP growth rates (5-year averages) for the developed and transition economies (Figure 7a) and for developing regions (Figure 7b), including the historical performance for 2000 and an estimate for 2005 and the EPPA projection for 2010 through 2100. Projected growth rates show less variability than the recent historical period because the EPPA model does not attempt to capture business cycle fluctuations. Notable in the early performance of the Annex B regions is anticipation of economic recovery in Japan. Also the FSU and EET experienced large negative growth rates in the 1990s, and these regions are modeled to recover with growth exceeding that in the OECD regions for a couple of decades. Growth in all OECD regions and Economies in Transition slows gradually from 2020 onward, with all converging to a rate of around 1.8% by 2100. These trends reflect the changing size and productivity of the labor forces of these regions.

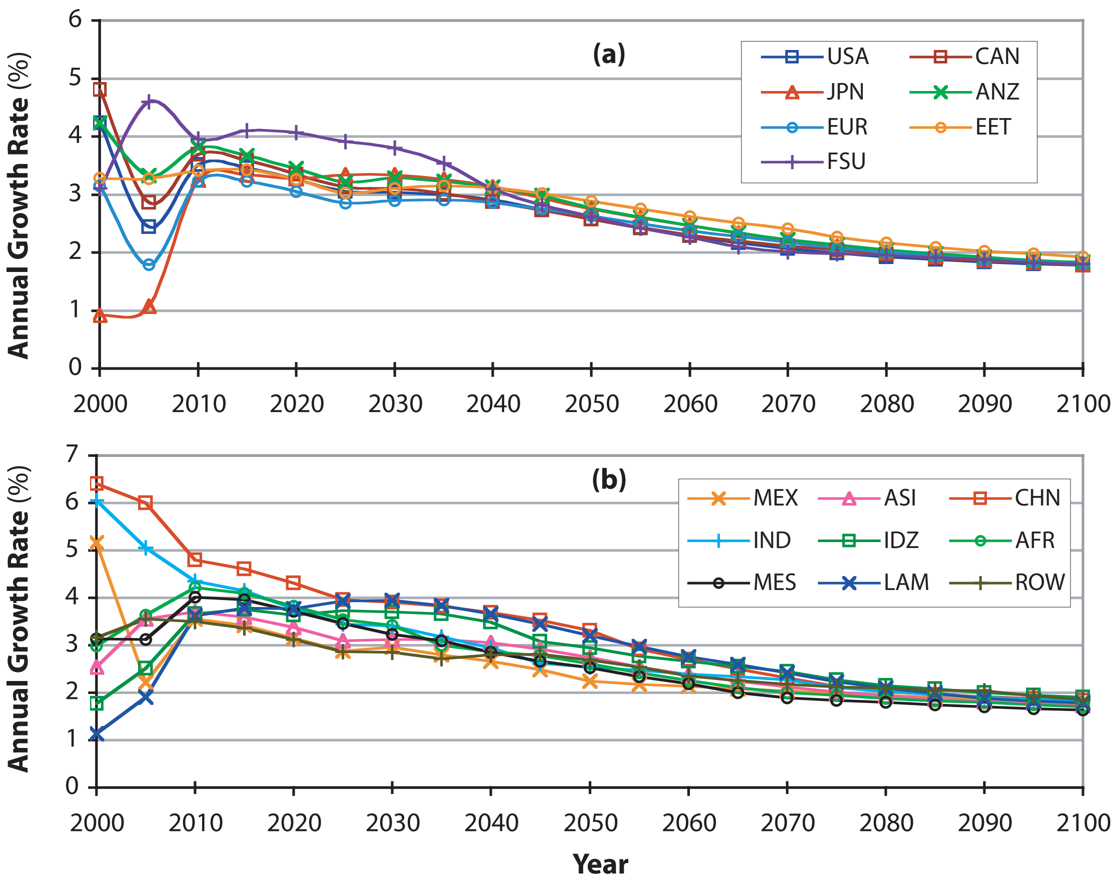

Figure 7. Annual GDP Growth Rates: **(a)** Developed and Transition Countries, **(b)** Developing Countries.

The variation in recent growth experience of developing regions is wider than for the OECD regions. China (CHN) attained remarkably high growth rates over the past 20 years or so, and the EPPA projections show this rate coming down over the next decade, declining to rates closer to those of other developing regions. By the period 2020 to 2040 all of the developing regions exhibit growth in the range of 3 to 4% per year. After 2040, growth in all developing regions slows following the general pattern in the developed regions, so that all regions are growing in the range of 1.8 to 2.0% growth in 2100.

Table 19 shows the results of these growth rates when experienced over a century. The results computed by the model follow the convention in the GTAP data set of converting foreign currencies into US dollars using market exchange rates (MER), and the first column shows the levels of the year 2000. The third column shows the 2100 GDP levels of individual countries and regions expressed as a multiple of the 2000 level. All show substantial growth as would be expected from the rates in Figure 7.

Comparisons *across* regions of economic size and well-being require conversion of the economic data developed in the model to the equivalent using purchasing power parities (PPP) presented in **Table 20**. Such a conversion has been made using estimates of the Penn World Tables (Heston *et al.*, 2002) and is presented in the second column of Table 19 for the year 2000, and stated in per capita terms in column four of Table 19. Estimation of changes in the PPP exchange rates over the century is beyond the scope of this EPPA analysis, but a rough impression of 2100 conditions can be constructed on the assumption that they remain constant. This estimate is shown in the fifth column, again stated in per capita terms.

Table 19. 21st Century GDP Growth.

	(1) **2000 GDP level, MER** (trillion 1997$)	(2) **2000 GDP level, PPP** (trillion 1997$)	(3) **2100 GDP multiple of 2000 GDP, MER**	(4) **2000 GDP per capita, PPP** (thousand 1997$)	(5) **2100 GDP per capita, PPP** (thousand 1997$)	(6) **Annual Average GDP per capita growth rate, 2000-2100** (%)
USA	9.1	9.1	11.9	31.9	273.4	2.2
CAN	0.7	0.9	12.6	28.7	277.9	2.3
MEX	0.5	0.7	9.3	6.9	39.9	1.8
JPN	4.4	3.0	12.3	24.0	313.0	2.6
ANZ	0.5	0.7	14.5	29.0	292.5	2.3
EUR	9.2	11.0	11.3	28.3	430.1	2.8
EET	0.3	0.9	14.6	9.7	214.0	3.1
FSU	0.6	2.8	16.2	9.5	196.1	3.1
ASI	1.3	3.7	14.1	17.4	155.1	2.2
CHN	1.2	5.5	23.3	4.3	95.5	3.2
IND	0.5	2.6	15.6	2.6	24.6	2.3
IDZ	0.2	0.9	14.3	4.2	37.1	2.2
AFR	0.6	2.3	12.1	3.0	11.3	1.4
MES	0.6	1.4	9.7	8.2	29.3	1.3
LAM	1.6	3.6	15.9	8.5	79.5	2.3
ROW	0.7	2.9	10.9	4.7	24.8	1.7
World	**32.0**	**51.9**	**12.6**	**8.6**	**72.2**	**2.1**

Table 20. MER-PPP Conversion Rates.

USA	1.00
CAN	1.21
MEX	1.51
JPN	0.69
ANZ	1.27
EUR	1.20
EET	2.82
FSU	4.31
ASI	2.93
CHN	4.46
IND	5.37
IDZ	3.99
AFR	3.85
MES	2.50
LAM	2.16
ROW	4.26

The GDP growth rates projected for different regions are within the range of historical growth rates as computed by Maddison (2001) and shown in **Table 21**. The regions used by Maddison (2001) are close to the regions reported by EPPA, but we have not attempted to make them exactly consistent. As Maddison (1999) notes, there was an acceleration of GDP growth after 1820 in the West leading to a 44-fold increase in GDP per capita in Western Europe and Japan and a 57-fold increase in North America from 1820-1995. In the longer history, he notes three epochs of growth 1000-1500, 1500-1820, and 1820-1995, with global economic growth negligible in the earlier epochs.

EPPA projections for Western economies are similar to rates of growth of these economies since 1950, and thus somewhat optimistic relative to performance since 1820. If the next century were to witness disruptions such as world wars, or significant economic depressions such as occurred in the 1930s, these projections may be overly optimistic. On the other hand, the

Table 21. Annual Average GDP Per Capita Growth.

	1500-1820	1820-1870	1870-1913	1913-1950	1950-1973	1973-2001
Western Europe	0.14	0.98	1.33	0.76	4.05	1.88
Eastern Europe	0.10	0.63	1.39	0.60	3.81	0.68
Former USSR	0.10	0.63	1.06	1.76	3.35	–0.96
North America	0.34	1.41	1.81	1.56	2.45	1.84
Latin America	0.16	–0.03	1.82	1.43	2.58	0.91
Japan	0.09	0.19	1.48	0.88	8.06	2.14
China	0.00	–0.25	0.10	–0.62	2.86	5.32
India	–0.01	0.00	0.54	–0.22	1.40	3.01
Other Asia	0.01	0.19	0.74	0.13	3.51	2.42
Africa	0.00	0.35	0.57	0.92	2.00	0.19
World	**0.05**	**0.54**	**1.30**	**0.88**	**2.92**	**1.41**

Source: Maddison (2001).

evidence from the last 50 years is that the ability to manage the macroeconomies in these regions has improved from the pre-World War II period.

Historical rates of growth for developing countries regions as shown in Table 21 have been uneven, and generally less than the developed countries. China, Other Asia, and India have had good performance since 1973 but growth in Latin America and Africa has been very poor. In terms of the EPPA reference projections these regions and countries, overall, do not show substantially faster growth than the developed countries, with the exception of China. Still, the projection of consistent strong growth in these regions over a century is relatively optimistic if viewed against their actual experience over the past century or even in the post-World War II period. The projections leads to per capita incomes in PPP terms that are for the most part as high or higher as year 2000 levels in the US, but with very little difference in per capita growth the absolute difference between developed and developing countries widens substantially.

Overall, these projections were intended to represent continuation of economic experience observed in history, which they do. There are not intended to be prescriptive—obviously one might hope that growth performance in developing countries could improve beyond that projected here. If anything, however, these projections are on the optimistic side, particularly with respect to developing country regions. These projections by no means represent an estimate of the maximum growth that could be seen in countries if they pursued effective macroeconomic policies.

The sectoral composition of economic activity in each of the regional economies changes over time along the baseline solution. A main influence on sectoral shifts is the change in patterns of consumer demand with economic development. These shares are determined by many factors including changes in relative factor prices, intermediate demands, final demands, and international trade. A CGE model like EPPA, which is based on CES functions, tends to be share preserving, however, and as noted in Section 3.4, additional adjustments are made from period to period to reflect the way that consumer bundles are expected to adjust with per capita incomes. Sample results for the resulting patterns for a sample of regions are shown in **Figure 8**. For example, in many regions agricultural products represent less than 5% of final consumption in the base year, and its share continues to decline over the simulation period. For countries that currently have high agricultural shares (CHN, IND and AFR in Figure 8) this share declines substantially with time and growth. Two of the larger sectors are Other Industry Goods and Services (OTHR) and Services (SERV), and their relative shares change substantially for some regions as also shown in Figure 8. The services share increases for all the regions shown, and for the richer ones the share approaches the current level in the US. Where the services share increases most there is a corresponding reduction in the final demand for output of the OTHR sector.[8]

[8] Calibration of consumption shares by income level is a continuing focus of EPPA development as discussed in Section 9.

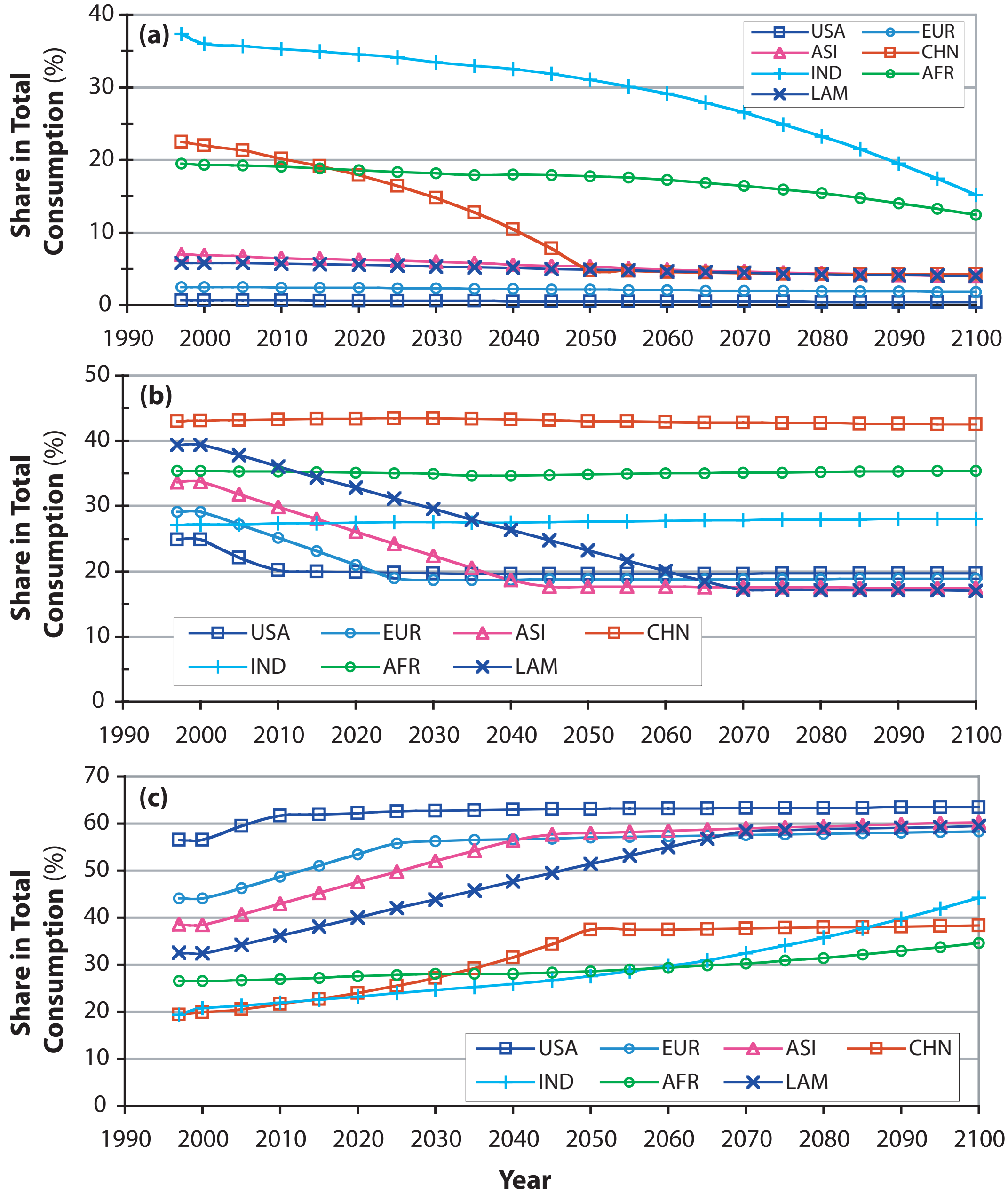

Figure 8. Sectoral Consumption Shares in the **(a)** Agriculture, **(b)** Other Industry Goods and Services (OTHR), and **(c)** Services Sectors.

Energy Intensity of Economic Activity. The energy intensity of GDP summarizes the relationship between economic growth and energy use. The relative changes in energy intensity over the simulation period are presented in **Figure 9**. Often much is made about the relative efficiency of different economies by comparing absolute values of energy intensities but this comparison depends crucially on the conversion of GDP to comparable units (*e.g.*, US dollars) and this, to be an accurate indicator, requires adjustment to reflect purchasing power differences

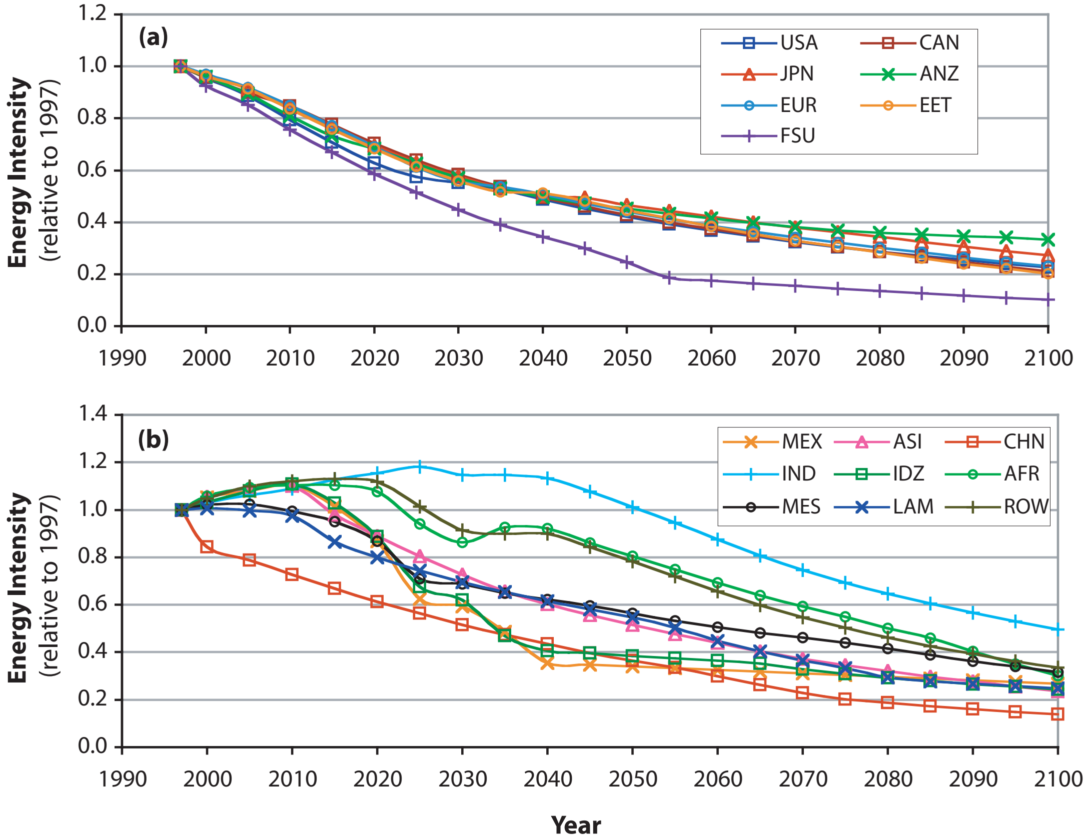

Figure 9. Energy Intensity of GDP: **(a)** Developed and Transition Countries, **(b)** Developing Countries.

(*e.g.*, use of PPP indices). To avoid a misdirected comparison of absolute levels we report the value as an index equal to 1.0 in 1997.

As shown in Figure 9a, the EPPA model projects energy intensity to decline in the developed and transition economies over the simulation period—a continuation of the pattern of recent decades. The rate of decline is similar for most of these regions with the exception of the FSU. Intensity rose in the 1990s as GDP fell far more than energy use during the political transition, leaving an economy with substantial opportunities for improvement. Developing countries in Figure 9b also see substantial reductions in intensity over the century, but not necessarily in the early decades. China is another country with high energy intensity of GDP today, and it is modeled as realizing reductions throughout the period. Other developing countries (*e.g.*, MES, IND, AFR) are seen as still in an industrializing phase where intensity will rise for some time, but by 2040 all are on paths to lower energy use per unit of GDP.

Energy Prices, Consumption and Fuel Shares. Energy prices are another important factor influencing emissions and the costs of control. In an EPPA-type model energy prices, along with all other prices, are market-clearing prices and thus reflect changes in supply and demand. Prices rise over the simulation period, meaning that demand is growing more rapidly than supply and thus energy consumption is lower than it would have been otherwise. These generally rising prices are another reason why energy consumption grows slower than GDP. **Figure 10** shows the projected trend in the world oil price. Because oil trade is modeled as a Heckscher-Ohlin good there is a single world oil price, stated here as a multiple of the price in the 1997 base year. The price rises through 2030 after which the increase is partially mitigated by the availability and entry into the market of shale oil and biomass liquid technology. The continued rise in the oil price over the remainder of the simulation, and particularly after 2080, is driven by the depletion of the highest grades of the shale oil resource and competition with land for biomass.

Natural gas and coal are modeled as Armington goods, and as a result prices can differ among regions.[9] Within the EPPA model gas trade can be represented as a set of sixteen regions trading an Armington good (as coal is modeled) or as a set of three regional markets with perfect substitution inside each. **Figure 11** shows the price trends for natural gas for a selection of regions under the 16-region Armington assumption. Under this specification international gas trade has an influence on regional prices, but the domestic resource base still has a strong effect.

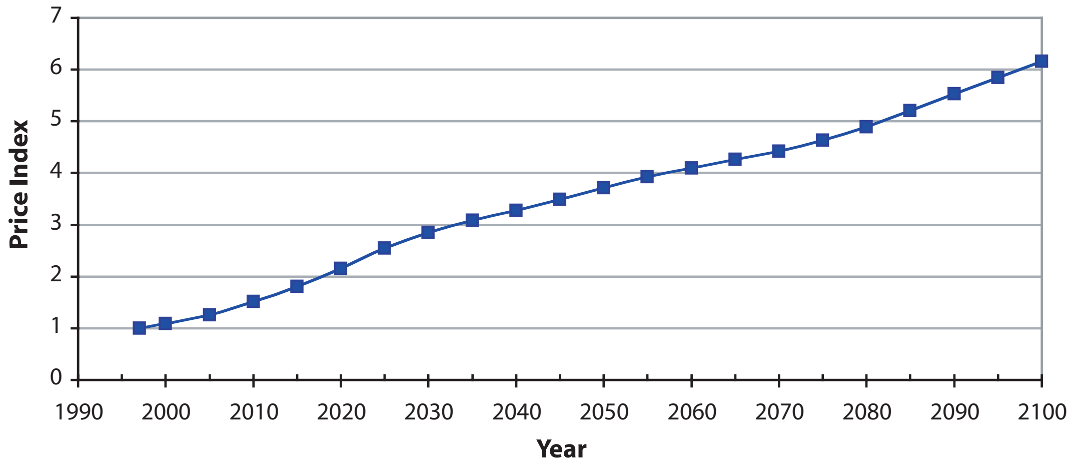

Figure 10. Evolution of the World Oil Price.

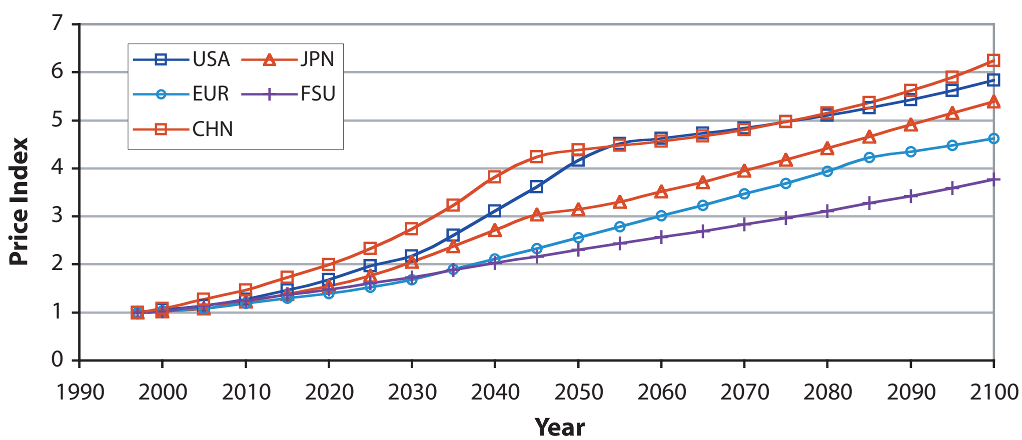

Figure 11. Evolution of Gas Prices, Selected Regions.

[9] As noted, in Section 3.2, versions of EPPA have been developed that consider gas as a Heckscher-Ohlin good, but here we report results where gas is an Armington good.

In the early decades, for example, prices rise most strongly in the USA, where depletion is well under way, and China where rapid demand growth presses on a limited supply. In these regions prices rise somewhat less rapidly after mid-century when coal gasification enters the market. The FSU on the other hand, with its extensive reserves, sees the lowest price increase among the countries shown.

For coal, also modeled using the Armington specification, the price pattern is a combined effect of international trade and the adequacy of domestic resources. Because of the larger resource base almost everywhere coal prices rise less than those for gas, as shown in **Figure 12**. China sees the greatest increase as rising electric demand confronts available domestic resources, and for Japan the electric demand growth is not so great but the coal resource is very limited. The lowest increases among the regions shown are in the FSU with its large reserves and in EUR. As noted previously, the CES production function tends to be "share preserving." It is used in the Armington specification, and as a result regions that already import a substantial fraction of coal (*e.g.*, Europe, Japan), are less constrained in the future by domestic resources and domestic price increases reflect more closely price increases in regions that are the source of their imports.

The combined effect on energy use of economic growth, productivity and technical change and energy prices can be seen in **Figure 13**, which shows global primary energy production and electric generation by type. In the absence of any policy to control greenhouse gas emissions, coal becomes the ever more dominant source of energy over the century, supplemented by shale oil later after 2050. Hydro, wind, and solar see large growth over the century but remain a small fraction of total primary energy. In this reference case nuclear power is assumed to see renewal or replacement of existing capacity but not substantial growth. Biomass liquids do come to carry a substantial share of demand after 2050, but the dominance of oil, gas and coal lead to rapid growth in emissions, as documented below.

A similar picture emerges for the electric power sector, presented in **Figure 14**. With no attempt to mitigate CO_2 emissions the sector is dominated by coal and natural gas (both traditional

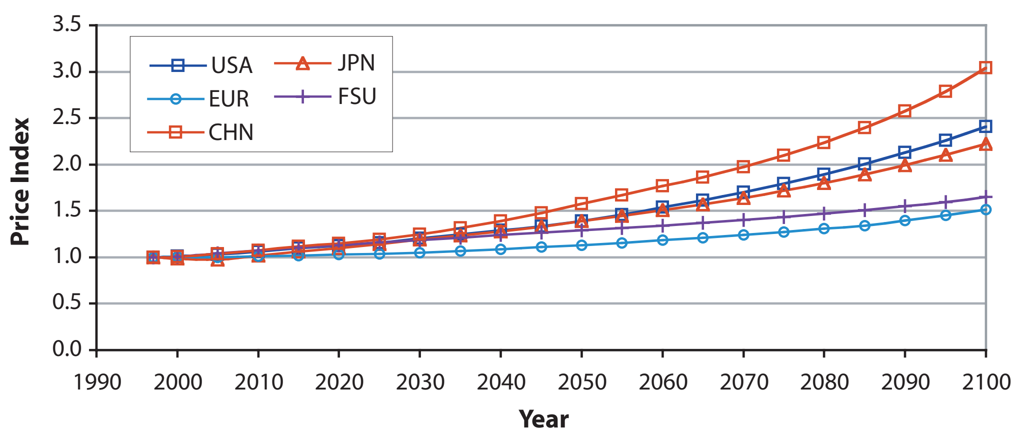

Figure 12. Evolution of Coal Prices, Selected Regions.

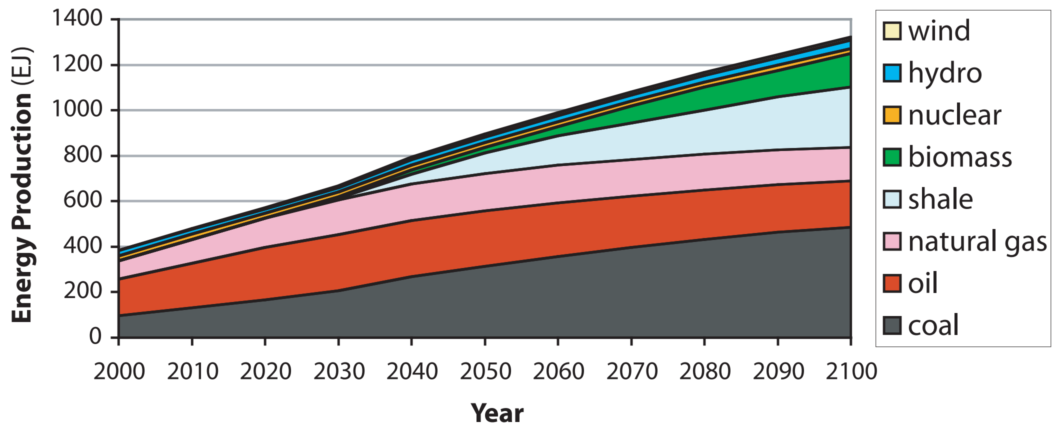

Figure 13. Global Primary Energy Production and Shares (EJ).

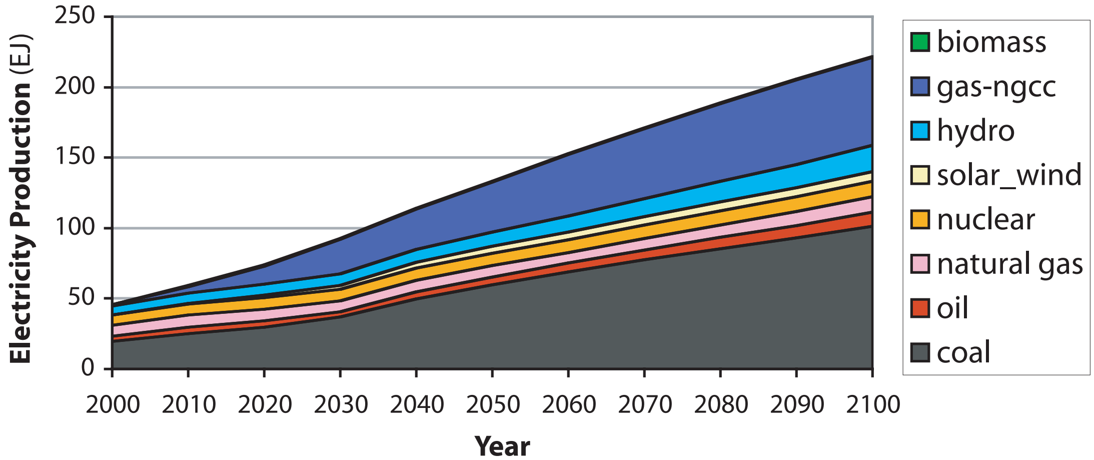

Figure 14. Electricity Production by Type.

gas and NGCC technologies), as it is currently. The role of wind and solar, hydro and nuclear power is played out exclusively within this sector under the structure of the EPPA model, and their pattern in Figure 13 is seen again here. Because of their higher costs, biomass-based electricity and technologies with capture and storage do not enter in the absence of a positive price on CO_2.

Although not shown here, there are strong differences among regions. Coal is used for electricity generation in regions with substantial coal resources, whereas gas is more widely used in regions with gas resources. In part, this pattern is driven by the Armington assumption for these fuels, which allows greater divergence in regional prices. The extent to which these markets will become more globalized or not would thus affect this pattern of fuel use in the electric sector.

It is worth noting that the combination of rising input prices and technology assumptions lead to a substantial increase in the efficiency of electric generation even in the absence of CO_2 control policies. **Figure 15** presents the efficiency of fossil electric generation implicit in the reference solution expressed as a global average. Generation efficiency, which was around 27% in the base period of the model rises to the neighborhood of 50% by the end of the century.

Emissions of Greenhouse and Urban Gases. We have sought to define reference projections as the level of emissions if there were no explicit greenhouse gas abatement policies. Now that some countries and individual companies have begun to implement mitigation measures in anticipation of future policies such a definition of the reference case may for some regions yield estimates for near-future years that diverge slightly from realized values or other short-term forecasts. This definition of the reference is maintained to allow estimation of the full cost of meeting climate-related commitments. In practice it is not always possible to clearly determine whether reductions have occurred because of anticipated climate policy or for other reasons.

Figure 16 shows the global greenhouse gas emissions that result from the economic growth over the century and the factors and the associated energy consumption and other activities that produce emissions. Economic growth is one of the most important, and uncertain, drivers of emissions growth, and to emphasize the uncertainty that surrounds the reference case displayed here the graph for CO_2 shows the sensitivity of the projections to growth assumptions. With the reference GDP growth emissions reach 25 GtC/yr by 2100. For the EPPA4 the average GDP growth rate over the century is approximately 2.5% per year, and the figure also shows the result with slower (2.0%) and faster (3.0%) economic growth. Just this one-half point increase or decrease in modeled growth can swing the 2100 level carbon emissions from 17 to 34 GtC/yr.

Figure 16 also shows the difference in reference projections between EPPA4 and the previous EPPA3 version (Babiker *et al.*, 2001). The 2100 CO_2 level in EPPA4 is up from the 23.0 GtC/yr projected with the EPPA3 reference. The nearly 3 GtC/yr increase in emissions is substantial but should be considered small in light of the uncertainty in forecasts of economic growth. Further regional and sectoral disaggregation, revisions of autonomous energy efficiency improvement in developing countries, the addition of a broader set of technological options, reevaluation of fossil fuel resources, and other changes also affect the reference outcome.

Reference emissions and cases with high and low economic growth for the other greenhouse gases also are included in Figure 16, with display of these differences and the EPPA3 reference.

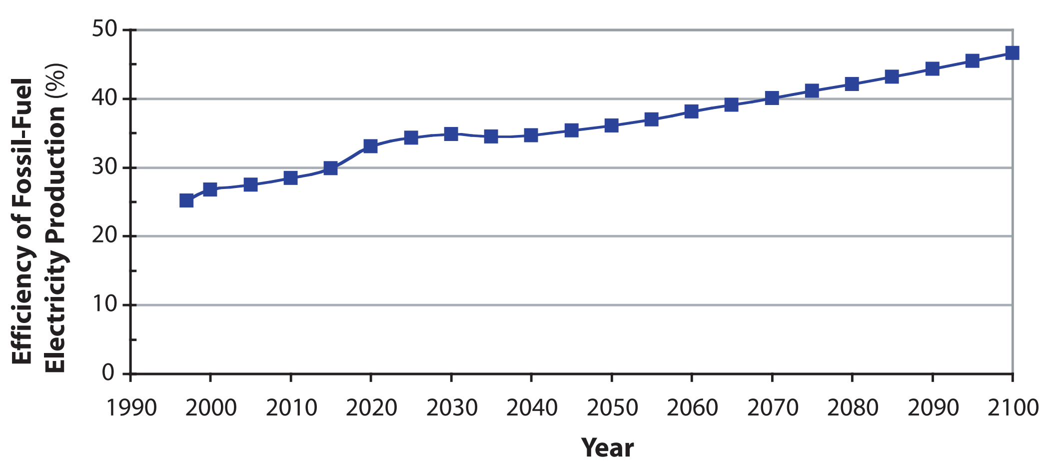

Figure 15. World Aggregate Fossil Electric Efficiency.

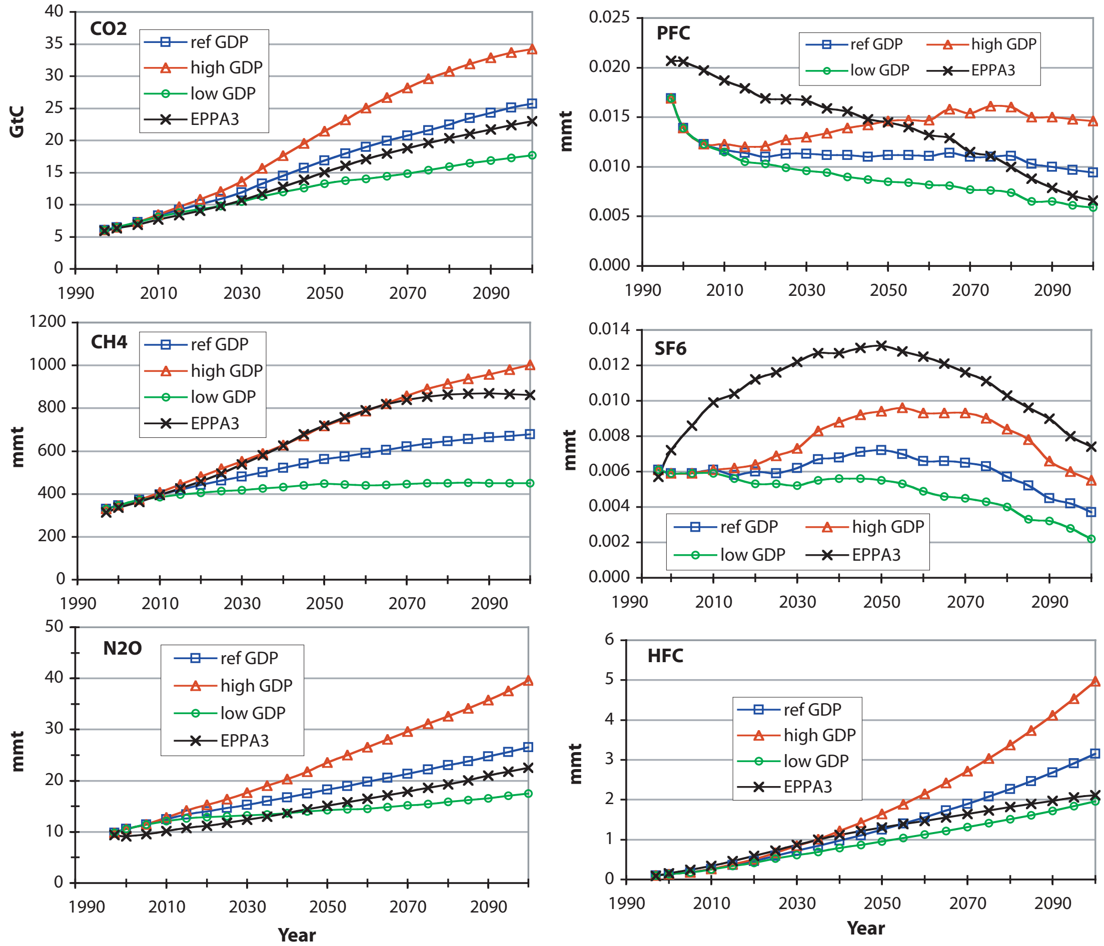

Figure 16. Emissions Projections for Greenhouse Gases (range and comparison with EPPA3).

The major changes in reference cases between model versions appear for CH_4, PFCs and SF_6. These solutions differ for a number of reasons in addition to the revised GDP growth rates, as detailed in Sarofim *et al.* (2005). Emissions factors for each sector were revised to be consistent with the new base year (1997) global emissions inventories developed by the US EPA (US EPA, 2001, 2002) and further adjusted to be consistent with inverse calculations for methane from rice (Chen, 2003; Chen and Prinn, 2005). As a result, PFC emissions in 1997 are lower in EPPA4 than in EPPA3, but base year (1997) emissions for other gases were not substantially changed. EPPA4 forecasts for CH_4 are somewhat lower than EPPA3 primarily because of the expected more rapidly falling emissions coefficient over time for methane from fossil fuel production, particularly in the FSU (primarily Russia). Nitrous oxide emissions in EPPA4 are somewhat higher than EPPA3 reflecting the higher economic growth, reevaluation of likely future emissions from adipic and nitric acid production, and revisions to agricultural sources based on new projections of growth of agricultural emitting activities from the International Food Policy Research Center (Rosegrant *et al.*, 2002). Significant changes in projections for PFCs, SF_6, and HFCs occurred as a result of further sectoral disaggregation that affects the growth of source sectors for these emissions including the Energy Intensive Industry, Other Industry and Transportation sectors and, for SF_6 in particular, the further disaggregation of the electric sector.

The projections for other substances relevant to atmospheric chemistry and the radiative balance are shown in **Figure 17**, along with the implications of higher and lower growth rates. In developing EPPA4 all of the inventories have been re-evaluated based on EDGAR 3.2 (Olivier and Berdowski, 2001). Emissions coefficients were re-estimated based on the cross-section benchmark data for 1997 (Sarofim *et al.*, 2005). In addition, to better simulate changes in

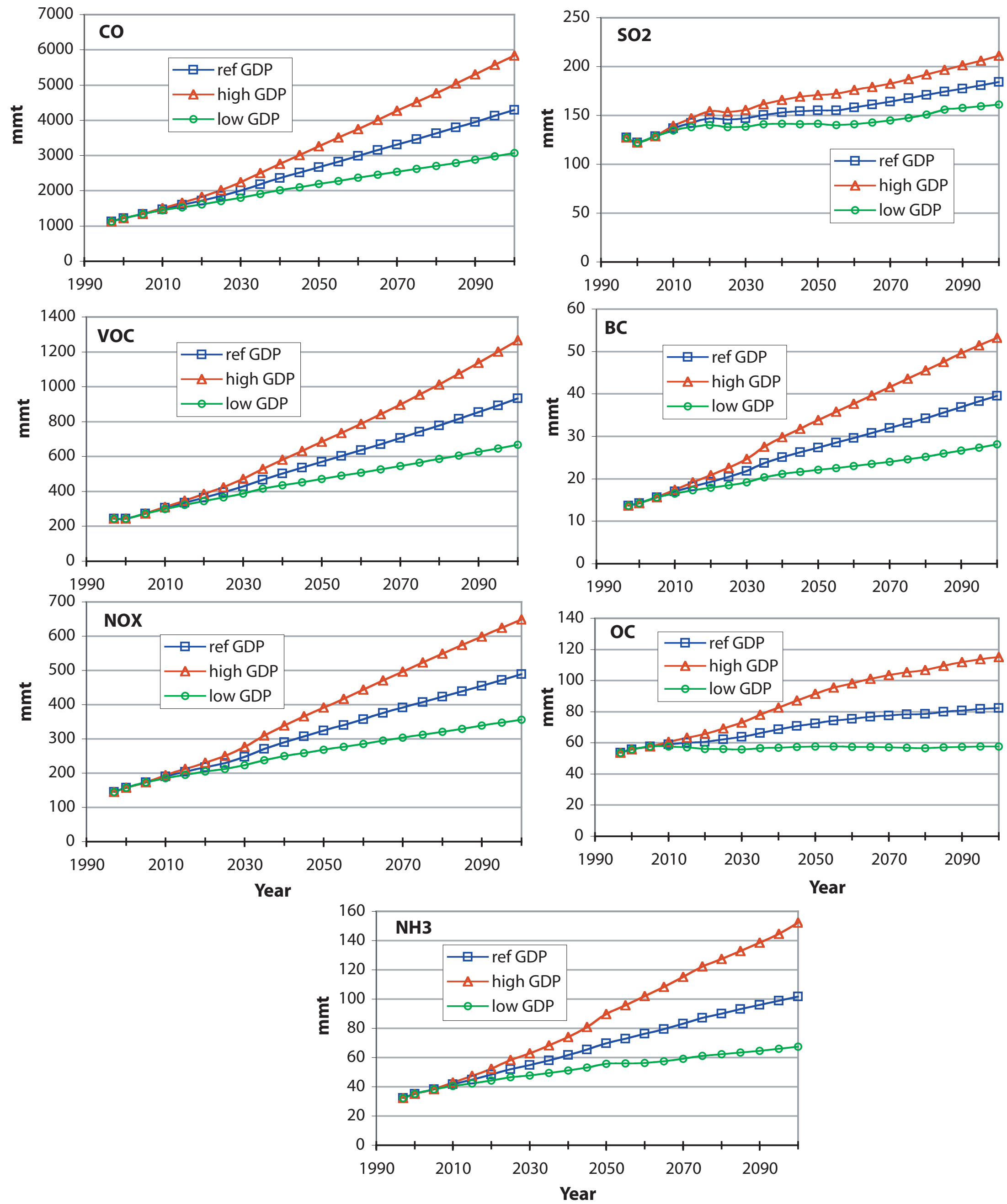

Figure 17. Emissions Projections for Criteria Pollutants.

these coefficients over time the cross-section data were augmented by information on best available practices. In most cases these revisions led to somewhat faster decline with income in the emissions coefficients. A higher GDP implies a more rapidly declining emissions factor.

These forecasts of criteria pollutants might imply violations of air quality standards in some regions (*e.g.*, US, Europe, Japan), and it can be argued that these air quality standards should be imposed in a reference forecast as an aspect of "business-as-usual." The variety and complexity of regulations, partial coverage of sources, and the fact that policies are often targeted at concentrations rather than emissions means that there is no ready translation of existing policies into specific caps on emissions from sources within countries. Moreover, given the increasing contribution of transboundary pollution sources, a country may find it unable to realistically meet its air pollution goals by limiting emissions of the domestic sources under its control. Our approach is thus to represent the existing "best available" technology rather than assume development of ever-cleaner combustion technology at no cost. Analysis of the impact on ecosystems and urban pollution of lower emissions of these substances is provided by Prinn *et al.* (2005) and Felzer *et al.* (2005).

8.2 Sample Policy Calculation

To demonstrate how the EPPA4 version performs when subjected to a policy scenario, we construct a calculation of atmospheric stabilization using the MIT Integrated Global System Model (Sokolov *et al.*, 2005) of which the EPPA model is a component. The assumption is stabilization at 4.7 W/m^2, which, taking account of the control of the non-CO_2 greenhouse gases is roughly equivalent to stabilization of CO_2 concentrations at 550 ppmv. Here we focus on the CO_2 results.

Such a calculation requires an assumption about burden sharing among the nations, and for purposes of illustrating the model function we make the highly stylized assumption that all nations and regions impose the same marginal price on carbon emissions beginning in 2010. The implication is that each region bears the economic burden of abatement that occurs in that region. The common price path that leads to atmospheric stabilization at 550 ppmv under reference EPPA conditions (and reference assumptions for other components of the IGSM) is shown in **Figure 18**. The initial price is $40 per tC, and it rises at a rate of 4% per year over the century, to reach a level of around $1500 per tC in 2100. The resulting path of global CO_2 emissions (stated in tC) is shown in **Figure 19**. From a 2010 level of 6.7 GtC the emissions rise to slightly over 9 GtC in 2040 but are reduced to around 6.5 GtC by the end of the simulation period.

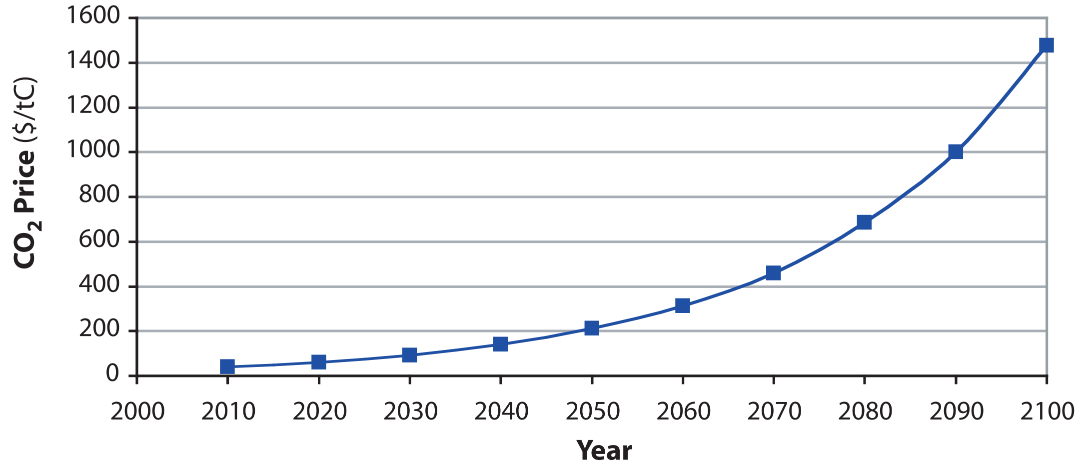

Figure 18. CO_2 Price in the 550 ppm Stabilization Scenario.

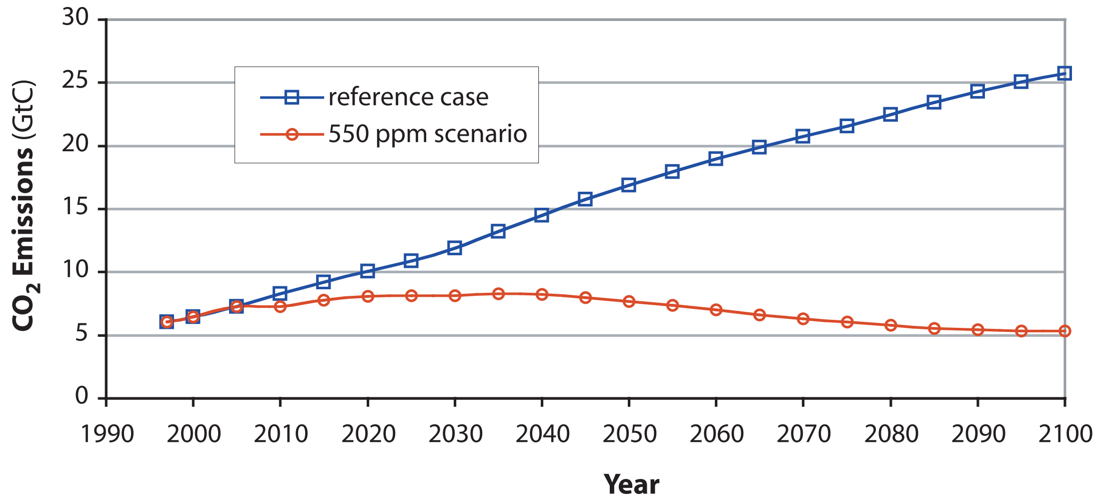

Figure 19. CO_2 Emissions in the Reference and 550 ppm Stabilization Scenarios.

Figure 20 displays the same fuel shares as Figure 13 as they are projected under the price pressures that would lead to 550 ppmv stabilization. Global primary energy production in 2100 is reduced from around 1300 EJ in the reference case to 950 EJ under the control case. Oil use is not much changed, because of the lack of a cost-effective substitute in the transport sector, but the magnitude of coal use is much reduced and shale oil never becomes a viable energy supplier. Though wind expands many-fold from present, it does not increase much in this control case relative to the reference. This reflects the modeling approach for including wind (described in Sections 3.2 and Section 5) that tends to limit the share of electricity that can be supplied by wind because of the intermittency of the resource. Biomass becomes a major source of primary energy. Again, nuclear is assumed not to grow substantially in this simulation.[10]

[10] As noted in Section 9, the reformulation of wind is a current development priority. Nuclear growth is seen as a combination economic/political issue and would be the subject of sensitivity testing in long-term policy assessments.

Figure 21 provides a similarly revised version of the electric production by energy type shown in Figure 14. Notable in this result is the growing role of carbon capture and storage over the century. By 2100 none of the coal in the electric sector (which is most of total coal use) is being burned without CO_2 capture. Gas use without capture grows in the early decades, largely through the expansion of NGCC technology, but is also driven out by the end of the century. The role of nuclear is limited by assumption, as noted earlier, and wind grows even more than in the reference but remains a minor contributor to total generation.

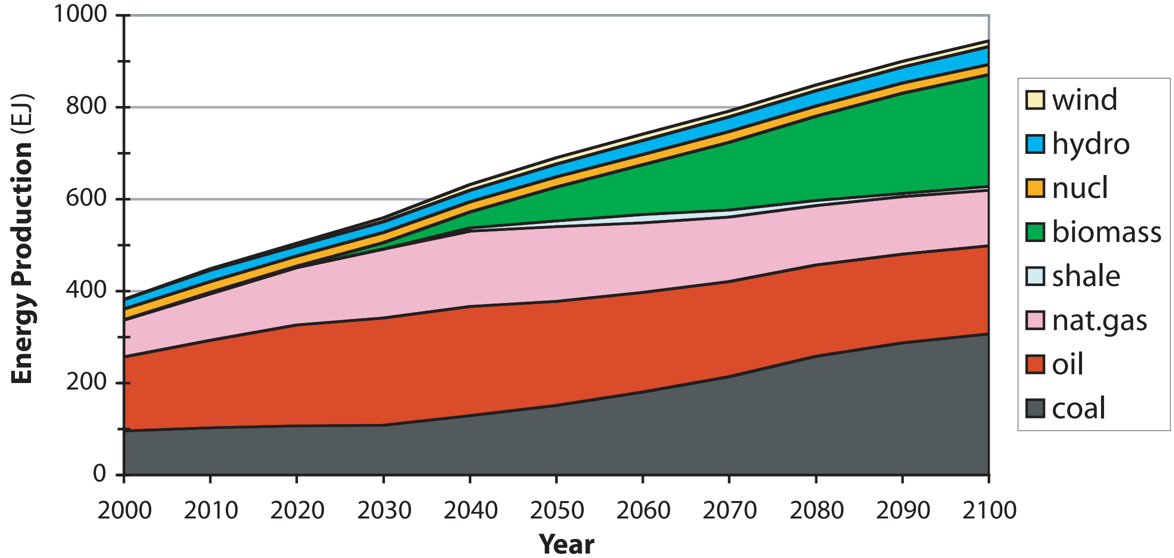

Figure 20. Global Primary Energy Production and Shares in the 550 ppm Stabilization Scenario.

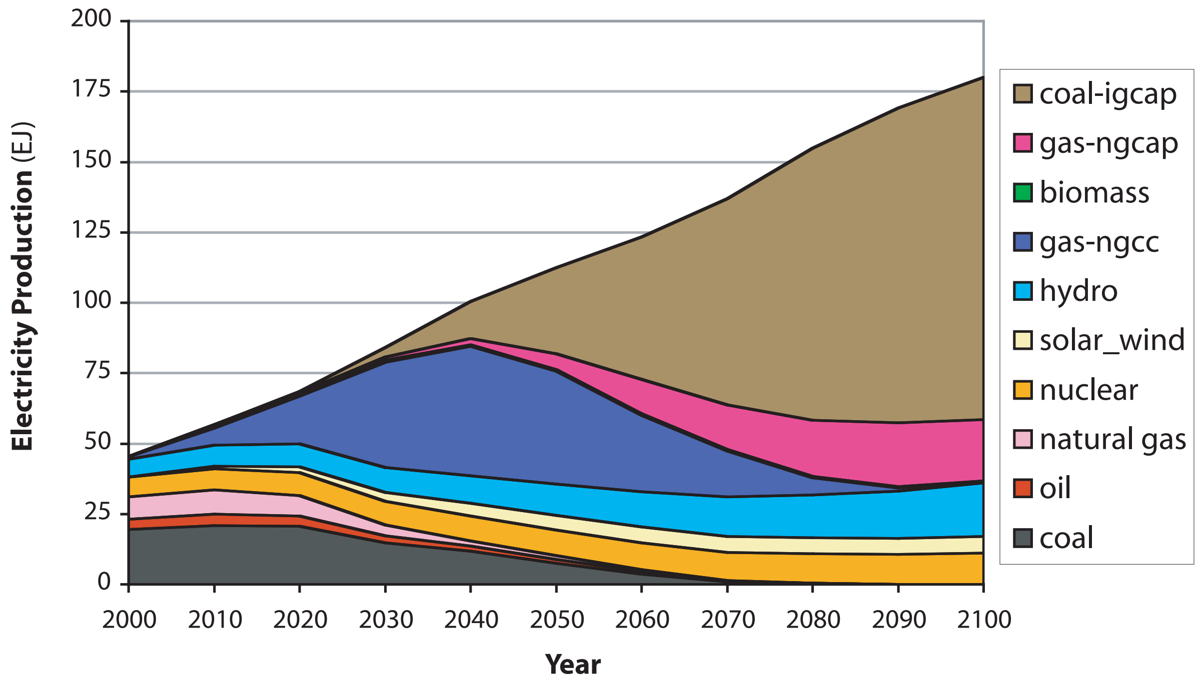

Figure 21. Electricity Production by Type in the 550 ppm Stabilization Scenario.

9. ONGOING MODEL DEVELOPMENT

Even while the EPPA model is being applied to studies of the climate threat, and assessment of policy proposals, effort continues to extend and improve the model. And continuous effort is required to keep its underlying data systems up to date, including implementation of Version 6 of the underlying GTAP data set, and to improve the estimates of key parameters. Within this general program of work a number of activities are under way or planned with regard to the structure of the model. Highlights include the following.

- **Forward-Looking Version**. A dynamic or forward-looking version of the model has been developed and is undergoing testing. Its structure is the same as that of the version described here except for the collapse of the EPPA4 vintaging structure to a putty-putty formulation and possibly a small reduction in the numbers of regions and sectors to reduce the dimensions of the model to a numerically tractable level.
- **Augmentation of Tax Data**. Labor and capital taxes have been improved in GTAP 6.0 and this will allow a more complete representation of national fiscal systems in the model. This extension will allow study of the government revenue effects of policies and improved analysis of the implications of an assumption that measures be revenue neutral. As implemented in the forward-looking version, this augmentation also will support improved analysis of the double-dividend issue.
- **Representation of Intermittent Sources**. An improved representation of intermittent sources (wind and solar) has been developed (Cheng, 2005) and will be implemented after further testing.
- **Evolution of Consumption Sector Shares**. As greater sector detail has been added to EPPA, there is more opportunity to reflect explicit sectoral changes in consumption as the economy grows. Work is underway to represent within EPPA recent work on how the composition changes with growth of per capita income.
- **Geographic Detail in Emissions Projections**. For inclusion in the IGSM system, geographic detail of the emissions of the chemically active species is needed in emissions projections, including latitude and longitude and the density of emissions in large urban areas. The conversion of emissions by the 16 regions in Table 1 is now handles by a post-processor. Building on research by Asadoorian (2005) this feature will be included within the EPPA structure.
- **Provision for Feedbacks and Linkage**. Experimental versions of the model have been developed in which the structure of the SAM and the various relations in the model have been modified to include feedbacks into the general equilibrium structure of the effects of emissions such as air pollution and health (Yang *et al.*, 2005) and the impacts of climate change on agriculture (Reilly *et al.*, 2004). In subsequent versions this extension will be included as a standard feature of the model.

As information is developed and new and likely more complex policy proposals are put forward to deal with the climate issue we will continue to improve and update the EPPA model to provide sound insights into the economics of the problem.

Acknowledgements

Thanks are due to many of our colleagues and students in the Joint Program. Their supportive comments and suggestions have greatly improved both the EPPA model and this document. This research was supported by the U.S Department of Energy, U.S. Environmental Protection Agency, U.S. National Science Foundation, U.S. National Aeronautics and Space Administration, U.S. National Oceanographic and Atmospheric Administration; and the Industry and Foundation Sponsors of the MIT Joint Program on the Science and Policy of Global Change: Alstom Power (France), American Electric Power (USA), BP p.l.c. (UK/USA), Chevron Corporation (USA), CONCAWE (Belgium), DaimlerChrysler AG (Germany), Duke Energy (USA), J-Power (Japan), Electric Power Research Institute (USA), Electricité de France, ExxonMobil Corporation (USA), Ford Motor Company (USA), General Motors (USA), Murphy Oil Corporation (USA), Oglethorpe Power Corporation (USA), RWE Power (Germany), Shell Petroleum (Netherlands/UK), Southern Company (USA), Statoil ASA (Norway), Tennessee Valley Authority (USA), Tokyo Electric Power Company (Japan), Total (France), G. Unger Vetlesen Foundation (USA).

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APPENDIX 1: MAPPING OF GTAP DATA TO EPPA FORMAT

```
set mapi Mapping for sectors and goods /
PDR.agri paddy rice
WHT.agri wheat
GRO.agri cereal grains nec
V_F.agri vegetables - fruit - nuts
OSD.agri oil seeds
C_B.agri sugar cane - sugar beet
PFB.agri plant-based fibers
OCR.agri crops nec
CTL.agri bo horses
OAP.agri animal products nec
RMK.agri raw milk
WOL.agri wool - silk-worm cocoons
FRS.agri forestry
FSH.agri fishing
COL.coal coal
OIL.oil oil
GAS.gas gas
OMN.othr minerals nec
CMT.othr bo meat products
OMT.othr meat products
VOL.othr vegetable oils and fats
MIL.othr dairy products
PCR.othr processed rice
SGR.othr sugar
OFD.othr food products nec
B_T.othr beverages and tobacco products
TEX.othr textiles
WAP.othr wearing apparel
LEA.othr leather products
LUM.othr wood products
PPP.eint paper products - publishing
P_C.roil petroleum - coal products
CRP.eint chemical - rubber - plastic products
NMM.eint mineral products nec
I_S.eint ferrous metals
NFM.eint metals nec
FMP.eint metal products
MVH.othr motor vehicles and parts
OTN.othr transport equipment nec
ELE.othr electronic equipment
OME.othr machinery and equipment nec
OMF.othr manufactures nec
ELY.elec electricity
GDT.gas gas manufacture - distribution
WTR.othr water
CNS.othr construction
TRD.serv trade
OTP.tran transport nec
WTP.tran water transport
ATP.tran air transport
CMN.serv communication
OFI.serv financial services nec
ISR.serv insurance
OBS.serv business services nec
ROS.serv recreational and other services
OSG.serv public admin - and defence - education - health
DWE.othr ownership of dwellings
CGD.cgd   Savings good /;
```

```
SET MAPR mapping GTAP regions /
AUS.anz Australia
NZL.anz New Zealand
CHN.chn China
HKG.chn Hong Kong
JPN.jpn Japan
KOR.asi Korea - Republic of
TWN.asi Taiwan - Province of China
IDN.idz Indonesia
MYS.asi Malaysia
PHL.asi Philippines
SGP.asi Singapore
THA.asi Thailand
VNM.row Viet Nam
BGD.row Bangladesh
IND.ind India
LKA.row Sri Lanka
XSA.row rest of South Asia
CAN.can Canada
USA.usa United States
MEX.mex Mexico
XCM.lam Central America and Caribbean
COL.lam Colombia
PER.lam Peru
VEN.lam Venezuela
XAP.lam rest of Andean Pact
ARG.lam Argentina
BRA.lam Brazil
CHL.lam Chile
URY.lam Uruguay
XSM.lam rest of South America
AUT.eur Austria
DNK.eur Denmark
FIN.eur Finland
FRA.eur France
DEU.eur Germany
GBR.eur United Kingdom
GRC.eur Greece
IRL.eur Ireland
ITA.eur Italy
NLD.eur Netherlands
PRT.eur Portugal
ESP.eur Spain
SWE.eur Sweden
BEL.eur Belgium
LUX.eur Luxembourg
CHE.eur Switzerland
XEF.eur rest of EFTA
HUN.eet Hungary
POL.eet Poland
XCE.eet rest of Central European associates
XSU.fsu former Soviet Union
TUR.row Turkey
XME.mes rest of Middle East
MAR.afr Morocco
XNF.afr rest of North Africa
BWA.afr Botswana
XSC.afr rest of SACU
MWI.afr Malawi
MOZ.afr Mozambique
TZA.afr Tanzania - United Republic of
ZMB.afr Zambia
ZWE.afr Zimbabwe
XSF.afr rest of southern Africa
UGA.afr Uganda
XSS.afr rest of sub-Saharan Africa
XRW.row rest of world /;
```

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