MIT Joint Program on the Science and Policy of Global Change

The MIT Emissions Prediction and Policy Analysis (EPPA) Model: *Revisions, Sensitivities, and Comparisons of Results*

Mustafa H. Babiker, John M. Reilly, Monika Mayer, Richard S. Eckaus, Ian Sue Wing and Robert C. Hyman

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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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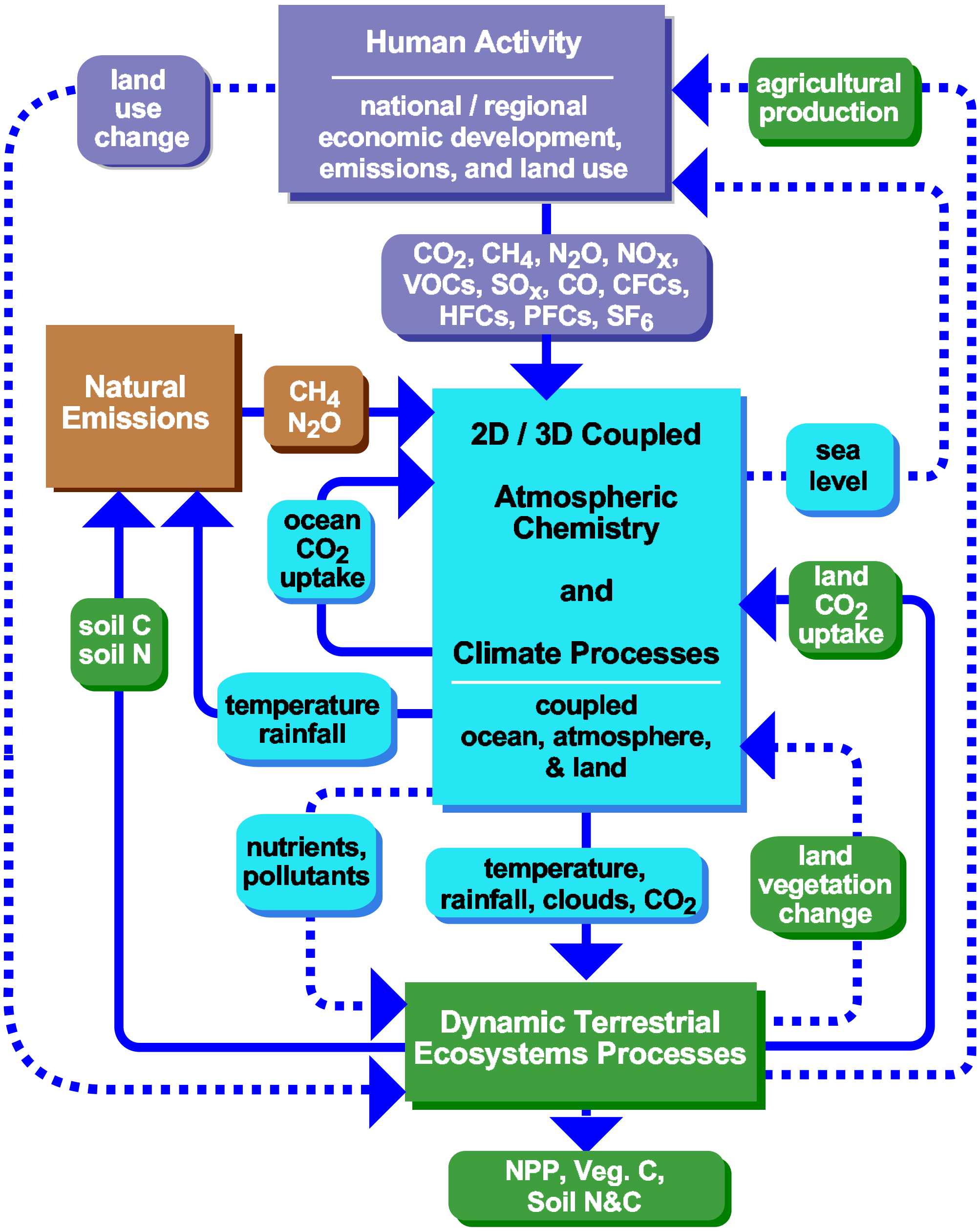
1 The EPPA Model: Overview

The Emissions Prediction and Policy Analysis (EPPA) model is a component of the Integrated Global Simulation Model (IGSM) of the Joint Program on the Science and Policy of Global Change (Figure 1, Prinn, Jacoby, Sokolov, Wang, Xiao, Yang, Eckaus, Stone, Ellerman, Melillo, Fitzmaurice, Kicklighter, Holian and Liu (1999)). EPPA simulates the world economy through time with the objective of producing scenarios of greenhouse gases (GHGs) and their precursors, emitted as a result of human activities. These emissions scenarios are used as inputs into a coupled atmospheric chemistry-climate model along with scenarios of natural emissions of GHGs from a Natural Emissions Model (Prinn et al., 1999), to produce scenarios of climate change induced by GHGs. The requirements of the IGSM dictate a number of the features of EPPA. These include 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)), aerosols (from sulfates (SO_x), black carbon and organic carbon), and other climatically important substances (nitrogen oxides (NO_x), carbon monoxide (CO), ammonia (NH_3) and non-methane volatile organic compounds (NMVOCs)); 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, the uncertainty in forecasts of future climate change, the effects on future climate of proposed GHG emissions policies, and the validity of Global Warming Potential (GWP) indices as currently prescribed under the Kyoto Protocol (see Reilly, Prinn, Harnisch, Fitzmaurice, Jacoby, Kicklighter, Stone, Sokolov and Wang, 1999; Prinn et al., 1999).

The EPPA model is also designed to evaluate the economic impacts of policies designed to limit GHG emissions. Questions of interest include the distribution of economic impacts across different countries, the effects of policies on compliance costs (for example, with or without emissions trading or with participation of different groups of countries), or how other economic policies (for example, limiting or subsidizing nuclear power; or changing taxes or subsidies on fossil fuels) affect the cost of measures for GHG control. Applications to some of these issues with the version of EPPA described here can be found in Babiker and Jacoby (1999) and Babiker, Reilly and Ellerman (1999). Previous versions of EPPA have been used to evaluate the interaction of climate policies and other economic policies (Jacoby, Eckaus, Ellerman, Prinn, Reiner and Yang, 1997), uncertainty (Webster, 1997), the implications of assumptions about malleability of capital (Jacoby and Sue Wing, 1999), and the cost implications of controlling multiple trace gases (Reilly et al., 1999). For many of

Figure 1: MIT Integrated Global Simulation Model



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

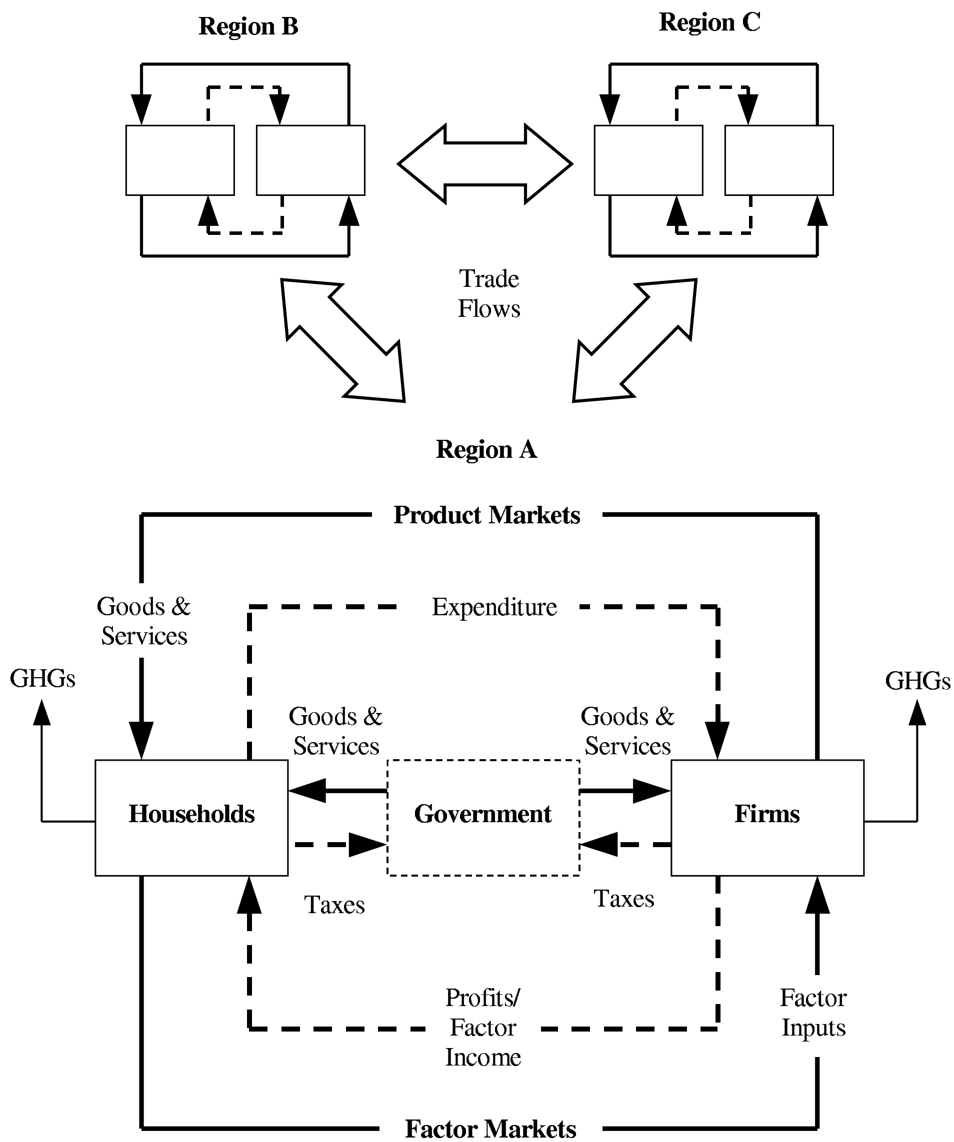
The assessment of the costs, equity implications, and welfare impacts of different policies, especially under alternative technological assumptions, requires specific features in EPPA. A general requirement is a comprehensive economic foundation for the model so that meaningful and complete estimates of costs can be made. There must also be regional disaggregation to include specific countries and regional blocs, and explicit representation of critical sectors (particularly energy resource and supply sectors) with technological alternatives. Inevitably data availability, the need to focus on parameters for which there is an empirical basis, and the need for computational efficiency each place 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.

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 shown in Figure 2. One can start with the supply of factor inputs (labor and capital services) to the producing sectors of the economy and continue to the supply of goods and services from the producing sectors to final consumers (households), who in turn control the supply of capital and labor services. One can also trace this circular flow in terms 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 transactions. Much of the gross production of some industries is used as intermediate inputs in other industries. The government is modelled 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.

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 the value of their rentals to producers, accrue to households as income. The value of these assets, thus, reflects the annual flow of returns to the economy.

Figure 2: Trade Among Circular Flow Economies in EPPA



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 1995. SAMs are developed from systems of national accounts and the input-output tables that quantify the interindustry flows of goods and services (Pyatt and Round, eds, 1985; Drud and Pyatt, 1986). 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 GHG 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 modelled as if there were a representative consumer maximizing utility by the choice among goods. A fundamental feature of EPPA's modelling 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 GHGs, especially carbon. If a carbon restriction increases the price of carbon-based fuels, the cost of production will not rise much for an industry that can easily substitute other inputs for energy—the industry will simply use other inputs in its place. Similarly, if consumers are able to shift easily from the use of energy, their economic well-being (technically, economic welfare measured by equivalent variation) will be affected only slightly. 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 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. Here the model employs a convention that is widely used in modelling international trade, the Armington assumption (Armington, 1969). Under this convention a domestically produced good is treated as different commodity from an imported good in 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 GHGs in response to climate policy. A carbon constraint placed on a subset of countries (for example, the OECD 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. The extent to which reduction in domestic GHG emissions is supplanted by higher emissions abroad is part of the so-called carbon leakage. Other features in EPPA also affect leakage such as effects on income abroad of changes in import and export demand and the effect on international energy prices.

Another important aspect of CGE models is the degree to which they capture the dynamics of the economy through time. The key behavioral aspect of CGE models in this respect is their representation of savings-investment decisions. In this regard, EPPA falls into a class of models known as recursive dynamic. The basic nature of the recursive dynamic approach is that savings and investment in the current period are based only on current period variables, as opposed to a forward-looking intertemporal optimization model (e.g. Ramsey, 1928; Cass, 1965; Koopmans, 1965). 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. There is an exogenous augmentation of the supplies of labor and natural resources. Also, energy use per 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 improvements in technology that create a progressively energy-saving bias of technical change. Also included in EPPA are energy alternatives (the so-called "backstop" technologies) that are currently unused, but which come into play as supplies of conventional energy resources deplete and their prices rise. These include carbon-free electric power generation that represents advanced nuclear or solar power technologies, shale oil production and coal gasification. It is assumed that these technologies remain uneconomical in the first few decades of the model's simulation horizon. However, they become available at future dates, in quantities that depend on their costs relative to those of current fuels, as endogenously determined within EPPA.

CGE models when solved maximize consumers' welfare and producers' profits subject to the technologies of production and consumption, consumers' endowments of primary factors and natural resources (capital, labor, and 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, and fixed factor in each period result in a shadow value of capital, wage rate, and return to the fixed factor. 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 taxes is treated like other taxes and their full value is transferred to the representative agent.

The shadow price or tax on each physical unit of GHG emissions is a critical indicator of the cost of a control policy. 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; Ellerman, Jacoby and Decaux, 1998; Ellerman and Sue Wing, 2000).

In addition to calculating the shadow price of carbon, CGE models also facilitate the computation of measures of the total costs 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, preferred by economists, 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. 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 (economy-wide and by industry) and the terms of trade.

We describe, herein, the standard version of EPPA. The SAM data set underlying the current version of EPPA provides considerable flexibility to disaggregate the model into different sectoral or regional groupings. In one particular modelling application (Babiker and Jacoby, 1999) a version of the model with 25 regional groupings was created in order to examine in detail the economic impacts of the Kyoto Protocol on developing economies. However, here we describe EPPA at its "reference" level of sectoral and regional detail and the reference values of its parameters. In general, we recognize that these values are uncertain (especially across regions and through time) and we consider these uncertainties in applications of the model.

2 EPPA 3.0 Equilibrium Structure and Parameters

EPPA was originally based on the OECD General Equilibrium Environment (GREEN) model (Burniaux, Nicoletti and Oliveira-Martins, 1992). The current version of EPPA is a fundamental revision of that model, both in its theoretical design and its data base. The basic income and product data come from a comprehensive energy-economy dataset (GTAP-E) that accommodates a consistent representation of energy markets in physical units in addition to detailed accounts of regional production and bilateral trade flows in economic values.[1] The model is calibrated on this dataset to generate a benchmark equilibrium in 1995 as a base year, and is then solved for a sequence of static equilibria through 2100 in five-year time steps.

The dataset for EPPA 3.0 aggregates the GTAP/IEA v.4 dataset, which covers 45 countries/regions, 50 economic sectors and five factors of production, into 12 regions, eight sectors and three factors. The regional, sectoral, and factor aggregation shown in Table 1, together with the substitution elasticities in Table 2 completely specify the benchmark equilibrium.

2.1 Equilibrium Structure

EPPA is formulated and solved as a mixed complementarity problem (MCP) using MPSGE, the Mathematical Programming Subsystem for General Equilibrium (Rutherford, 1995; Rutherford, 1999) within the Generalized Algebraic Modelling System (GAMS) mathematical modelling language (Brooke, Kendrick and Meeraus, 1996). In their simplest form, the key optimizing behavior and equilibrium conditions in EPPA may be summarized as follows.

Firms

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

$$\max_{y_{ri},x_{rji},k_{rfi}} \pi_{ri} = p_{ri}y_{ri} - C_{ri}(p_{rj}, w_{rf}, y_{ri}) \quad \text{s.t.} \quad y_{ri} = \varphi_{ri}(x_{rji}, k_{rfi}) \tag{1}$$

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

[1] This special database is provided by the Global Trade Analysis Project (GTAP) along with release 4 of their economy-trade database. The particular version of the integrated dataset used for EPPA was developed by Rutherford and Babiker (1998). For further information on GTAP see McDougall, Elbehri and Truong (1998).

Table 1: Dimensions of EPPA 3.0

Production sectors		Countries and regions	
Non-Energy		Annex B	
AGRIC	Agriculture[a]	USA	United States
ENERINT	Energy-intensive industries[b]	JPN	Japan
OTHERIND	Other industries and services[c]	EEC	Europe[d]
Energy		OOE	Other OECD[e]
OIL	Crude oil including tar sands	FSU	Former Soviet Union
GAS	Natural gas	EET	Central European Associates
REFOIL	Refined oil	Non-Annex B	
COAL	Coal	CHN	China
ELEC	Electricity	IND	India
Future Energy Supplies		EEX	Energy Exporting LDCs[f]
Shale oil	OIL equivalent	BRA	Brazil
Coal Gas	GAS equivalent	DAE	Dynamic Asian Economies[g]
Carbon-free electric	Renewables	ROW	Rest of the World[h]
Primary Factors			
Labor			
Capital			
Fixed factor resources for coal, oil, gas, shale oil, and agriculture			

[a]Includes paddy rice; wheat; grains other than rice and wheat; vegetables, fruit, nuts; oil seeds; sugar cane and beet; plant-based fibers; crops n.e.c.; bovine cattle (sheep and goats, horses); animal products n.e.c.; raw milk; wool; forestry; fishing; bovine cattle meat products; meat products n.e.c.; vegetable oils; dairy products; processed rice; sugar; other food products; beverages and tobacco.

[b]Includes pulp and paper; chemicals rubber and plastics; non-metallic mineral products; primary ferrous metals; non-ferrous metals.

[c]Includes other minerals; textiles; wearing apparel; leather goods; lumber and wood; fabricated metal products; motor vehicles; other transport equipment; electronic equipment; machinery and equipment; other manufacturing products; gas manufacturing and distribution; water; construction; trade and transport; other services (private); other services (public); dwellings.

[d]The 15 nations of the European Union as of 1995.

[e]Australia, New Zealand, Canada, Turkey, and the European Free Trade Area (Norway, Iceland, Switzerland).

[f]Middle East, Mexico, Venezuela, Indonesia, Andean Pact countries (Colombia, Peru, Ecuador, Bolivia) and, because of the regional aggregation of the GTAP 4 database, most of Africa except Morocco and South Africa are included in ROW.

[g]South Korea, Philippines, Thailand and Singapore.

[h]All countries and regions not elsewhere classified, including South Africa, Morocco, and much of Latin America and Asia.

Table 2: Default Values of Key Substitution Elasticities

	Description	Value	Comments
σ_{EVRA}	Substitution between energy resource composite and value-added	0.6	AGRIC only
σ_{NGR}	Substitution between nuclear resource and value-added	0.04-0.4	Nuclear electric sector, calibrated to match an exogenous elasticity of supply (see Section 3.4)
σ_{ER}	Substitution between energy-material bundle and the resource (land)	0.6	
σ_{AE}	Substitution between Armington material composite and energy	0.3	
σ_{VA}	Substitution between labor and capital	1.0	All sectors except nuclear
σ_{NVA}	Substitution between labor and capital	0.5	Nuclear electric sector only
σ_{ENOE}	Substitution between electric and non-electric energy	0.5	All sectors
σ_{EN}	Substitution among non-electric energy sources	1.0	All sectors except ELEC
σ_{CO}	Substitution between COAL- and OIL-fired electricity generation	0.3	ELEC only
σ_{COG}	Substitution between COAL-OIL aggregate and GAS-fired electricity generation	1.0	
σ_{GR}	Substitution between sectoral gross output and natural resources	0.6	All sectors with benchmark fixed factor (except nuclear generation), calibrated to match an exogenous elasticity of supply (see Section 3.4)
σ_{EVA}	Substitution between energy and value added composite	0.4	All sectors except ENERINT and OTHERIND, where it is 0.5
σ_{DM}	Armington substitution between domestic and imported goods	3.0	All goods except ELEC, where it is 0.3
σ_{MM}	Armington substitution among imports	5.0	Non-energy goods
		4.0	Energy goods, except refined oil, where it is 6.0, and electricity, where it is 0.5
σ_{CS}	Temporal substitution between consumption and saving	1.0	Final demand sector
σ_{C}	Substitution across consumption goods	–	A function of the income level in each region, reflecting econometric estimates of income elasticities for the different goods in the model (see Section 3.6)

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 problem in (1). First, the linear homogeneity of the cost function implied by duality theory enables us to re-express (1) 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:

$$p_{ri} = c_{ri}(p_{rj}, w_{rf}) \tag{2}$$

where c is the unit cost function.[2]

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

$$x_{rji} = y_{ri}\frac{\partial c_{ri}}{\partial p_{rj}} \tag{3}$$

and the demand for factor f is

$$k_{rfi} = y_{ri}\frac{\partial c_{ri}}{\partial w_{rf}} \tag{4}$$

Households

In each region, a representative agent is endowed with the supplies of the five 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:

$$\max_{d_{ri}, s_r} W_{ri}(d_{ri}, s_r) \quad \text{s.t.} \quad M_r = \sum_f w_{rf}K_{rf} = p_{rs}s_r + \sum_i p_{ri}d_{ri} \tag{5}$$

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 (5), given by:

$$p_{rw} = E_r(p_{ri}, p_{rs}) \tag{6}$$

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

$$d_{ri} = \bar{m}_r\frac{\partial E_r}{\partial p_{ri}} \tag{7}$$

[2] Note that CRTS also implies that marginal cost equals average cost.

and that for savings is

$$s_r = \bar{m}_r \frac{\partial E_r}{\partial p_{rs}} \tag{8}$$

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

Market clearance and equilibrium prices

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:

$$y_{ri} = \sum_j y_{rj} \frac{\partial C_{rj}}{\partial p_{ri}} + \bar{m}_r \frac{\partial E_r}{\partial p_{ri}} \tag{9}$$

and

$$K_{rf} = \sum_j y_{rj} \frac{\partial C_{rj}}{\partial w_{rf}} \tag{10}$$

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

2.2 The Structure of Final Demand and Savings

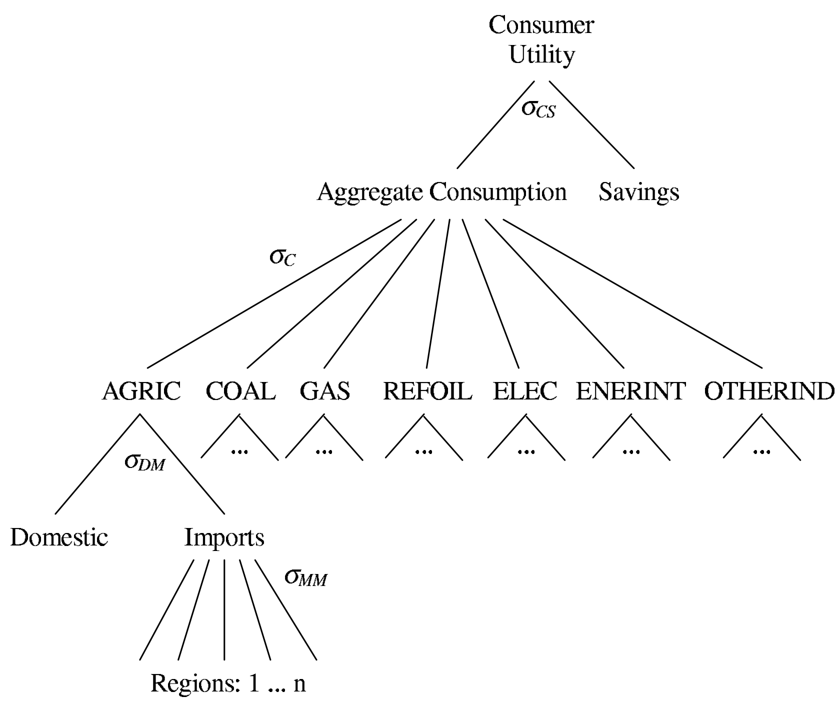
One characteristic that distinguishes EPPA 3.0 from the OECD GREEN model is the structure of consumer demand. Previous EPPA versions, following GREEN, aggregated the Armington output of each of the eight sectors into four consumption bundles (Food & Beverages, Energy, Transport & Communications, and Other Goods & Services) via a Leontief transformation matrix. These four consumption bundles were then combined to generate the utility good.

EPPA 3.0, by contrast, uses a nested CES structure to describe preferences. As illustrated in Figure 3, the nesting structure aggregates all Armington goods into a single consumption good, which is then aggregated together with savings to determine the level of consumer utility. The substitution elasticities are reported in Table 2. This specification of consumption alleviates the need to model the representative agent as saving a fixed share of income each period, that is unresponsive to prices in equilibrium. In EPPA 3.0, savings enters directly into the utility function, which generates the demand for savings and makes the consumption-investment decision endogenous.

2.3 The Structure of Production

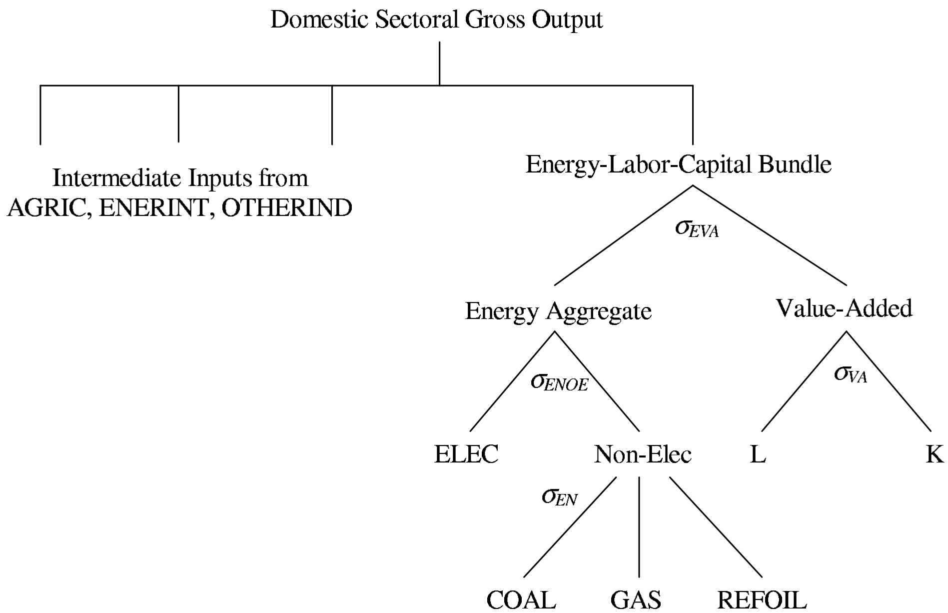
Previous versions of EPPA followed OECD GREEN in modelling the production structure as being identical across sectors. In EPPA 3.0 the production structures differ across industries,

Figure 3: Structure of Household Demand*



* There is a structure for each good identical to that which is represented explicitly for the Agriculture sector. This is represented in the diagram by "...".

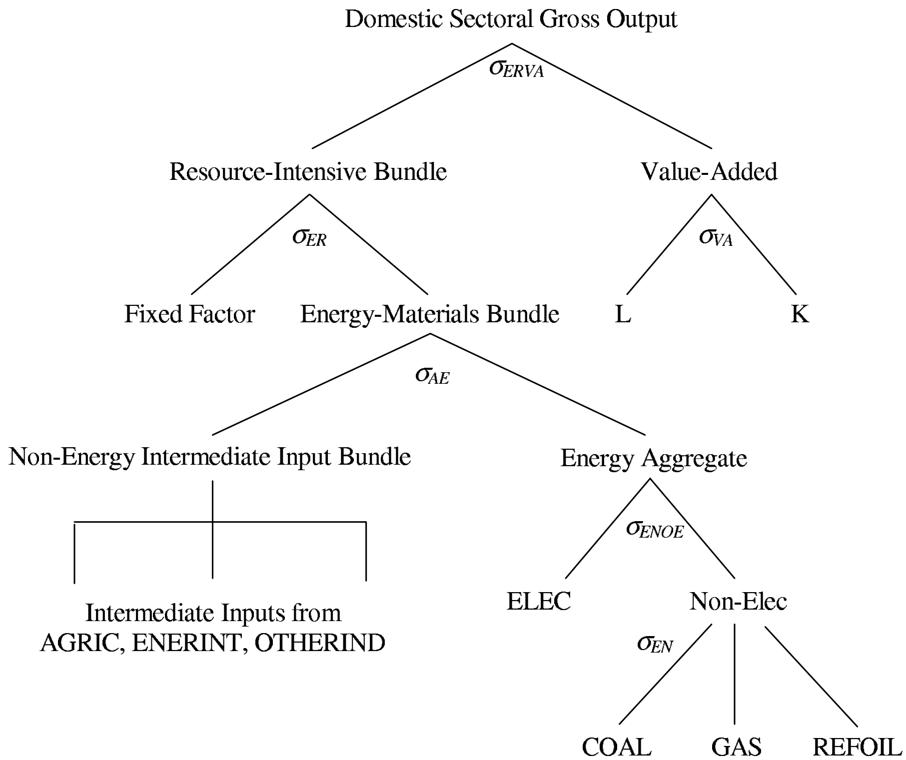
Figure 4: Structure of Production in ENERINT and OTHERIND



according to sectoral variations in the way in which inputs are aggregated. Production technologies are described using nested CES functions. The elasticities reported in Table 2 are *long-run* values, derived from Burniaux et al. (1992), Nainar (1989), Nguyen (1987), Pindyck (1979) and expert elicitations. A "bottom-up" engineering approach, based on expert elicitations, was used to formulate aggregation structures which reflect key tradeoffs among the inputs to each sector. These structures are described below.

In the energy intensive sector (ENERINT) and other industries and services (OTHERIND), which comprise the bulk of output for most economies, the production of gross output requires intermediate inputs of non-energy Armington goods as determined by a fixed coefficients and a labor-capital-energy bundle (Figure 4). In this and other diagrams, the connection of entities using slanted lines (e.g. within the value-added or energy aggregates) represents the relationship between output and the inputs of Cobb-Douglas or CES production functions that exhibit positive elasticities of substitution. The connection of entities using vertical and horizontal lines (e.g. the production structure that aggregates intermediate goods and energy-labor-capital bundle) represents the relationship between output and the inputs in a fixed coefficient (Leontief) production function whose elasticity of substitution is zero. The energy-labor-capital bundle is composed of an aggregate of Armington energy inputs and a composite of labor and capital, i.e. value-added. In this structure the elasticity σ_{EVA} controls the substitution of aggregate energy for non-energy aggregate value-

Figure 5: Production Structure in Agriculture



added, the elasticity σ_{ENOE} controls the substitution of electricity energy for non-electric energy commodities, and the elasticity σ_{EN} controls substitution among the latter fuels. The energy-related substitution elasticities are important, as these parameters exert the most direct influence on the cost of carbon control policies.

In all sectors of the model intermediate goods as well as inputs of coal, oil, gas and refined oil are Armington aggregates of domestic and imported commodities. Imported goods in each commodity category are themselves Armington aggregates of the output of that industry in each of the EPPA regions.

The structure of the agriculture sector (Figure 5), which forms a large share of developing economies such as India and China, reflects the role played by natural resources (in this case arable land) in the production of output. At the top level of the nesting structure there is a resource-intensive bundle made up of a fixed factor that represents land, and an energy-intensive materials bundle. This structure represents an often-used disaggregation in agriculture between output per unit of land and output per unit of capital and labor.

The fuel supply sectors in EPPA (coal, oil and natural gas) share a number of characteristics of the energy intensive and other industry sectors. As shown in Figure 6, the

Figure 6: Production Structure in Primary Energy Sectors (COAL, OIL, GAS)

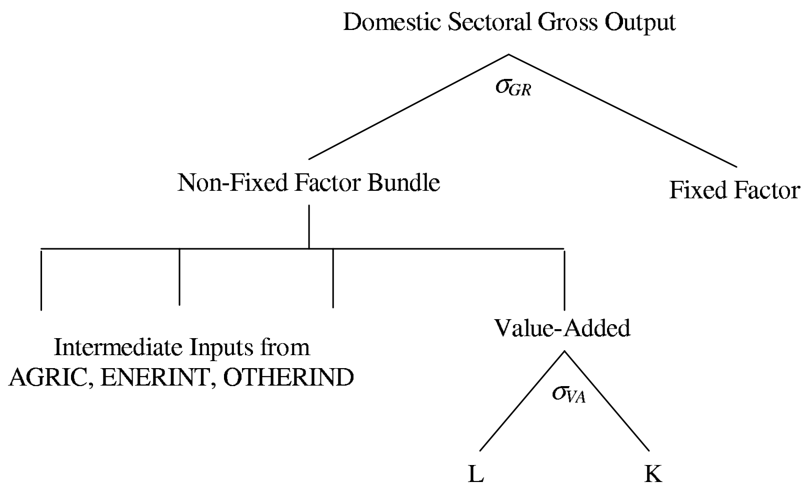


Figure 7: Production Structure in Oil Refining Sector

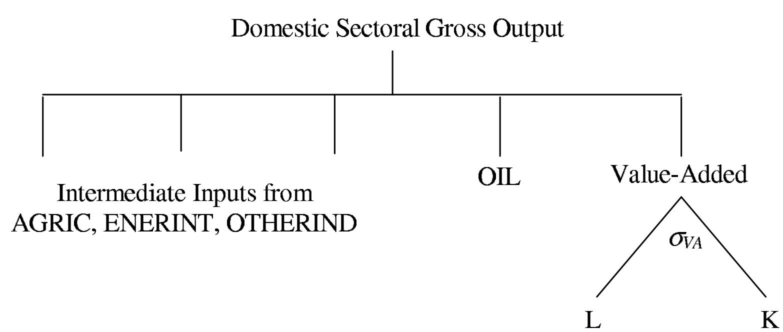
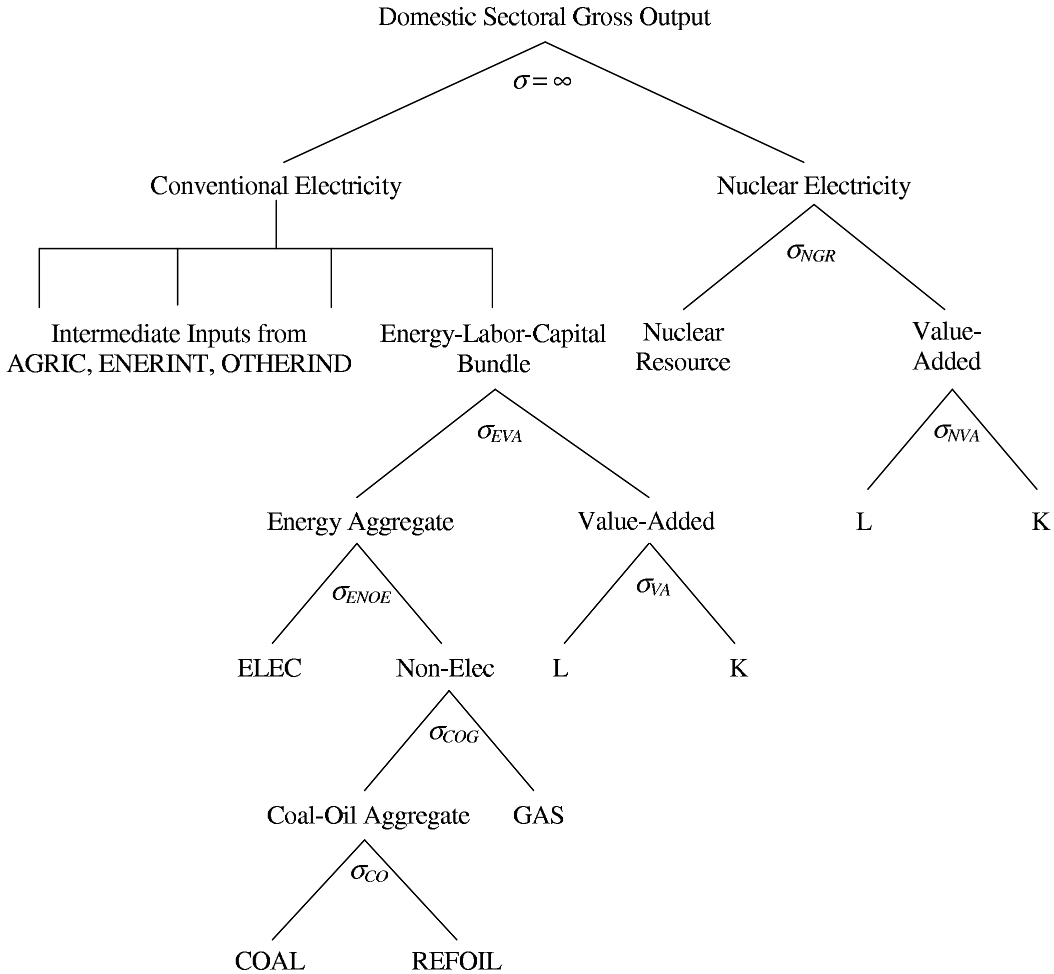


Figure 8: Production Structure in the Electric Sector



fixed factor is at the top level of the nesting structure, so that natural resource supplies and the substitution elasticity σ_{GR} constrain the rate of production—as expected in extractive industries. Also similar to ENERINT and OTHERIND there is no substitution among intermediate inputs, and the structure of substitution among electric and non-electric energy inputs is the same. The refining sector differs in that the input of crude oil enters into production in a fixed relationship with value added and non-energy intermediate goods. This formulation ensures that the crude energy good OIL is a necessary input to the manufacture of refined energy products, thus preventing economic substitution from violating the laws of thermodynamics.

In order to more accurately model the impact of carbon emission restrictions on the electric power sector, EPPA 3.0 contains separate representations of conventional and nuclear generation. The conventional component is an aggregate of fossil fuel-fired and hydro-

Table 3: Conventional vs. Nuclear Generation Electric Sector (Billion 1996 US $)

	Percent Nuclear	Weighted Average Cost Breakdown[a]								Coal/ Nuclear Ratio[b]
		Coal				Nuclear				
		Capital	O&M	Fuel	Total	Capital	O&M	Fuel	Total	
USA	20.1	11.9	5.1	7.9	24.9	18.2	8.9	6.2	33.3	0.75
JPN	29.7	24.0	12.5	19.4	55.8	24.9	16.8	15.7	57.5	0.97
EEC	35.1	13.3	7.9	21.4	42.5	19.8	7.5	9.4	36.6	1.16
OOE	20.1	11.2	7.7	19.6	38.4	19.8	7.9	4.7	32.4	1.19
EEX[c]	2.0	18.9	3.4	21.1	43.4	31.3	5.5	7.9	44.7	0.97
CHN	1.3	8.5	5.5	17.8	31.8	15.0	6.5	6.1	27.6	1.15
FSU	14.1	12.6	7.7	26.0	46.3	18.9	4.5	3.6	26.9	1.72
IND	1.7	8.8	4.3	22.1	35.1	19.2	6.1	7.6	32.8	1.07
EET	14.1	11.9	7.4	17.3	36.6	15.8	11.5	4.6	31.8	1.15
DAE	11.1	11.4	8.2	14.9	34.4	16.8	9.6	4.3	30.7	1.12
BRA	0.9	14.2	3.3	28.4	45.9	19.6	7.5	7.9	35.0	1.31
ROW	1.0	–	–	–	–	–	–	–	–	–

[a]Source: (OECD/NEA-IEA, 1998).
[b]Ratio of kWh produced by coal fired generation to kWh produced by nuclear generation in 1996.
[c]No EEX Countries Reported cost data for the 1998 Study. Values shown are in 1987 US $.

powered generation. The electric sector in the GTAP dataset is an aggregate of all types of power generation, so that these generation components had to be disaggregated using information from other sources. OECD data on the relative intensities of capital, labor and fuel inputs to conventional and nuclear electric power by region (OECD/NEA-IEA, 1998, shown in Table 3) was used for this purpose. The resulting partition of input flows between fossil-fired and nuclear electric output is shown in Table 4. The nesting structure of nuclear technology admits nuclear fuel as a fixed-factor resource input at the top level, together with an aggregate of labor and capital, with the elasticity of substitution calibrated to match assumed regional elasticities of supply (2.0 for Japan and 1.0 for other regions producing nuclear power). We assume an elasticity of substitution of 0.5 between labor and capital in the value-added branch of the nesting structure. The maximum rate of growth in the nuclear fuel resource supply is exogenously set at 0.5 percent per annum across regions, and is used to constrain the expansion of nuclear power. The exogenous trajectory of the resource is used as a proxy for the effect of regulatory policies that restrict the operation of the nuclear power sector: for instance, a moratorium on construction or a phaseout of nuclear power can be represented by a zero or negative growth rate of the fixed factor (Babiker et al., 1999).

Table 4: Benchmark Input-Output Data for Nuclear Electric Generation (Billion 1996 US $)

	Capital	**Labor**	**Fuel**	**Output**
USA	21.6	11.4	5.6	0.201
JPN	21.4	8.7	13.2	0.297
EEC	17.1	6.2	9.1	0.351
OOE	17.9	4.7	5.3	0.201
FSU	13.2	4.9	4.8	0.141
EET	13.2	4.9	4.8	0.141
DAE	29.8	5.4	8.0	0.111

2.4 Trade

Except for the representation of trade in the GAS sector, we maintain the same trade structure as previous EPPA versions. Given the considerable transportation costs involved in trade in coal, gas and refined oil, we treat these energy products as Armington goods. All goods in the model except electricity are traded in world markets. Crude oil is imported and exported as a homogeneous product, subject to tariffs and export taxes. All other goods, including energy products such as coal and natural gas, are characterized by product differentiation with an explicit representation of bilateral trade flows calibrated to the base year, 1995. Bilateral trade flows involve export taxes, import tariffs, and international transport margins, all of which are explicitly represented in the model.

3 The Dynamic Process of EPPA 3.0

There are six particularly critical features of EPPA 3.0 that govern the evolution of the economy and its energy-using characteristics over time. These are the rate of capital accumulation, population and labor force growth, changes in the productivity of labor and energy, structural change in consumption, fossil fuel resource depletion, and the availability of initially unused "backstop" energy-supply technologies. We discuss each of these features below.

3.1 The Capital Stock and Its Evolution

A crucial improvement in EPPA 3.0 over previous model versions is the representation of capital investment. The GTAP dataset includes an explicit set of accounts that detail the demand for investment by sector in each region for the 1995 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 GTAP v.4 release give rise to capital-output ratios that diverge significantly from the range of 2-4 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.[3] 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.[4] Each regional economy is modeled as having two forms of capital in any period. One portion of the aggregate capital stock is "malleable", in that the mix of inputs with which this type of capital is used can be altered in response to changing relative prices. The other is old, "rigid" capital, for which the proportions of the inputs with which this type of capital is used is fixed. Associated with each type of capital is

[3] 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.

[4] The remainder of this section draws heavily on Jacoby and Sue Wing (1999).

a sub-model that represents the transformation of primary factors and intermediate inputs into outputs of the production sectors shown in Table 1.

The two formulations are specified in a manner identical to previous EPPA versions. The production structures shown in Figures 4-8 represent the malleable component of production in each sector. The second part of each structure (which is not shown) is represented by a Leontief production function. This captures the industry-specific, non-malleable component of the capital stock that is associated with production that is fixed in its input proportions. The larger the share of sectoral output that originates in the rigid portion of the production structure, the less substitutable are other inputs for fossil fuels at the level of the various sectors and the aggregate economy, and the greater is the inertia of the energy-carbon system. The larger the proportion of aggregate capital that is malleable, the greater are the possibilities for substitution in the short run. The larger the proportion of aggregate capital of the rigid type, the more the initial price response will tend to persist over time.

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 $(1 - \phi)$ can be thought of as that proportion of previously-installed malleable capital which 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. 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 $v = 1, \dots, 4$, implemented in the agriculture, electric power, energy intensive, and other industry sectors. This means that the model has 16 sector- and vintage-specific stocks of rigid capital, plus a single aggregate stock of malleable capital.

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

$$K^m_{t+1} = I_t + (1 - \phi)(1 - \delta)K^m_t. \tag{11}$$

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 ($i \in \{AGRIC, ELEC, ENERINT, OTHERIND\}$) that survives depreciation, but remains in the sector in which it was installed with its factor proportions "frozen" in place:

$$K^r_{i,t+1,v} = \phi(1-\delta)K^m_{i,t} \text{ for } v = 1. \tag{12}$$

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 constrained to be identical to those in period t. The coefficient of this production function remains 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 (2-4) is simply the amount of each vintage that remains after depreciation

$$K^r_{i,t+1,v+1} = (1-\delta)K^r_{i,t,v} \text{ for } v = 2, 3, 4. \tag{13}$$

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.

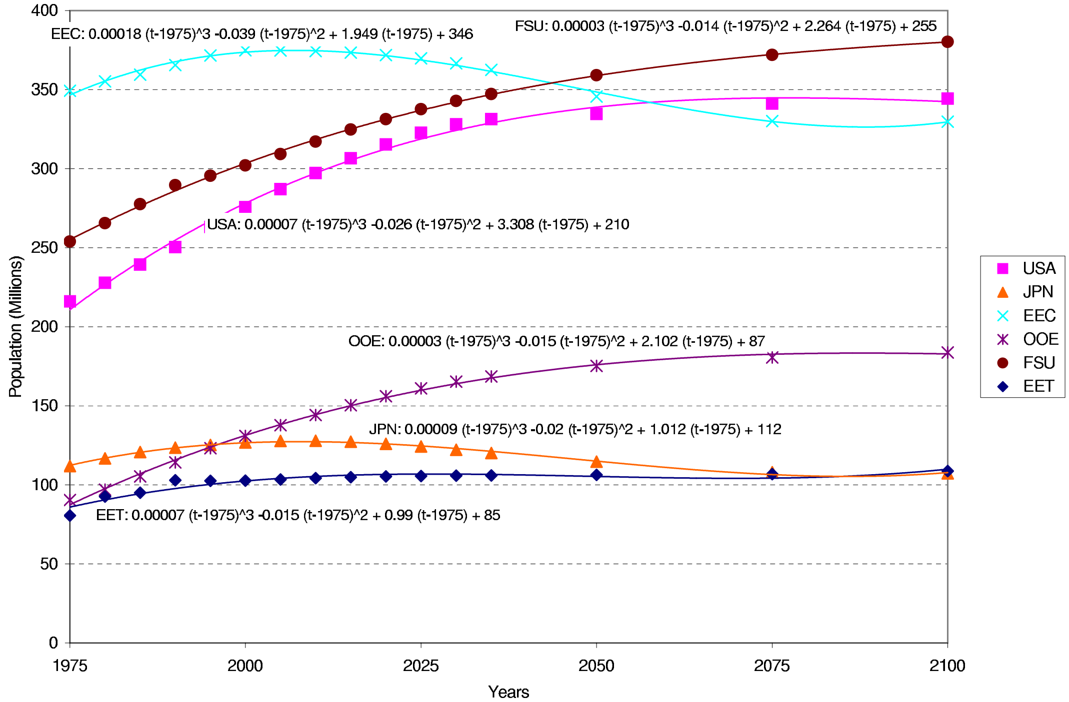
3.2 Population, Productivity and Labor Supply

A number of key variables within the EPPA model are determined by algebraic relationships among outputs of the model in per capita terms (see especially Section 3.6). This requires that the model keep track of the population in each region over the simulation horizon. Regional population in EPPA 3.0 is specified as an exogenous long-run trend, fitted as a cubic equation to quinquennial data using a least-squares procedure. The data are from two sources: statistics for 1975-1990 from the Penn World Table Mark 5.6 mid-year population projections (Summers and Heston, 1991), and for 1995-2100 from World Bank (1994). The trends and fitted equations for population are shown in Figure 9.

From a dynamic perspective, the trade flow and social accounting matrices that underlie EPPA's equilibrium structure constitute a single data-point that represents a snapshot of the economies in the model in at a point in time. Like many other CGE models in the climate policy arena, EPPA relies on assumed exogenous rates of productivity growth from this starting point to drive the increase of endowments of the factors that are not reproducible or accumulable within the model. A key input in this category is labor, whose supply in

Figure 9: EPPA 3.0 Population Trends

A. Developed and Transition Economies



B. Developing Economies

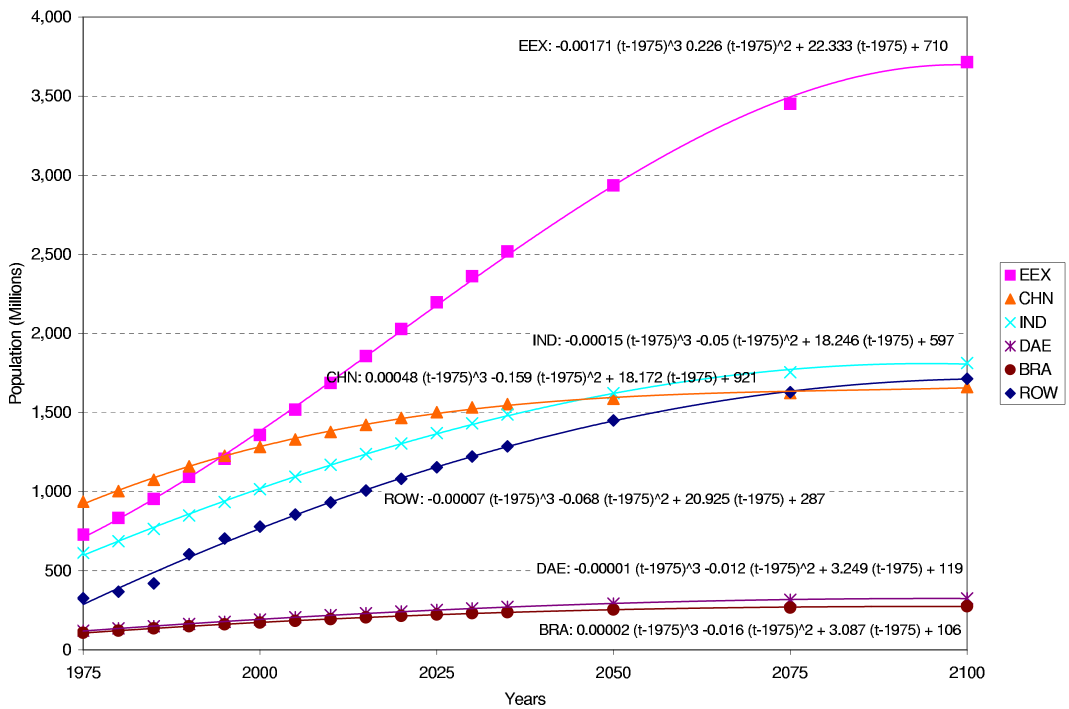


Table 5: Initial and Final Growth Rates of Labor Augmentation

	1995 growth rate	2100 growth rate
USA	4.20%	1.44%
JPN	3.54%	1.44%
EEC	3.36%	1.44%
OOE	3.06%	1.44%
EET	5.40%	1.57%
FSU	4.50%	1.44%
EEX	3.60%	1.65%
CHN	8.22%	1.65%
IND	7.62%	1.65%
DAE	7.08%	1.49%
BRA	4.80%	1.65%
ROW	4.26%	1.65%

quantity terms (i.e. physical units of worker-hours) is determined by population demographics and labor force participation decisions, but whose supply in value terms has historically outstripped the growth in quantity due to these factors.

We do not explicitly represent the sources of this dichotomy within the model. Rather, as in previous versions of EPPA, it is assumed that the inputs of labor to each of the regional economies are augmented by Harrod-neutral technical change. Specifically, for region r and time t the supply of labor is scaled from its base-year value L_{r0} by an augmentation parameter whose rate of growth g_{rt} represents the combined effect of increased labor input in natural units and chained rates of increase of labor productivity:

$$L_{rt} = L_{r0} \times \prod_{t=0}^{T} (1 + g_{rt})^t. \tag{14}$$

To be consistent with the stylized facts of economic growth, we assume that growth of labor augmentation slows over time as the gross output of the economies in the model expand. This is achieved by specifying the rates of growth of the region-specific augmentation parameters as a function that declines over time. First, the growth rates at the beginning of the simulation horizon g_{r0} are chosen that enable EPPA to reproduce observed average rates of increase of GDP over the period 1995-2000, as recorded by International Monetary Fund (2000). Next, growth rates at the end of the simulation horizon g_{rT} are assumed. (These two sets of figures are shown in Table 5.) Finally, the initial and terminal growth rates are incorporated into a logistic function that determines the value of the growth of the labor augmentation parameter in each time period g_{rt}:

$$g_{rt} = (g_{r0} - g_{rT}) \frac{1+\alpha}{1+\alpha e^{\beta t}} + g_{rT}. \tag{15}$$

The values of the logistic parameters α and β are set at 0.1 and 0.07, respectively, which allows the growth rates in each region to maintain their initially high levels for a few periods before tapering off gradually toward the end of the simulation horizon.

Finally, in the early periods of the simulation horizon minor *ad hoc* adjustments to the values of g_{rt} given by equation (15) are made to proxy for the impact of economic events in the late 1990s such as the continuing contraction of the Former Soviet Union's economy, and the slowing of growth of the Dynamic Asian Economies due to the Asian financial crisis. The rates of growth of GDP produced by the model that result from these assumptions are discussed in Section 5.

3.3 Energy-Saving Technical Change

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, Stoker and Judson, 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.

Within EPPA, the representation of energy-saving technical change through the AEEI parameter is a way of directly forecasting, on the basis of modellers' assumptions, the effects of innovation on the growth of the economy and its use of energy. The algebraic specification of the regional trends in energy use are separate from the trends in productivity discussed in the foregoing section. However, these trends are jointly chosen by the modellers in constructing EPPA's baseline scenario to generate that generate future trajectories of output, energy use and emissions that all appear plausible in the light of history.[5]

[5]In using the AEEI there is the implicit assumption that their economic determinants are not affected by the general equilibrium system of prices and demands, which is unrealistic. Nevertheless, despite the criticism of the AEEI in the literature (e.g. Hogan and Jorgenson, 1991; Williams, Larson and Ross, 1987; Williams, 1990; Manne and Richels, 1992; Grubb, Edmonds, ten Brink and Morrison, 1993), using secular trends in the decline of unit energy demand has allowed us the control to generate results while sidestepping

Table 6: Growth Rates of Energy Efficiency

EPPA Region	Annual Growth Rate
USA	1.301%
JPN, EEC, OOE	1.210%
CHN	1.980%
IND	1.430%
EET, FSU, EEX, DAE, BRA, ROW	1.100%

Following the approach first outlined in Edmonds and Reilly (1985), we specify an index of energy efficiency that grows over time, whose rate of increase is assumed to be equal to the rate of decline in energy use per unit output. We differentiate the growth of energy efficiency across regions and sectors according to the assumption that those industries responsible for producing primary energy commodities (coal, crude oil and natural gas) experience no energy efficiency improvement. The coefficients on energy input to these sectors therefore remain unchanged from their calibrated benchmark values that are derived from the base-year social accounting matrices.

For all other sectors in each economy, it is assumed that energy efficiency increases at an equal rate γ, which is region-specific and varies over time. Table 6 shows the assumed initial rates of growth of AEEI γ_{r0}, which were developed through a combination of expert elicitation, examination of the historical rates of decline of countries' energy-GDP ratios (e.g. Schmalensee et al., 1998), and surveys of the use of the AEEI parameter in other climate policy models (Yates, 1995). We assume that the growth of energy efficiency gradually slows over time according to a logistic function, representing a process by which producers exhaust the technical potential for saving energy. Thus, for sector i in region r at time period t, energy efficiency λ is determined by the equation:

$$\lambda_{i,r,t} = \begin{cases} \exp\left[\gamma_{r0} \times (t-1)\left(1 - \frac{t-1}{T}\right)\right] & i \in \text{non-primary energy sectors} \\ 1 & \text{otherwise} \end{cases} \tag{16}$$

where T is the length of the forecast horizon, equal to 100 years.

Following Edmonds and Reilly (1985), the coefficient on energy input per unit output by sector, region and time period is scaled from its benchmark value by the factor $1/\lambda$. The

the difficult task of explicitly representing the processes of development and deployment of new energy-saving technologies.

Figure 10: Trends in the Coefficient on Energy Input to Non-Primary Energy Sectors

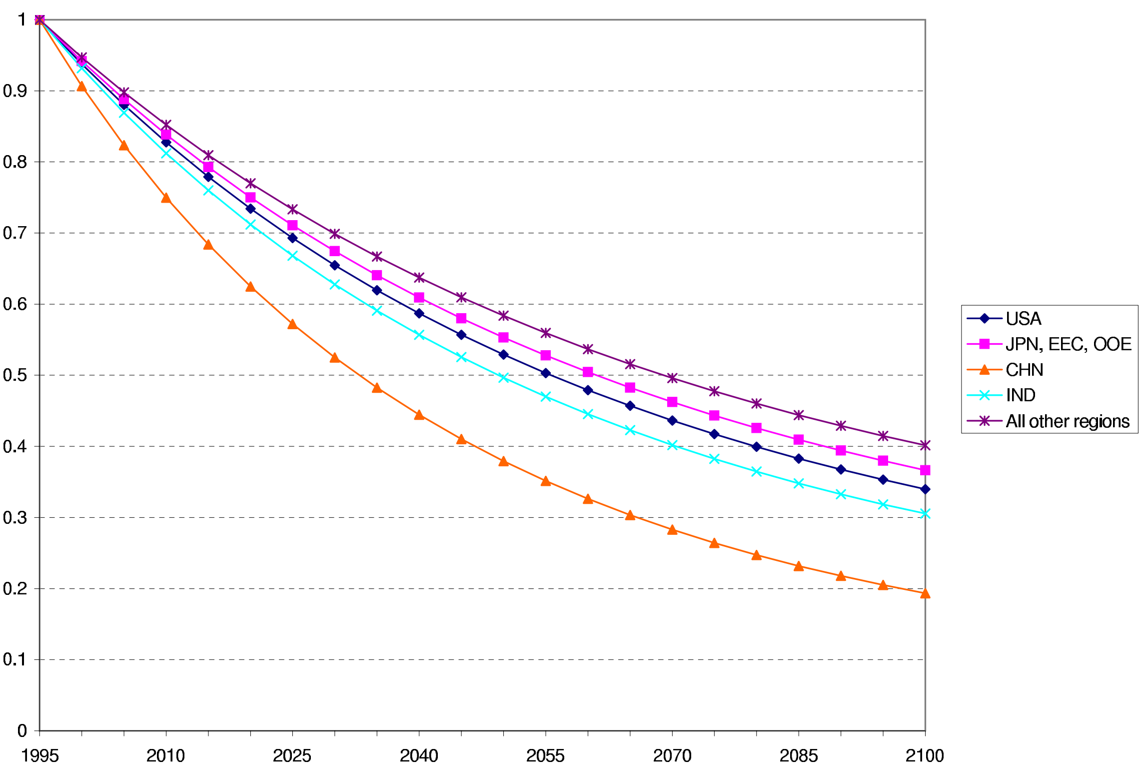


Table 7: Growth Rates of Natural Resource Inputs to Agriculture.

EPPA Region	Annual Growth Rate	Remarks
Developed and transition economies	1.0%	
EEX, BRA, DAE	1.0%	
IND	4.2% 3.75% 3.0% 2.5%	1995-2020 2020-2040 2045-2070 2075-2100
CHN	3.0%	
ROW	2.5%	

evolution of this factor is shown in Figure 10. Rates of decline are generally similar across regions with the exception of 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—which we project will continue over the next century. The evolution of energy efficiency in OECD countries is similar to but slightly faster than that in the developing and transition economies, with the US exhibiting the most rapid decline in its sectoral energy coefficients. The actual path of energy use per unit output that results from the model simulation depends on energy prices and other structural changes.

3.4 Natural Resource Inputs

Previous versions of EPPA represented the supply of resources differently for coal, oil and gas, and alternative fossil fuels (the so-called "backstop" energy resource supplies). As in OECD GREEN, these versions of the model had oil and gas resource components that included separate descriptions for price responsive resource recovery, the conversion of resources to reserves, and the production of energy goods from reserves. For coal and backstop fossil resources depletion was not explicitly modelled. In revising the resource model, we strove to treat resources consistently across fuels, base them on actual estimates of ultimately recoverable resources, and simplify the mathematical treatment of resources in the energy sectors.

All fossil energy resources are modeled in EPPA 3.0 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 6, plus the depletion model and representations

Table 8: Resource value as a share of total production costs in 1995 for coal, oil, and natural gas.

	Coal	**Oil**	**Gas**
USA	0.1	0.33	0.25
JPN	0.1	–	–
EEC	0.1	0.33	0.25
OOE	0.1	0.33	0.25
EEX	0.1	0.66	0.25
CHN	0.12	0.33	0.25
FSU	0.1	0.50	0.25
IND	0.15	0.33	0.25
EET	0.1	0.33	0.25
DAE	0.1	0.33	0.25
BRA	0.1	0.33	0.25
ROW	0.1	0.33	0.25

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, Reilly, Gardener and Brenkert (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).[6] Production in any one

[6]To understand the procedure employed, imagine that fossil energy commodity e is produced using a CES technology from resources R_e and an amalgam of other inputs X. Recall that for a CES production function the associated unit cost function is

$$p_e = \left(s_{\mathrm{R}e} p_{\mathrm{R}}^{1-\sigma_e} + (1 - s_{\mathrm{R}e}) p_{\mathrm{X}}^{1-\sigma_e}\right)^{\frac{1}{1-\sigma_e}}$$

where p_e is the output price of fossil fuel e, p_{R} is the price of the resource input, p_{X} is an aggregate price of the unit bundle of other inputs, $s_{\mathrm{R}e}$ is the benchmark value share of the resource in fuel e, and σ_e is the elasticity of substitution. The unit demand function for resources R_e^{D} can be found by differentiating the unit cost function with respect to the price of resource inputs

$$R_e^{\mathrm{D}} = s_{\mathrm{R}e} \left(\frac{p_{\mathrm{R}}}{p_e}\right)^{-\sigma_e}.$$

The technical coefficient on the resource is related to the assumed value of the resource $\bar{R}_e$ in the benchmark 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 (Table 8) 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

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economic accounts by

$$\bar{R}_e = s_{\mathrm{R}e}\bar{y}_e.$$

At the initial equilibrium point this benchmark value must be consistent with the demand for the resource specified above, so that

$$y_e R_e^{\mathrm{D}} = y_e s_{\mathrm{R}e} \left(\frac{p_{\mathrm{R}}}{p_e}\right)^{-\sigma_e} = \bar{R}_e$$

for the benchmark output $y_e = \bar{y}_e$. In a new equilibrium where prices and quantities depart from their benchmark values, this expression may be inverted to obtain the (unobservable) price of the resource:

$$p_{\mathrm{R}} = p_e \left(\frac{y_e s_{\mathrm{R}e}}{\bar{R}_e}\right)^{1/\sigma_e}.$$

In the production of fossil fuels resources are treated as a fixed factor. Substituting the above into the cost function gives

$$p_e^{1-\sigma_e} = s_{\mathrm{R}e} p_e^{1-\sigma_e} \left(\frac{y_e s_{\mathrm{R}e}}{\bar{R}_e}\right)^{\frac{1-\sigma_e}{\sigma_e}} + (1 - s_{\mathrm{R}e}) p_{\mathrm{X}}^{1-\sigma_e}$$

which may be inverted to yield an expression for output in terms of the relative price of non-fixed inputs to production:

$$y_e = \bar{R}_e s_{\mathrm{R}e}^{\frac{1}{\sigma_e - 1}} \left[1 - (1 - s_{\mathrm{R}e}) \left(\frac{p_{\mathrm{X}}}{p_e}\right)^{1-\sigma_e}\right].$$

The calibration problem consists of finding an expression for the elasticity of supply for the output good with respect to the price of output, relative to that of the mobile factors:

$$\eta^{\mathrm{S}} = \frac{\partial y_e}{\partial \left(p_e/p_x\right)} \Big/ \frac{y_e}{\left(p_e/p_x\right)}$$

In the benchmark all prices are unity by construction, which enables us to write the final expression for the output supply elasticity as

$$\eta^{\mathrm{S}} = \sigma_e \frac{1 - s_{\mathrm{R}e}}{s_{\mathrm{R}e}}.$$

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:

$$R_{et} = R_{et-1} - 5F_{et-1} \tag{17}$$

This specification captures the major long-run dynamics of resource prices. We discuss this further and compare it to popular alternatives below. The missing element of this formulation, compared with previous EPPA specifications, is short-run price behavior in response to, for example, limited reserves. Here we recognize that our principal interest is the ability to set a reference price path in the near-term, which we specify as being the period 1995-2010. Over such a time-frame reserve limitations are only one of a number of factors that can affect the behavior of prices. Others include pricing decisions by OPEC, short-run expectations, the level of fuel inventories, and the demand for heating and cooling driven by macroeconomic or weather fluctuations. Rather than model these explicitly, we set energy prices exogenously through the year 2010. Setting this constraint on the price path implies a value (i.e. price × quantity) of the resource for the first five periods of the reference case. After 2010, the long-run resource model applies. In the long run, fuel price trajectories are driven by the grade structure of the underlying resource base.

Resource rents in EPPA are a combination of Ricardian and monopoly rents that are reflected in the 1995 base data and short-run price path.[7] 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 obtains in the reference.

In EPPA 3.0, the improving technological capability to produce resources is reflected in estimates of the total energy content of resources available in 1995 (Table 9). These resource estimates in Tables 10-12, 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

[7]Ricardian rents are the result of technological limits on the rate of production. Monopoly rents occur when owners of a significant share of the resource constrain production to increase profits. For a discussion of some of the issues arising in measuring these rents and accounting for the resource share in natural resource-intensive industries see (Nordhaus and Kokklenberg, eds, 1999, especially chapters 3 and 4).

Table 9: Total Fossil Resources by EPPA Region in 1995 (EJ)

	Oil	Gas	Coal	Shale Oil[a]
USA	990	832	53039	275000
JPN	–	–	272	–
EEC	321	177	15880	–
OOE	2500	1239	31008	122000
EET	60	140	27089	–
FSU	5300	10025	165032	200000
EEX	12700	5762	9903	40000
CHN	752	389	31305	–
IND	60	70	10529	–
BRA	255	90	1032	–
DAE	30	59	155	–
ROW	401	490	5416	–

[a]Shale oil is based on Edmonds, Reilly, Gardener and Brenkert (1985) and Müller-Wenk (1998, p. 69).

Table 10: Oil Resources in EPPA (EJ)

	Currently Economically Recoverable Resources				Subtotal	Tar Sands[a]
	Identified	Undiscovered[b]	Identified + Undiscovered	Currently Uneconomic[c]		
USA	297	255	521	469	990	–
JPN	–	–	–	–	–	–
EEC	120	57	169	152	321	–
OOE	163	251	399	360	759	1700
EET	19	25	42	18	60	–
FSU	750	878	1628	1464	3091	2200
EEX	4610	1498	6003	3470	9472	3200
CHN	183	248	431	321	752	–
IND	38	12	48	12	60	–
BRA	74	74	146	109	255	–
DAE	3	19	22	8	30	–
ROW	–	401	401	–	401	–
Total	6257	3718	9810	6383	16191	7100

[a]Based on Edmonds et al. (1986, Table 8-4) converted to EJ at 6.1×10^6 EJ/bbl, and Müller-Wenk (1998, p. 69).

[b]Represents USGS median estimate of undiscovered resources.

[c]Currently uneconomic resources were based on the ratio of currently uneconomic to economic grades reported in Edmonds et al. (1986). This ratio was applied to the total of identified and undiscovered from Masters, Root and Turner (1998). These reflect currently non-economic resources such as enhanced recovery and other currently inaccessible resources on the basis that in the future technology will improve so as to make these recoverable.

Table 11: Natural Gas Resources in EPPA (EJ)

	Identified	Undiscovered	Subtotal	Currently Uneconomic[a]	Total
USA	332	297	594	238	832
JPN	–	–	–	–	–
EEC	84	48	127	51	177
OOE	306	530	826	413	1239
EET	42	55	94	47	140
FSU	4724	2490	7160	2864	10025
EEX	2378	1766	4116	1646	5762
CHN	38	222	260	130	389
IND	23	24	47	23	70
BRA	19	46	64	26	90
DAE	11	29	39	20	59
ROW	–	490	490	–	490
Total	7957	5997	13817	5458	19274

[a]Currently uneconomic resources were based on the ratio of currently uneconomic to economic grades reported in Edmonds et al. (1986). This ratio was applied to the total of identified and undiscovered from Masters et al. (1998). These reflect currently non-economic resources such as enhanced recovery and other currently inaccessible resources on the basis that in the future technology will improve so as to make these recoverable.

Table 12: Coal Resources in EPPA

	Anthracite Resources (MT)		Lignite Resources (MT)		Total	Energy
	Recoverable	Additional	Recoverable	Additional	(MT)	(EJ)
USA	106495	468864	134063	669944	1810821	53039
JPN	804	175	–	–	9292	272
EEC	–	–	–	–	542180	15880
OOE	49849	526045	49714	235990	1058659	31008
EET	–	–	–	–	924849	27089
FSU	10400	2100000	137000	3100000	5634400	165032
EEX	–	–	–	–	338087	9903
CHN	62200	363200	52300	304700	1068800	31305
IND	68047	86088	1900	3932	359459	10529
BRA	–	–	2845	22239	35246	1032
DAE	–	–	–	–	5286	155
ROW	–	–	–	–	184899	5416
Total	130247	449288	57045	330871	11971978	350660

Source: United Nations (1995).

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. In previous versions of EPPA, tar sands were included as part of a backstop fossil technology (Burniaux et al., 1992). Physical and technical considerations lead us to instead treat these as a more costly grade of conventional oil. This treatment is consistent with the economics of these sources since all of these grades are currently being produced in various parts of the world. Implicit in this expanded definition of resources is the assumption that technology will improve and discovery of these resources will proceed as prices rise and currently-known reserves are used.

Also included in EPPA are the shale oil resources given in Table 10. 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., 1985; Rogner, 1997) the resource quality varies in grade. We thus make shale oil available in the four regions (USA, Other OECD countries, Former Soviet Union and Energy-exporting LDCs) 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, as shown in Table 10. 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 assumptions underlying shale oil output are included in the following section on backstop technologies.

3.5 Backstop Energy Supply Technologies

The term "backstop" technology describes an energy source that is not yet commercial, is physically a perfect substitute for an existing energy carrier, and is available in unlimited supply at a constant marginal cost (Nordhaus, 1979). Except perhaps for the plutonium breeder nuclear reactor, it is hard to think of a pure backstop technology. Most energy technologies are based on a graded resource that makes it unlikely that the fuels derived from the resource base will be produced at constant marginal cost over EPPA's 100-year simulation horizon. Considering renewable electric energy technologies, for example, there is an enormous amount of energy in incident solar radiation or atmospheric wind energy or ocean wave energy, but the quality of these resources varies markedly by site, much as with subterranean deposits of fuel minerals. Thus, expanding beyond the sunniest, windiest,

Table 13: Input Shares for Backstop Technologies

	Capital	Labor	Coal	Other Industry	Shale Oil
Carbon-free electric	0.5	0.2	–	0.3	–
Carbon-based gas	0.3	0.2	0.4	0.1	–
Carbon-based liquid	0.4	0.3	–	0.2	0.1

and highest-frequency wave sites, or to shale deposits of lower grade, will generally cause the cost of energy production to increase. Further, because insolation, wind and waves provide energy only intermittently, using these sources to produce a large share of the world's electricity would require complementary investments in back-up capacity, storage technology (e.g. pumped hydro), interruptible service and an extensive grid system to facilitate balancing of demand and supply. All of these would increase the effective cost, particularly as capacity expanded.

Backstop technologies for oil, gas and electricity are modelled separately within EPPA. Their production structures are shown in Figure 11. The oil and gas technologies are hydrocarbon-based, representing coal gasification and shale oil, which are assumed to produce perfect substitutes for natural gas and crude oil, respectively. The electricity technology is a carbon-free renewable alternative, intended to represent a combination of solar, wind, and other technologies, and is assumed to substitute perfectly for conventional thermal and nuclear generation.

In line with the foregoing discussion, none of these is a backstop in the pure sense, because each requires the input of a fixed factor that gives rise to non-constant marginal costs of production. Coal gasification and shale backstops utilize coal and oil shale, respectively, both of which are depletable resources. The fixed factor resource input to renewable electricity is meant to capture variations in quality (both geographic and temporal) of the underlying resource, and to represent limitations such as competing land uses that constrain the growth of supply.

The degree to which labor, capital and intermediate inputs can substitute for these resources is governed by the nesting structure and elasticities that are assumed for each technology. For renewable electricity, competing uses for the land, wind, biomass and tidal or riverine water flows strongly influence the siting of generation equipment, a phenomenon which we model by nesting capital and natural resource inputs in fixed proportions to each other (Figure 11 Panel A). However, it is thought that such rigidity can be compensated for by additional inputs. This is represented by the substitutability between the capital-fixed

Figure 11: EPPA 3.0 Backstop Technologies

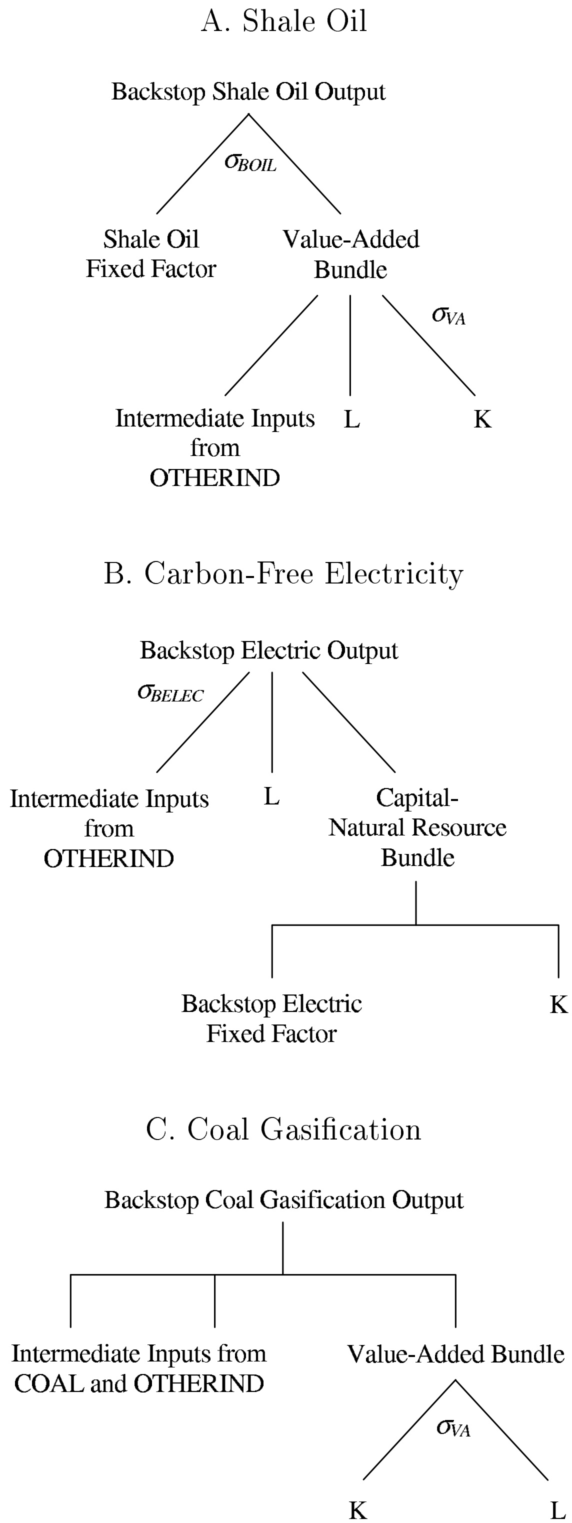


Table 14: Mark-up on Cost of Production for Backstop Technologies

	Carbon-free electric	Carbon-based liquid	Carbon-based gas
USA	1.54	2.8	3.5
JPN	1.21	–	4.0
EEC	1.52	–	4.0
OOE	2.63	2.5	3.0
EEX	2.4	2.5	3.5
CHN	7.72	–	2.8
FSU	5.45	2.5	2.8
IND	4.36	–	2.8
EET	3.78	–	2.8
DAE	1.73	–	2.8
BRA	3.61	–	2.8
ROW	1.88	–	2.8

factor aggregate, labor and intermediate goods, which is controlled by the elasticity σ_{BELEC} whose default value is equal to 0.5.

The technology for producing shale oil is different. Although labor, capital and goods from the Other Industry sector substitute for each other within the value-added bundle (governed by the elasticity σ_{VA}—see Table 2), their contribution to output is fundamentally determined by the quantity of resources that they mine and process into fuel (Figure 11 Panel B). This limit is modelled by having the shale resource substitute for the aggregate of value-added and intermediate goods in the production of output, with a low elasticity (σ_{BOIL}, equal to 0.2). The technology for producing coal gas, while it does not rely on any fixed factor resources directly, is similar to shale oil. This fuel cannot be produced from labor and capital alone: so that while these inputs can substitute for one another, value-added and inputs of coal and intermediate goods are modelled as having a fixed relationship in production (Figure 11 Panel C).

Table 13 provides the factor shares for these technologies that by definition sum to one. We apply a cost multiplier to capital, labor and material inputs for these technologies (Table 14). This is the mark-up above the base-year cost of the fuel for which they are perfect substitutes. For example, the markup factor for synfuel oil in the US is 2.8. Thus, all else being equal, the shale backstop technology would be a competitive energy source once oil prices are 2.8 times the price of crude oil in 1995. Simulations of EPPA will, of course, not show this result exactly because all else is not in fact equal (e.g. prices of labor and capital change over the time horizon of the simulation).

In terms of energy and emissions accounting, we make a number of assumptions in modelling backstop technologies. With regard to the gasification technology, its efficiency in converting the energy in coal into gas is assumed to be 50 percent, and the resulting gaseous fuel is assumed to have the same carbon coefficient as natural gas. The efficiency factor, when combined with the differences in the carbon emissions per exajoule of gas and coal implies that two-thirds of the carbon in the coal is emitted in the gasification process and one-third remains in the gas to be emitted upon consumption.

For crude oil from shale, the specific emissions of carbon during the extraction process are 20 percent of the carbon per unit of oil produced.[8] The carbon content of the oil in the shale is assumed to be the same as refined oil. Thus, carbon emissions from production are 20 percent 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. The shale oil resource estimates in Table 10 are recoverable amounts based on the assumption that a fraction is used as process energy. We therefore deplete the resource only by the amount produced (i.e. we do not include the amount used as process energy as implied by the carbon coefficient).

3.6 Structural Change in Consumption

The 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 national income declined from about 17 percent to around 2 percent in the United States and from 34 percent to 3 percent in Japan. This type of structural change is not readily captured in a CGE 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 the US and Japanese agriculture shares 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. In addition, many econometric studies also have used a relationship proposed by Frisch (1959) to estimate demand systems where the substitution elasticity also depends on income (Lahiri, Babiker

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

and Eckaus, 2000).

Homogeneity in EPPA is convenient because it simplifies the solution of the model. Thus, EPPA 3.0 includes a process that changes both the elasticity of substitution of consumption with per capita income and the share parameters of consumption gradually over the time horizon of the model while retaining the homogeneity within a period. The relationships were estimated using weighted least squares regression on cross-section data for the components of consumption from the GTAP database. The populations of the regional aggregates represented in this dataset were used as weights. The weighted linear-logarithmic form regression of σ on per-capita GDP y was estimated as:

$$\sigma = 0.485829 + 0.104019 \log y \tag{18}$$

Changes in shares s of national income for Agricultural, Other Industry and Energy Intensive sectors are shown below:

$$s_{\text{AGRIC}} = 0.336348 - 0.499258y \tag{19}$$

$$s_{\text{OTHERIND}} = 0.572121 + 0.460912y \tag{20}$$

$$s_{\text{ENERINT}} = 0.062746 + 0.025724y \tag{21}$$

These equations are used in the model to determine the values of $s_{i,t}$[9] for each region as its per capita income changes, except for the mature developed regions of the world (USA, Japan, the EEC and Other OECD nations). At per capita income levels of these wealthier countries there is little evidence of further change in consumption shares.

[9] $i \in \{AGRIC, ENERINT, OTHERIND\}$

4 Greenhouse Gas Emissions

4.1 Modelling Framework and Inventories

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 and non-methane volatile organic compounds (NMVOCs) that are all important for the chemistry components of the IGSM. With the updating of EPPA to the 1995 GTAP database, we have completely revised the non-CO_2 emissions component of the model. In this version of EPPA, GHGs and related gases are treated as inputs into production and household consumption. The reasoning is that with a constraint on emissions the producer (household) must pay a price for any emissions that result from the production (consumption) process. An intuitive way of thinking about this representation is that producers or consumers must pay a fee for disposal services for emitting these gases into the atmosphere. If there is no constraint on emissions this disposal service is free. However, if the atmospheric sink for these pollutants is a scarce resource that must be rationed, then GHG emissions must be reduced below their no-constraint levels, which imputes a price to each of these gases that is calculated endogenously.

Table 15 classifies the major sources of GHG emissions identified for control in Annex A of the Kyoto Protocol, and the activities within EPPA to which they correspond. A similar classification is provided by Table 16 for emissions of criteria pollutants. These various gases come from a wide variety of activities related to industrial production, fossil energy use, household activities such as biofuel use and waste disposal, and agricultural production and land use. In the current version of the model all of these gases are modeled as Leontief (fixed coefficient) inputs to the activities identified in Tables 15 and 16. This device facilitates the projection of emissions in tandem with the evolution of the various activities in the model's simulations. However, the fixed relationship between economic output and pollution implied by this method does not allow us to accurately estimate costs of emissions control. This component of the model is the subject of ongoing work.

Inventories of emissions, broken down by EPPA activity and by region for the model's 1995 base year are provided in Table 17. In general, these data were generated using existing inventories and reports on the emissions of various gases, with some updating from other published sources for consistency across regions where necessary. Those familiar with the national communications required under the Framework Convention on Climate Change

Table 15: Sources of Emissions and Corresponding EPPA Activities for GHGs Covered by the Kyoto Protocol

Greenhouse Gas Source	EPPA Activity
CO_2	
Coal combustion	Coal consumption in all sectors
Oil combustion	Refined oil consumption in all sectors
Natural gas combustion	Natural gas consumption in all sectors
Cement production	Energy intensive industry production
Biomass burning, deforestation, biofuel combustion	Agriculture production
CH_4	
Coal seams	Coal production
Petroleum production	Oil production
Transmission 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, biomass burning, deforestation	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, biomass burning, deforestation	Agriculture production
HFCs	
Air conditioning, foam blowing, other	Other Industry Production
PFCs	
Semiconductor production, solvent use, other	Not included
Aluminum smelting	Energy intensive industry production
SF_6	
Electrical switchgear	Electricity production
Magnesium production	Energy intensive industry production

Table 16: Sources of Emissions and Corresponding EPPA Activities for Other IGSM Gases Not Covered by the Kyoto Protocol

Criteria Pollutant Source	EPPA Activity
SO_2	
Coal combustion	Coal consumption in all sectors
Oil combustion	Oil consumption in all sectors
Gas combustion	Gas consumption in all sectors
Non-ferrous metals, cement, iron & steel, chemicals	Energy intensive industry production
Refinery processes	Refined oil production
Biomass burning, deforestation, biofuel combustion, uncontrolled waste burning	Agriculture production
Biofuel use in households	Household consumption
NMVOCs	
Coal combustion	Coal consumption in all sectors
Petroleum use in transportation	Oil consumption in all sectors
Natural gas combustion	Gas consumption in all sectors
Refining 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
Biomass burning, deforestation, biofuel combustion, uncontrolled waste burning	Agriculture production
NO_x	
Coal combustion	Coal use in all sectors
Oil combustion	Oil use in all sectors
Natural gas combustion	Natural gas use in all sectors
Cement, iron & steel, chemicals	Energy intensive industry production
Refinery processes	Refined oil production
Biofuel use in households,	Household consumption
Biomass burning, deforestation, biofuel combustion, uncontrolled waste burning	Agriculture production
CO	
Oil, gas and coal combustion	Ex post calculation from REFOIL consumption
Iron & steel, chemicals	Energy intensive industry production
Refinery processes	Refined oil production
Other industrial processes	Other Industry production
Biofuel use in households	Household consumption
Biomass burning, deforestation, biofuel combustion, uncontrolled waste burning	Agriculture production

Table 17: Benchmark 1995 Emissions of Non-CO_2 Greenhouse Gases

EPPA Sector	World Total	USA	JPN	EEC	OOE	FSU	EET	EEX	CHN	IND	DAE	BRA	ROW
Methane (MT CH_4)													
AGRIC	163.544	9.187	0.876	9.862	6.050	6.280	1.940	31.866	26.061	27.657	6.015	12.596	25.152
COAL	30.242	3.040	0.094	2.130	0.900	3.379	1.061	2.801	12.880	2.797	0.415	0.049	0.697
OIL	5.567	0.271	–	0.020	1.655	0.058	0.001	2.651	0.144	0.127	0.083	0.035	0.522
GAS	47.749	6.050	–	0.468	0.329	18.669	1.254	17.931	1.508	0.373	0.048	0.359	0.761
ENERINT	18.439	1.122	1.125	1.545	0.300	0.082	0.071	3.470	3.744	0.561	2.134	2.151	2.132
OTHERIND	14.661	0.609	0.668	0.965	0.187	0.049	0.075	3.718	1.672	0.410	2.062	1.883	2.362
Landfills	27.382	11.100	0.364	7.294	2.126	3.025	1.896	0.504	0.264	0.106	0.193	0.211	0.300
Domestic Sewage	1.146	0.159	0.006	0.254	0.080	0.199	0.246	0.064	0.034	0.014	0.025	0.027	0.038
Total	308.730	31.538	3.133	22.539	11.627	31.741	6.545	63.005	46.306	32.046	10.974	17.311	31.964
Nitrous Oxide (MT N_2O)													
AGRIC	8.422	0.858	0.043	0.897	0.487	0.589	0.256	1.443	1.705	0.952	0.152	0.390	0.650
COAL	0.130	0.028	0.005	0.014	0.005	0.012	0.007	0.006	0.040	0.008	0.002	0.001	0.002
REFOIL	0.372	0.202	0.019	0.073	0.022	0.013	0.015	0.013	0.005	0.002	0.004	0.002	0.003
ENERINT	0.628	0.106	0.024	0.292	0.045	0.007	0.011	0.035	0.040	0.006	0.023	0.017	0.021
Total	9.553	1.194	0.090	1.276	0.559	0.621	0.289	1.497	1.791	0.968	0.182	0.410	0.676
PFCs (10^3 metric tons CF_4 equivalent)													
ENERINT	20.756	4.149	0.020	2.321	4.062	3.516	0.607	2.608	1.304	0.599	–	1.161	0.408
SF_6 (10^3 metric tons SF_6)													
ELEC	3.535	0.921	0.282	0.520	0.356	0.397	0.124	0.242	0.275	0.104	0.810	0.057	0.177
ENERINT	2.321	0.697	0.259	0.430	0.152	0.092	0.036	0.294	0.104	0.430	0.610	0.035	0.118
Total	5.856	1.618	0.541	0.950	0.508	0.489	0.161	0.537	0.379	0.147	0.142	0.092	0.294
HFCs (10^3 metric tons HFC-134a equivalent)													
OTHERIND	90.765	34.610	12.850	21.380	6.943	4.581	1.447	4.126	1.042	0.434	1.820	0.348	1.184

(FCCC) can attest to the fact that even for developed countries, existing reports are incomplete, inconsistent among countries, and subject to significant revision. For example, in comparing national methane budgets with the global EDGAR methane inventory, Amstel (1998) identified substantial variations due to differences in the emission factors employed or activity levels reported for emission sources, and gaps in either set of accounts. The inventories presented in this paper reflect our attempt to resolve these problems and to produce a global data set that is broadly consistent with both estimated natural emissions and recent trends in atmospheric concentrations given the atmospheric chemistry and climate model that is part of our IGSM. For this reason the data necessarily involve some extrapolations and approximations. The following sections discuss the main features of the development of both our emissions inventories and changes in emissions coefficients over time.[10]

4.2 CO_2 and CO

The burning of fossil fuels releases carbon to the atmosphere mostly in the form of CO_2, with a smaller proportion in the form of CO, especially when combustion is incomplete. Inventories and reporting systems for carbon (e.g. of Energy: Energy Information Agency (1999), US Environmental Protection Agency (1999) or national communications under the FCCC) report total carbon released (whether as CO_2 or CO) and the carbon coefficients typically applied to fossil fuels similarly reflect their carbon content on a stoichiometric basis, independent of its oxidation pathway. Because CO ultimately is further oxidized to CO_2 in the atmosphere, the stoichiometric assumption is often adequate for general carbon accounting and is commonly employed in integrated assessment models.

In EPPA, carbon emissions are accounted for by applying constant coefficients to the energetic flows of coal, refined oil and natural gas that are inventoried in the GTAP-E database for 1995. The carbon coefficients, in MT carbon per EJ, are 24.686 for coal, 18.40 for refined oil and 13.473 for gas, values which are assumed to remain constant across regions and over time. Actual measured variations in coal and natural gas coefficients are relatively small, with greater variation observed among the specific emissions of different refined oil products. The carbon coefficient for EPPA's aggregate commodity refined oil was derived by dividing the total estimated carbon emissions from oil consumption by the total consumption of refined petroleum products based on data for the US (US Environmental Protection Agency, 1999). This result was assumed to be representative of the broad mix of refined products consumed in all regions. However, in the context of climate chemistry CO plays a prominent role in the fate of other GHGs in the atmosphere. The MIT IGSM explicitly

[10]For a more detailed exposition, see Mayer and Hyman (2000).

models these chemical processes, and thus requires estimates of emissions of carbon in each form. This split of carbon emission between CO_2 and CO is carried out as a post-processor calculation on the basis of coefficients related to process- and fuel-specific consumption.

4.3 Other Greenhouse Gases

For Annex B countries, FCCC reports on emissions of CH_4 and N_2O were the basis for 1995 inventories by source. Some adjustments were made to the reported figures to reflect more recent IPCC guidance on indirect N_2O emissions as a result of nitrogen released by agricultural practices. In particular, the revised Intergovernmental Panel on Climate Change (1996) methodology includes indirect N_2O formation induced by emission and consecutive deposition of NO_x and NH_3, nitrogen leaching and runoff, and sewage. We updated N_2O emissions based on estimates by Mosier and Kroeze (1998) and US Environmental Protection Agency (1999). National communications under the FCCC also did not include estimates of emissions of CH_4 from industrial sewage. These were estimated using data from International Energy Agency (1998), which were distributed to EPPA regions in proportion to the output of the food processing industry in 1995, as given by the GTAP database.

For Non-Annex B regions, we used emissions data from International Energy Agency (1998), Mosier and Kroeze (1998), the EDGAR 2.0 emissions inventory for 1990 (Olivier, Bouwmann, van der Mass, Berdowski, Veldt, Bloos, Visschedijk, Zandveld and Haverlag, 1995), Food and Agricultural Organization (FAO) data on agricultural activities (Daberkow, Isherwood, Poulisse and Vroomen, 1999), and activity specific emissions coefficients from Intergovernmental Panel on Climate Change (1996). We used estimates of the growth in activities such as fertilizer use, ruminant animal production, and aggregate economic output during the 1990s to adjust the 1990 data in the EDGAR database to 1995 levels, and constrained the resulting estimates to conform to the global totals and regional/sectoral distributions reported by International Energy Agency (1998), Mosier and Kroeze (1998) and Sass, Fisher and Ding (1999). For SF_6, PFCs, and HFCs we based our estimates on Harnisch (1999) and Harnisch, Jacoby, Prinn and Wang (2000). For each gas, the resulting activity-specific emissions were divided by the 1995 benchmark level of each emitting activity in the EPPA model to generate emissions coefficients for subsequent use.

Table 18: Benchmark 1995 Emissions of Carbon Monoxide (MT CO)

EPPA Sector	World Total	USA	JPN	OOE	EEC	EET	FSU	EEX	CHN	IND	DAE	BRA	ROW
COAL	28.405	0.476	0.284	0.641	1.041	1.676	3.877	1.446	17.871	0.382	0.448	0.063	0.200
AGRIC	0.107	0.001	–	0.001	0.003	0.005	0.026	0.008	0.062	–	–	–	0.001
OTHERIND	1.011	0.008	0.011	0.032	0.014	0.023	0.096	0.077	0.560	0.135	0.004	0.002	0.049
ENERINT	2.864	0.048	0.229	0.078	0.136	0.052	0.307	0.160	1.441	0.158	0.109	0.059	0.088
ELEC	1.042	0.279	0.037	0.045	0.108	0.069	0.104	0.050	0.241	0.077	0.015	0.002	0.016
Hholds	23.380	0.140	0.006	0.486	0.780	1.528	3.345	1.150	15.568	0.011	0.320	–	0.047
REFOIL	290.426	64.279	5.307	12.878	39.904	5.553	22.305	60.999	24.999	13.912	18.683	8.917	12.690
AGRIC	0.113	0.016	0.003	0.004	0.007	0.002	0.026	0.027	0.012	0.001	0.004	0.004	0.006
OTHERIND	181.018	38.466	3.379	8.048	24.202	3.274	15.682	38.179	17.539	6.659	11.689	5.578	8.326
ENERINT	0.373	0.130	0.013	0.014	0.048	0.004	0.022	0.041	0.043	0.010	0.029	0.013	0.008
ELEC	0.226	0.015	0.009	0.002	0.020	0.004	0.050	0.064	0.021	0.002	0.021	0.002	0.017
Hholds	108.696	25.653	1.904	4.810	15.628	2.269	6.526	22.687	7.385	7.239	6.941	3.321	4.334
GAS	3.785	0.624	0.041	0.069	2.030	0.086	0.479	0.308	0.029	0.020	0.020	0.007	0.072
AGRIC	0.159	0.098	–	0.002	0.011	0.001	0.025	0.010	–	–	0.004	–	0.008
OTHERIND	0.688	0.232	0.006	0.031	0.121	0.017	0.154	0.093	0.008	0.001	0.002	0.002	0.023
ENERINT	0.577	0.167	0.004	0.020	0.100	0.027	0.093	0.107	0.016	0.014	0.002	0.004	0.023
ELEC	0.555	0.128	0.031	0.017	0.025	0.007	0.208	0.098	0.005	0.005	0.012	0.001	0.018
Hholds	1.807	–	–	–	1.773	0.034	–	–	–	–	–	–	–
All Fuel Use	322.616	65.379	5.631	13.588	42.976	7.315	26.661	62.752	42.900	14.314	19.152	8.986	12.962
REFOIL	0.173	0.014	0.024	0.006	0.036	0.015	0.004	0.013	0.040	0.006	0.006	0.005	0.004
ENERINT	33.787	2.099	4.451	1.242	5.713	2.187	9.536	0.790	4.350	0.701	1.175	1.018	0.525
AGRIC	470.568	12.970	0.638	8.417	10.757	4.481	21.419	220.145	27.774	52.053	13.245	54.108	44.561
Hholds	179.646	4.240	0.005	2.232	0.476	0.131	0.508	63.560	39.401	38.735	4.471	2.588	23.301
Other Sources	684.174	19.322	5.118	11.898	16.982	6.814	31.467	284.508	71.566	91.493	18.897	57.719	68.391
All sources	1,006.791	84.702	10.749	25.486	59.959	14.129	58.128	347.260	114.465	105.807	38.048	66.704	81.353

Table 19: Benchmark 1995 Emissions of Sulfur Dioxide (MT SO_2)

EPPA Sector	World Total	USA	JPN	OOE	EEC	EET	FSU	EEX	CHN	IND	DAE	BRA	ROW
COAL	76.388	16.033	1.417	3.451	8.248	6.435	7.478	4.064	22.874	3.299	1.386	0.352	1.352
AGRIC	0.631	0.022	0.001	0.002	0.027	0.057	0.139	0.048	0.330	–	0.002	–	0.004
OTHERIND	5.368	0.150	0.023	0.134	0.144	0.265	0.512	0.438	2.984	0.451	0.022	0.009	0.237
ENERINT	15.742	0.966	0.458	0.329	1.362	0.591	1.635	0.909	7.682	0.527	0.583	0.274	0.426
ELEC	50.931	14.876	0.935	2.896	6.480	5.160	4.657	2.473	9.654	2.320	0.735	0.068	0.677
Hholds	3.716	0.020	0.001	0.090	0.234	0.362	0.535	0.197	2.224	0.001	0.045	–	0.007
REFOIL	37.298	3.998	0.586	1.432	6.216	1.219	5.165	7.386	3.484	1.504	3.468	1.046	1.794
AGRIC	3.172	0.125	0.021	0.128	0.239	0.149	0.817	0.869	0.333	0.048	0.109	0.142	0.193
OTHERIND	9.093	1.497	0.270	0.469	1.612	0.143	0.526	1.619	0.740	0.522	0.988	0.292	0.415
ENERINT	8.422	1.037	0.100	0.435	1.630	0.276	0.688	1.324	1.152	0.383	0.756	0.408	0.234
ELEC	12.450	0.376	0.045	0.195	1.976	0.587	3.019	3.032	1.038	0.117	1.134	0.105	0.826
Hholds	4.161	0.963	0.149	0.206	0.759	0.065	0.115	0.542	0.220	0.434	0.481	0.101	0.126
GAS	1.554	0.374	0.022	0.013	1.067	0.012	–	0.026	0.031	–	–	0.001	0.007
AGRIC	0.087	0.061	–	–	0.022	–	–	0.001	–	–	–	–	0.001
OTHERIND	0.427	0.145	0.008	0.008	0.241	0.002	–	0.012	0.008	–	–	–	0.003
ENERINT	0.352	0.104	0.006	0.005	0.201	0.003	–	0.013	0.016	–	–	0.001	0.003
ELEC	0.238	0.064	0.008	–	0.152	0.007	–	–	0.007	–	–	–	–
Hholds	0.451	–	–	–	0.451	–	–	–	–	–	–	–	–
All Fuel Use	115.240	20.406	2.025	4.896	15.531	7.667	12.643	11.477	26.389	4.802	4.854	1.398	3.153
REFOIL	10.711	2.056	0.195	0.416	1.988	0.375	1.756	1.935	0.803	0.285	0.434	0.235	0.233
ENERINT	23.279	0.999	0.413	1.012	4.714	1.520	5.079	2.426	2.543	0.284	1.139	0.360	2.790
AGRIC	4.564	0.234	0.007	0.438	0.502	0.029	0.145	1.921	0.145	0.274	0.086	0.467	0.317
Hholds	0.732	0.009	–	0.014	0.002	–	0.002	0.174	0.285	0.126	0.016	0.005	0.098
Other Sources	39.286	3.298	0.615	1.879	7.206	1.924	6.982	6.456	3.777	0.969	1.675	1.068	3.439
All Sources	154.525	23.703	2.639	6.775	22.736	9.590	19.625	17.932	30.166	5.771	6.529	2.466	6.592

Table 20: Benchmark 1995 Emissions of Nitrogen Oxides (MT NO_x)

EPPA Sector	World Total	USA	JPN	OOE	EEC	EET	FSU	EEX	CHN	IND	DAE	BRA	ROW
COAL	23.809	4.578	0.444	1.005	1.790	1.032	2.533	1.223	8.227	1.958	0.421	0.104	0.495
AGRIC	0.183	0.006	–	0.001	0.006	0.011	0.047	0.011	0.099	–	–	–	0.001
OTHERIND	1.652	0.039	0.012	0.045	0.031	0.053	0.173	0.103	0.895	0.226	0.005	0.002	0.068
ENERINT	4.690	0.254	0.244	0.110	0.292	0.118	0.552	0.214	2.305	0.263	0.146	0.071	0.123
ELEC	16.931	4.277	0.187	0.843	1.440	0.826	1.707	0.878	4.706	1.470	0.265	0.032	0.302
Hholds	0.354	0.002	–	0.007	0.021	0.024	0.054	0.017	0.222	–	0.005	–	0.001
REFOIL	55.446	13.814	1.771	3.013	10.497	1.028	3.347	9.983	3.079	1.604	3.142	1.658	2.511
AGRIC	0.406	0.047	0.010	0.025	0.049	0.023	0.078	0.082	0.043	0.004	0.012	0.013	0.020
OTHERIND	31.729	7.976	1.026	1.798	5.969	0.529	1.804	5.727	1.877	0.744	1.772	0.996	1.512
ENERINT	1.420	0.389	0.050	0.086	0.336	0.042	0.066	0.124	0.149	0.031	0.086	0.038	0.025
ELEC	2.689	0.128	0.109	0.043	0.336	0.074	0.654	0.670	0.228	0.023	0.227	0.022	0.174
Hholds	19.203	5.274	0.576	1.061	3.808	0.361	0.745	3.380	0.781	0.802	1.045	0.589	0.781
GAS	11.362	4.433	0.302	0.453	1.507	0.307	2.412	1.324	0.111	0.082	0.119	0.021	0.291
AGRIC	0.845	0.663	–	0.009	0.041	0.003	0.067	0.027	0.001	0.001	0.011	–	0.022
OTHERIND	3.046	1.564	0.031	0.168	0.452	0.056	0.423	0.257	0.022	0.003	0.005	0.005	0.062
ENERINT	2.433	1.126	0.022	0.109	0.376	0.088	0.255	0.294	0.044	0.038	0.006	0.011	0.065
ELEC	4.429	0.958	0.233	0.129	0.380	0.131	1.558	0.734	0.037	0.041	0.092	0.004	0.133
Hholds	0.609	0.123	0.017	0.039	0.258	0.029	0.109	0.013	0.007	–	0.005	–	0.010
All Fuel Use	90.617	22.824	2.517	4.471	13.794	2.368	8.291	12.530	11.417	3.645	3.682	1.783	3.297
REFOIL	2.283	0.521	0.161	0.097	0.412	0.091	0.326	0.296	0.173	0.045	0.075	0.046	0.042
ENERINT	4.763	0.341	0.421	0.198	0.813	0.244	0.723	0.500	0.846	0.154	0.229	0.116	0.178
AGRIC	20.024	1.009	0.038	0.531	0.710	0.172	0.779	9.800	0.844	1.582	0.476	2.373	1.712
Hholds	4.394	0.073	–	0.079	0.010	0.002	0.014	1.151	1.548	0.782	0.111	0.039	0.586
Other Sources	31.463	1.944	0.620	0.904	1.946	0.509	1.840	11.746	3.410	2.563	0.892	2.574	2.517
All Sources	122.081	24.768	3.137	5.375	15.740	2.877	10.132	24.276	14.827	6.208	4.573	4.356	5.813

Table 21: Benchmark 1995 Emissions of Non-Methane Volatile Organic Compounds (MT NMVOCs)

EPPA Sector	World Total	USA	JPN	OOE	EEC	EET	FSU	EEX	CHN	IND	DAE	BRA	ROW
COAL	1.489	0.050	0.036	0.035	0.057	0.074	0.196	0.080	0.855	0.047	0.029	0.008	0.022
AGRIC	0.014	–	–	–	–	0.001	0.004	0.001	0.008	–	–	–	–
OTHERIND	0.135	0.001	0.002	0.004	0.002	0.003	0.013	0.010	0.075	0.018	0.001	–	0.007
ENERINT	0.383	0.006	0.031	0.010	0.020	0.007	0.041	0.021	0.192	0.021	0.015	0.008	0.012
ELEC	0.114	0.037	0.004	0.003	0.014	0.010	0.005	0.005	0.024	0.008	0.002	–	0.002
Hholds	0.843	0.005	–	0.017	0.021	0.052	0.134	0.043	0.556	–	0.013	–	0.002
REFOIL	53.768	9.060	1.938	2.475	8.312	0.912	2.640	11.937	2.770	4.330	5.412	1.379	2.602
AGRIC	0.014	0.003	–	0.001	0.001	0.001	0.003	0.003	0.001	–	–	–	0.001
OTHERIND	33.096	5.417	1.238	1.548	5.042	0.537	1.856	7.477	1.944	2.075	3.392	0.863	1.709
ENERINT	0.057	0.026	0.001	0.003	0.010	0.001	0.002	0.004	0.004	0.001	0.003	0.001	0.001
ELEC	0.041	0.004	0.002	0.001	0.006	0.002	0.008	0.010	0.003	–	0.003	–	0.003
Hholds	20.560	3.611	0.697	0.923	3.253	0.372	0.772	4.443	0.818	2.254	2.014	0.514	0.890
GAS	0.293	0.124	–	–	0.155	0.014	–	–	–	–	–	–	–
AGRIC	0.026	0.025	–	–	0.001	–	–	–	–	–	–	–	–
OTHERIND	0.075	0.058	–	–	0.015	0.002	–	–	–	–	–	–	–
ENERINT	0.058	0.042	–	–	0.013	0.003	–	–	–	–	–	–	–
ELEC	0.016	–	–	–	0.013	0.004	–	–	–	–	–	–	–
Hholds	0.118	–	–	–	0.113	0.005	–	–	–	–	–	–	–
All Fuel Use	55.550	9.234	1.974	2.509	8.524	1.000	2.836	12.017	3.625	4.377	5.441	1.387	2.624
REFOIL	4.374	0.511	0.202	0.124	0.358	0.103	2.107	0.506	0.165	0.059	0.115	0.065	0.061
OTHERIND	31.868	6.191	2.362	1.110	5.205	1.008	2.816	4.104	3.449	2.134	0.821	0.807	1.861
ENERINT	1.262	0.332	0.195	0.034	0.406	0.046	0.100	0.025	0.031	0.016	0.035	0.034	0.008
OIL	18.064	0.147	0.004	0.770	0.886	0.107	3.152	11.140	1.103	0.258	0.021	0.242	0.235
GAS	4.573	1.316	0.040	0.253	0.135	0.183	2.174	0.348	0.023	0.021	0.012	0.008	0.060
AGRIC	44.218	1.741	0.249	1.068	1.663	0.479	1.864	18.605	3.830	5.039	1.169	4.436	4.077
Hholds	31.563	0.727	0.001	0.355	0.080	0.023	0.085	11.610	6.223	7.160	0.752	0.470	4.079
Other Sources	135.922	10.964	3.053	3.713	8.733	1.949	12.298	46.338	14.823	14.687	2.924	6.062	10.380
All Sources	191.472	20.197	5.027	6.222	17.256	2.949	15.134	58.355	18.448	19.064	8.366	7.449	13.004

Table 22: Benchmark 1995 Emissions of Organic Carbon Particulates (MT OC)

EPPA Sector	World Total	USA	JPN	OOE	EEC	EET	FSU	EEX	CHN	IND	DAE	BRA	ROW
Coal	5.919	0.285	0.048	0.074	0.612	0.475	0.812	0.263	2.718	0.401	0.135	0.021	0.077
AGRIC	0.122	0.002	–	–	0.007	0.012	0.029	0.007	0.064	–	–	–	0.001
OTHERIND	0.360	0.003	0.001	0.003	0.009	0.013	0.026	0.022	0.206	0.062	0.002	0.001	0.014
ENERINT	0.984	0.017	0.021	0.007	0.089	0.030	0.082	0.045	0.531	0.072	0.050	0.016	0.025
ELEC	2.117	0.255	0.026	0.036	0.330	0.138	0.207	0.104	0.667	0.266	0.051	0.004	0.034
Hholds	2.335	0.009	0.001	0.028	0.176	0.282	0.469	0.085	1.250	0.001	0.032	–	0.004
REFOIL	1.616	0.147	0.029	0.044	0.154	0.043	0.110	0.439	0.143	0.140	0.176	0.084	0.108
AGRIC	0.150	0.018	0.006	0.009	0.016	0.005	0.030	0.032	0.014	0.002	0.005	0.005	0.007
OTHERIND	0.167	0.020	0.003	0.004	0.014	0.001	0.005	0.053	0.020	0.008	0.017	0.009	0.013
ENERINT	0.060	0.008	0.001	0.002	0.006	0.001	0.002	0.012	0.012	0.003	0.008	0.004	0.002
ELEC	0.046	0.001	0.001	–	0.002	0.001	0.004	0.019	0.006	0.001	0.006	0.001	0.005
Hholds	1.194	0.101	0.018	0.029	0.116	0.035	0.069	0.323	0.090	0.127	0.140	0.066	0.080
All Fuel Use	7.536	0.432	0.077	0.118	0.766	0.517	0.922	0.701	2.861	0.541	0.311	0.105	0.184
AGRIC	34.222	1.540	0.076	1.000	1.280	0.320	1.530	15.700	1.670	3.120	0.946	3.860	3.180
Hholds	11.946	0.303	–	0.159	0.034	0.009	0.036	4.540	2.370	2.330	0.319	0.185	1.660
Other Sources	46.168	1.843	0.076	1.159	1.314	0.329	1.566	20.240	4.040	5.450	1.265	4.045	4.840
All Sources	53.704	2.275	0.154	1.277	2.080	0.847	2.488	20.941	6.901	5.991	1.576	4.150	5.024

Table 23: Benchmark 1995 Emissions of Black Carbon Particulates (MT BC)

EPPA Sector	World Total	USA	JPN	OOE	EEC	EET	FSU	EEX	CHN	IND	DAE	BRA	ROW
COAL	3.481	0.197	0.034	0.044	0.222	0.204	0.351	0.216	1.752	0.280	0.086	0.021	0.075
AGRIC	0.067	0.001	–	–	0.002	0.005	0.013	0.005	0.040	–	–	–	0.001
OTHERIND	0.276	0.002	0.001	0.002	0.004	0.007	0.013	0.022	0.168	0.043	0.001	0.001	0.014
ENERINT	0.722	0.012	0.015	0.005	0.033	0.015	0.040	0.045	0.432	0.051	0.035	0.016	0.025
ELEC	1.420	0.179	0.018	0.025	0.122	0.068	0.102	0.104	0.543	0.186	0.035	0.004	0.034
Hholds	0.996	0.004	–	0.012	0.061	0.110	0.183	0.041	0.569	–	0.014	–	0.002
REFOIL	2.667	0.250	0.052	0.079	0.281	0.077	0.191	0.672	0.207	0.256	0.290	0.139	0.172
AGRIC	0.300	0.036	0.012	0.019	0.033	0.011	0.060	0.063	0.029	0.003	0.010	0.010	0.015
OTHERIND	0.094	0.020	0.003	0.004	0.014	0.001	0.005	0.021	0.008	0.003	0.007	0.004	0.005
ENERINT	0.035	0.008	0.001	0.002	0.006	0.001	0.002	0.005	0.005	0.001	0.003	0.001	0.001
ELEC	0.024	0.001	0.001	–	0.002	0.001	0.004	0.007	0.002	–	0.002	–	0.002
Hholds	2.214	0.186	0.035	0.055	0.227	0.064	0.120	0.575	0.163	0.248	0.268	0.124	0.149
All Fuel Use	6.148	0.447	0.086	0.124	0.504	0.281	0.542	0.888	1.959	0.536	0.376	0.160	0.246
AGRIC	5.401	0.242	0.012	0.158	0.201	0.050	0.241	2.480	0.263	0.493	0.149	0.610	0.502
Hholds	1.792	0.045	–	0.024	0.005	0.001	0.005	0.681	0.355	0.349	0.048	0.028	0.250
Other Sources	7.193	0.287	0.012	0.182	0.206	0.052	0.246	3.161	0.618	0.842	0.197	0.638	0.752
All Sources	13.341	0.735	0.098	0.306	0.710	0.333	0.788	4.049	2.577	1.378	0.573	0.798	0.998

Table 24: Benchmark 1995 Emissions of Ammonia (MT NH_3)

	AGRIC	Hholds	All Sources
USA	2.530	0.389	2.919
JPN	0.182	0.077	0.259
OOE	1.790	0.137	1.927
EEC	3.150	0.294	3.444
EET	0.926	0.076	1.002
FSU	2.560	0.216	2.776
EEX	7.820	1.470	9.290
CHN	9.440	1.230	10.670
IND	6.050	1.050	7.100
DAE	0.813	0.179	0.992
BRA	2.440	0.175	2.615
ROW	4.190	0.735	4.925
Total	41.891	6.028	47.919

4.4 Other Criteria Pollutants, Ammonia, and Carbonaceous Particulate Emissions

For NO_x, SO_2, CO, NMVOCs, and ammonia (NH_3) the main data sources used to derive 1995 inventories were the (i) EDGAR 2.0 emissions inventory for 1990, (ii) energy use for coal, gas, and refined oil as specified in EPPA for 1995, and (iii) data from International Energy Agency (1996) for consumption of refined petroleum products. The default emission coefficients for criteria pollutants for fossil fuel combustion are based on EDGAR coefficients (Olivier et al., 1995). As far as possible we relied on published sources for 1995 emissions data (US Environmental Protection Agency, 1997; Streets and Waldhoff, 2000; van Aardenne, Carmichel, Levy, Streets and Hordijk, 1999; European Environment Agency, 1997; Government of Japan, 1997) in order to take into account recent control technologies. Our estimates of 1995 emissions for all gases by source, mapped to EPPA's sector and region definitions, are shown in Tables 19-21. In all our emissions projections we assume that countries meet their SO_2 targets negotiated under the Convention on the Long-Range Transboundary Air Pollution or other relevant emissions control agreements.[11] This procedure results in

[11] e.g. The 1979 Convention on Long-Range Transboundary Air Pollution: 1985 Helsinki Protocol on the Reduction of Sulphur Emissions or their Transboundary Fluxes by at least 30 percent, and 1994 Oslo Protocol on Further Reduction of Sulphur Emissions. In the current version of EPPA we assume that these SO_2 emission targets are achieved at no cost.

the following emissions (in MT): USA 16.83 (US Environmental Protection Agency, 1997); Japan 0.85 (Government of Japan, 1997); Other OECD nations 4.169 (Government of Australia, 1997; Government of New Zealand, 1997; United Nations Economic Commission for Europe, 1999); the European Union 10.684 and European economies in transition 6.557 (United Nations Economic Commission for Europe, 1999); and 25.178 for China (Streets and Waldhoff, 2000). Emission coefficients for black carbon aerosol (BC) and organic carbon aerosol (OC) were taken from Cooke, Liousse, Cachier and Feichter (1999) using the coefficients for bulk aerosol. BC and OC emission estimates from biomass burning are based on Liousse, Penner, Chuang, Walton and Eddleman (1996). The estimated benchmark emissions of these substances are shown in Tables 18-24.

4.5 Changes in Emissions Coefficients Over Time

A key additional consideration for projecting future emissions is the way in which these emission coefficients are likely to change over time, independent of climate policy. In our approach we classify emission coefficients into two categories. The first and more straightforward is the group of coefficients that is used to estimate emissions of various local air pollutants that result from fossil fuel burning. For these, EPPA provides the physical quantities of the different fuels, and the coefficients are based on measured data that is widely available. It has also been widely observed that the levels of these pollutants tend to decline as economies become wealthier, a phenomenon that is thought to reflect a demand for environmental quality that is income elastic (Selden and Song, 1994; Grossman and Krueger, 1995). By fitting power series functions to the data, we are able to capture the decline of emission coefficients over time as a function of the increase in GDP per capita.[12] The other category of emission coefficients is used to derive emissions from sources other than fossil fuel use. Here EPPA lacks the physical process detail to project tons of ore smelted, hectares of rice paddies, head of ruminant animals, or other relevant physical indicators of the emissions described in Tables 15 and 16. We make this category of emission coefficients time dependent in order to reflect the fact that over time there has tended to be a decrease in material outputs of the economy relative to the quantity of output measured in economic terms. For energy, this stylized fact has been represented by the AEEI parameter.

There are a number of phenomena that permit the economy's dollar-value of output to grow relative to physical output such as head of livestock or numbers of microprocessors. The first is a shift in the composition of production at the sectoral level, such that the mix of products within each sector tends toward higher quality, higher priced goods. For example,

[12] An exponential function is used in the case of SO_2 emissions from coal combustion.

Table 25: Average Exponential Rates of Change of EPPA Emissions Coefficients, 1995-2100

Pollutant	Activity	USA	JPN	OOE	EEC	EET	FSU	EEX	CHN	IND	DAE	BRA	ROW
CO_2	Deforestation	-0.041	-0.039	-0.042	-0.039	-0.043	-0.047	-0.041	-0.053	-0.05	-0.059	-0.047	-0.053
PFC	ENERINT	-0.025	-0.024	-0.027	-0.024	-0.027	-0.026	-0.021	-0.03	-0.029	-0.021	–	-0.025
NMVOCs	OTHERIND	-0.018	-0.017	-0.018	-0.018	-0.021	-0.019	-0.02	-0.032	-0.032	-0.022	-0.024	-0.024
SO_2	ENERINT	-0.018	-0.017	-0.018	-0.018	-0.021	-0.019	-0.043	-0.043	-0.043	-0.043	-0.043	-0.043
CH_4	AGRIC	-0.018	-0.018	-0.018	-0.015	-0.019	-0.019	-0.013	-0.029	-0.026	-0.018	-0.018	-0.021
N_2O	AGRIC	-0.019	-0.018	-0.018	-0.015	-0.015	-0.018	-0.018	-0.031	-0.027	-0.021	-0.016	-0.022
SO_2 CO N_2O and NMVOCs	Hholds	0.001	-0.001	-0.001	0.002	-0.001	0.002	0.007	0.001	0.006	0.005	0.005	0.011

to get the physical output of the aggregate agriculture sector (AGRIC) one literally needs to add together the values of apples and oranges (and wheat, rice, beef, lumber, and hundreds of other products). In the energy-intensive industry sector (ENERINT) a changing array of chemicals is being aggregated with cement, steel, and aluminum production. And even within a relatively homogeneous subset of this industry like ferrous and non-ferrous metals, trends toward (for example) increased recycling and the manufacture of high-performance steel has tended over time to reduce the material intensity of the economic output of the sector. The EPPA model does not contain the level of detail necessary to directly represent these kinds of changes. A consistent change in the product mix over time can lead to a trend in emissions coefficients attached to aggregate sector production even if, for example, emissions per ton of iron ore, head of livestock, or per hectare of rice are not changing.

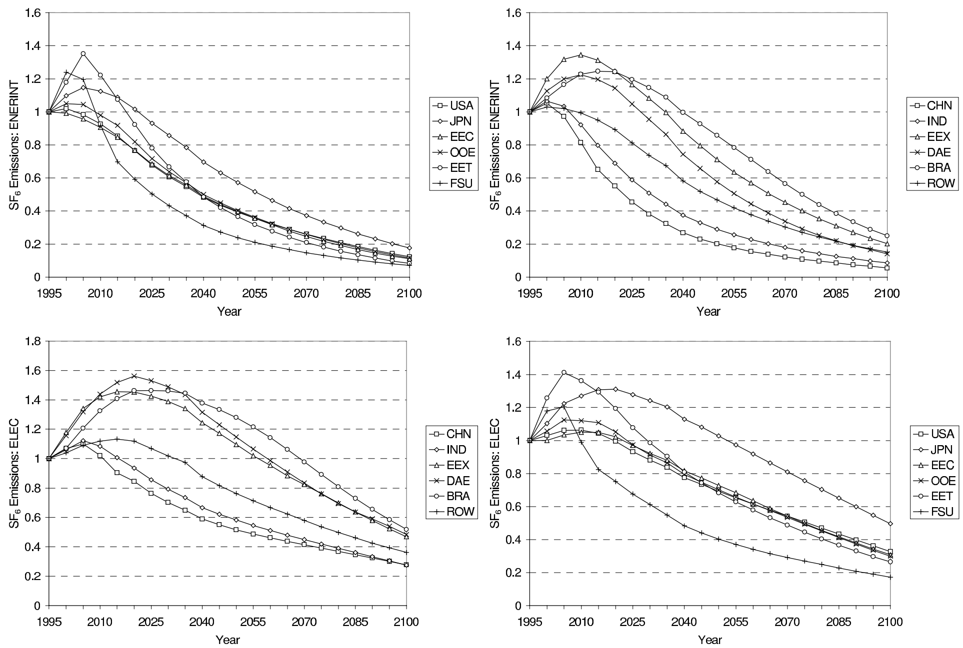
To capture both of the above types of trends we assessed historical data and detailed forecasts of physical quantities relative to GDP and sector output that are directly indicative of processes that lead to emissions of GHGs and other pollutants. We used these trends and relationships to establish trends in emissions coefficients that would correct for the fact that EPPA, itself, did not capture the changes in product mix and structural change in the economy below the scale of resolution of the model.

For SF_6, PFCs and HFCs we based our estimates on Harnisch (1999) and Harnisch et al. (2000), who assessed the growth in the specific activities that are responsible for these emissions and came up with plausible trends in emissions coefficients at this detailed level. Our emissions coefficients change over time to reflect the middle case estimates reported in these papers. For CH_4, N_2O, and NH_3 agricultural emissions are quite important, particularly in developing countries. We evaluated projections of growth in world and regional rice production and area, harvested area, nitrogen fertilizer use, and livestock production, making assumptions about population and yield growth to extend these projections through 2100, and applying emissions coefficients from Intergovernmental Panel on Climate Change (1996) and Bouwman, Lee, Asman, Dentener, van der Hoek and Olivier (1997) to generate a reference emissions projection. For this purpose, projections of agricultural production, land use, yield and fertilizer use were from Agcaoili and Rosegrant (1995), Oram and Hojjati (1995), Daberkow et al. (1999) and Brown (1995). The change in the coefficients governing CH_4 emissions from the OTHERIND sector are modelled using the same trends as in agriculture, due to the fact that the bulk of these methane emissions emanate from the food and beverage processing industry. For the final consumption sector in EPPA we assume CH_4 emission coefficients that are consistent with the assumption of a constant level of consumption-related methane emissions per capita.

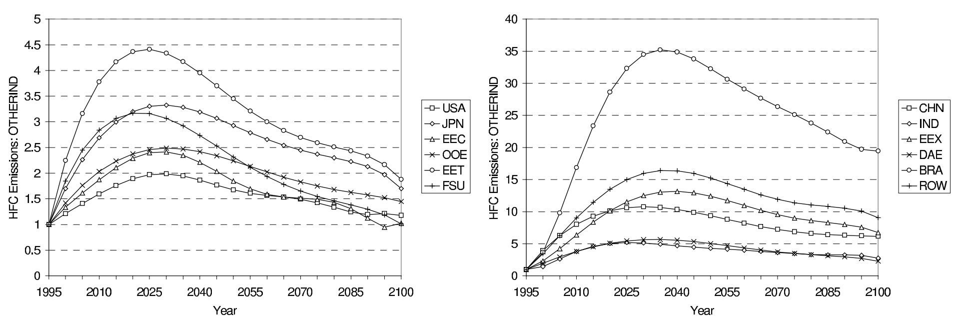
Energy intensive industry production is another important source of emissions for many

Figure 12: Assumed Regional Trends in Emissions Coefficients for Non-CO_2 Gases

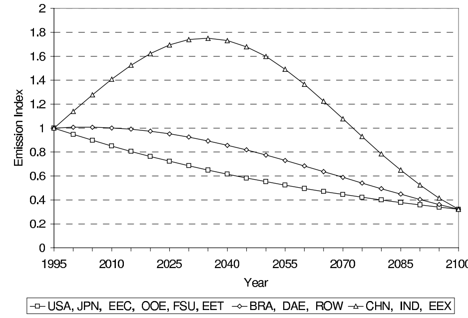
SF_6 from Energy Intensive Industry and Electricity Generation



HFCs from Other Industry



Non-SO_2 gases from Energy Intensive Industry



of these gases. In this case, we used historical statistics to estimate an elasticity of increase in physical output to overall GDP growth in real economic terms. This elasticity varies by stage of development. We computed a separate elasticity for developed countries, middle-income countries, and poor countries. In general, this elasticity was far below unity in developed countries, about unity in middle-income countries, and considerably higher in poor countries. Long-term data on physical production existed mainly for crude steel production and we used this for an overall proxy for physical quantity of energy intensive production. Data on historical output in physical units were from Mitchell (1998), real GDP (non-purchasing power parity, adjusted to be consistent with the EPPA data) from Penn World tables (Summers and Heston, 1991) and on trends in emission from US Environmental Protection Agency (1997).

NMVOC emissions from solvent use is related to other industry. As for emission coefficients from fossil fuel combustion we fit the dependence of the coefficient on GDP per capita with a power series. For biofuel use in households we based our reference projections on population growth. Agricultural waste and savannah burning emissions are assumed constant through time, emissions from deforestation decline, assuming that in 2100 only 10 percent non-sustainable use occurs. We used emissions coefficients per unit of oil and gas applicable to electric power generation from oil and coal for shale oil and coal gas, respectively, on the basis that the centralized production of these fuels would be subject to similar emissions controls. In the reference scenario these fuel sources begin to enter after 2030 as fossil fuel prices from conventional sources rise.

Changes in coefficients over time, derived as described above and in more detail in Mayer and Hyman (2000), are specified in the model as period-by-period coefficients. For those trends in emissions coefficients given in Table 25, the time path is approximated well by an exponential rate of change over time. For other emissions sources, the trends in the coefficients are more complex (Figure 12). Emissions from household use of biofuels, while reported by the EPPA model are exogenous assumptions, and, as described above, are related to population growth. The rate of growth for these emissions in each region is given in Table 25.

5 Characteristics of the Reference Solution

The set of assumptions and parameters reported in the previous sections give rise to a reference set of projections of GNP and energy growth and changes in relative prices and the composition of each of the 12 regional economies. The assumptions about labor productivity growth and exogenous changes in energy efficiency and the values of other parameters have been chosen to represent our best judgment. But, the results are a projection rather than a firm prediction of the future. Even projections of economic change over the next few years are subject to error and uncertainty, and reasonable cases can be made for other projections that might vary considerably from these. Reference projections, however, have been repeatedly shown to be the single most important factor affecting estimates of the costs of meeting a specified greenhouse gas emissions target. It is thus important to have a clear picture of the reference projections from a model as one factor that can explain estimates of policy costs derived from it. This section presents some of the key projected variables. We provide comparable historical data where possible to show the extent to which the forecasts are a continuation or break from historical trends.

5.1 GNP Growth and Composition

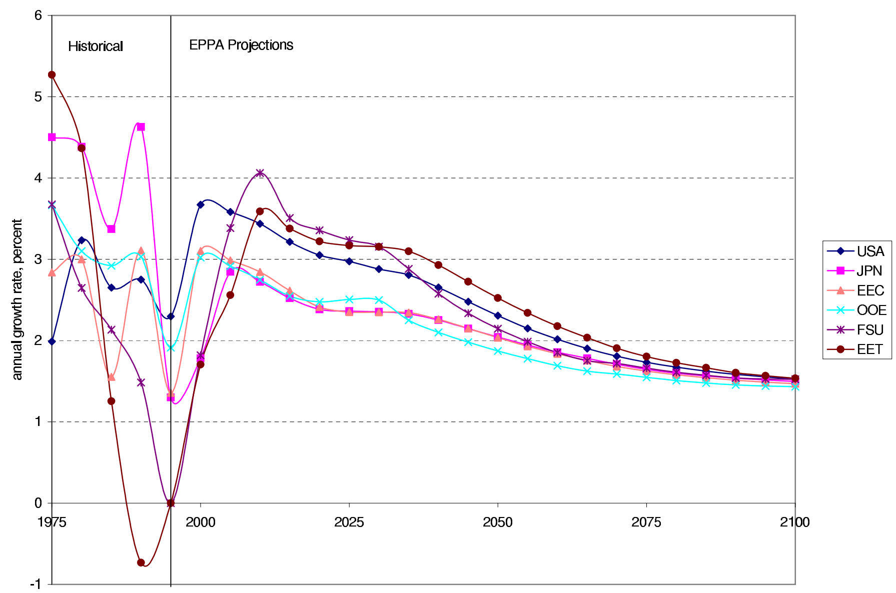
Figure 13 shows developed and transition economies (Panel A) and developing regions (Panel B) GDP average annual growth rates (5-year period averages) for the historical period of 1971 to 1995 and for EPPA projections of GNP growth through 2100.[13] Over the past 25 years these rates have been in the 2 to 5 percent range. Japan exhibited the most rapid growth for much of first part of this period but growth there slowed to only 1.3 percent for the 1990-95 period. Projected growth rates show less period-to-period variability as the EPPA model does not attempt to capture business cycle fluctuations. Among the OECD regions, projected growth for the US slows gradually from the unprecedentedly rapid rates experienced from 1995-2000. Japan's growth recovers somewhat. Growth in all OECD regions slows very gradually through 2040 and somewhat more rapidly after that, with all regions converging to a rate of 1.5 percent by 2100. These trends are indicative of the changing size and productivity of the regions' labor forces, which in turn reflect lagged trends in their populations.

The FSU and EET experienced large declines in GDP (negative growth rates) in the 1990s. The projections show these regions to recover and for their growth rates to slightly

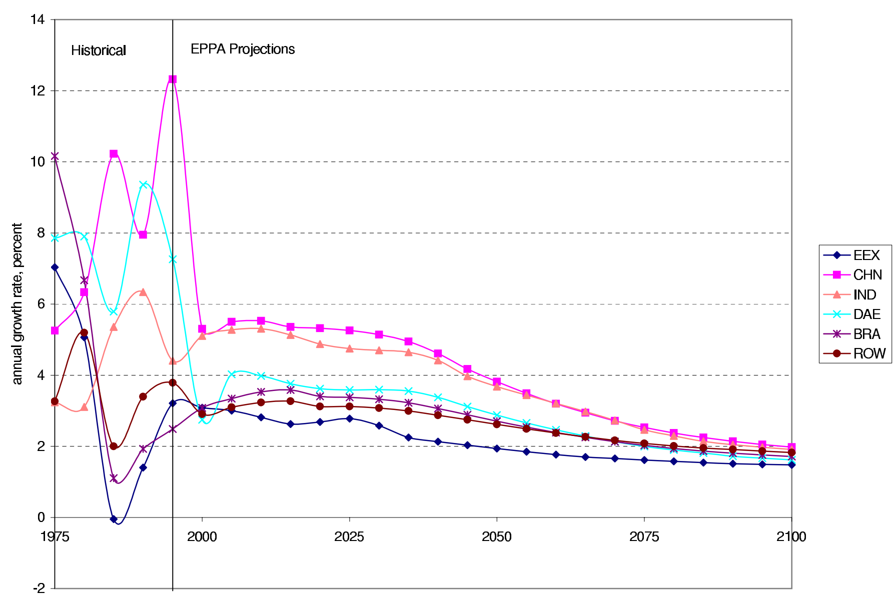
[13]There are slight differences in the definition of GDP and GNP. Growth rates are not substantially affected by these differences so that the historical GDP and projected GNP growth rates presented here are comparable.

Figure 13: Assumed Rates of GNP Growth

A. Developed and Transition Economies



B. Developing Economies



exceed those in the OECD regions over the first half of the next century before converging to a similar 1.5 percent rate of growth by 2100.

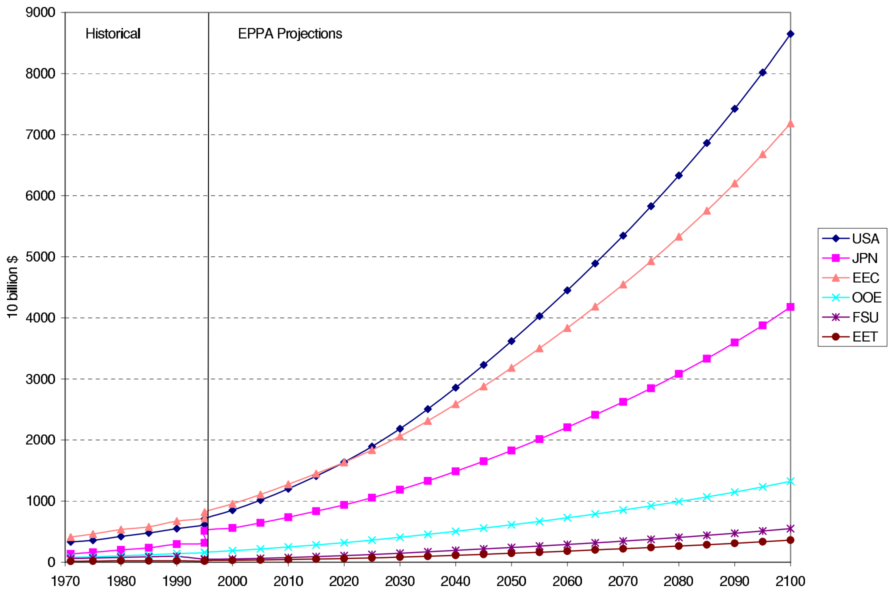
Among developing regions, China experienced remarkably high growth rates, particularly over the past 20 years. The variation in the historical growth among these regions and from period-to-period is far wider than for the OECD regions. The EPPA projections show China and India exhibiting more rapid growth for most of the next century than other developing regions but the rate of growth in China is far slower than in recent decades. The remaining developing regions exhibit growth in the range of 3 to 4 percent through 2040, although EEX (including oil exporters and much of Africa) lags somewhat behind in the 2 to 3 percent range. After 2040, growth in all developing regions slows following the general pattern in the developed regions but converging to a slightly higher rate of 1.8 percent growth in 2100.

Figure 14 shows the resulting levels of GNP in the EPPA regions. The more rapid growth in the USA leads to an economy becoming larger than the EEC by 2020. More exact comparisons across regions of economic size and well-being would require conversion of economic data presented here using indices of purchasing power parity (PPP). Such indices attempt to correct for measurement biases that change consistently over the course of development. The results presented here use the convention in the GTAP data set of converting foreign currencies into US dollars using exchange rates unadjusted for PPP. Therefore, cross-region comparisons of GNP per capita or energy use per dollar of GNP based on these results alone can be misleading. Nevertheless, converting these data to PPPs will have no effect on the regional patterns of growth over time that we assume in EPPA. Thus, these unadjusted numbers are valid for making projections of regions' emissions trajectories. China's and India's economies grow as a share of developing countries and overall, developing countries GNP, measured at 1995 exchange rates, increase from 13.6 percent in 1995 to 36 percent in 2100.

The composition of each of the regional economies also changes over time along the baseline solution. The agriculture share of total output is plotted in Figure 15. These shares are determined by many factors (changes in relative factor prices, intermediate demands, final demands, and trade). As discussed previously, EPPA includes adjustment in the shares and substitution elasticity of per capita income increases toward the current level of the developed regions of the OECD. This feature means that share of agriculture in final demand, in the absences of other changes, would decline with increases in income per capita and this would tend to decrease the share of agriculture in production and increase the share of other industry in production in this regions. Such a trend is evident in China, India, EET, and Brazil though less pronounced or not evident in other regions. Changes in trade and comparative advantage among regions in agricultural production, the rate of per capita income improvement, and the level of development all contribute to changes in the composition of

Figure 14: Reference GDP

A. Developed and Transition Economies



B. Developing Economies

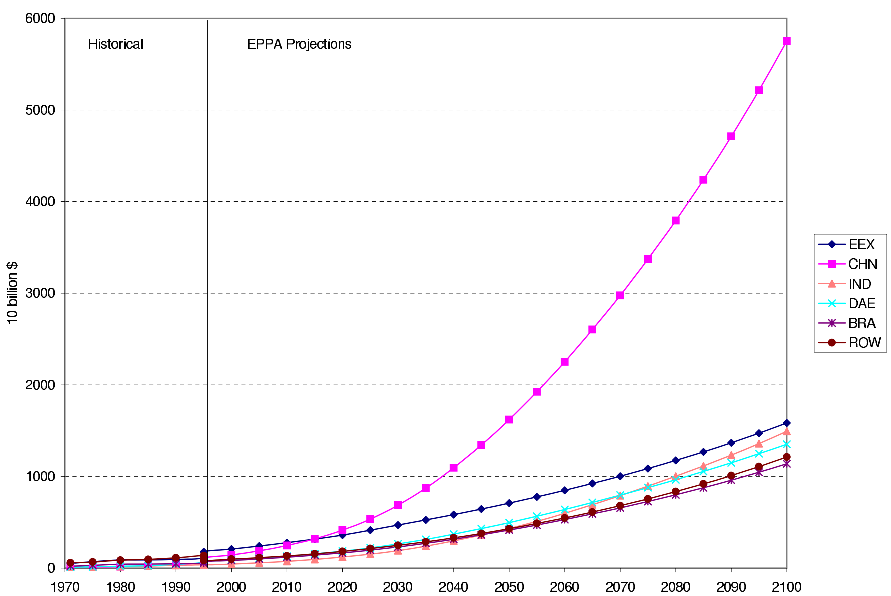
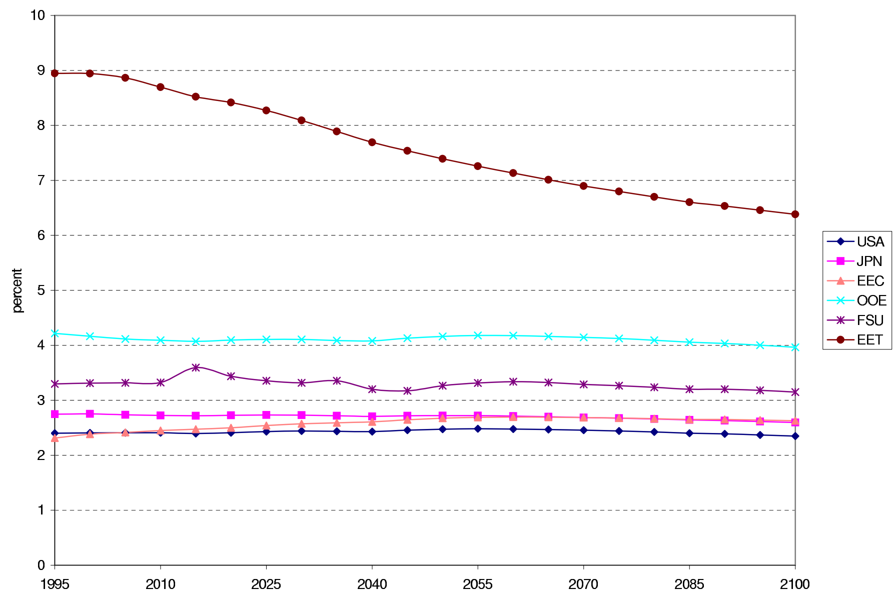


Figure 15: Share of Agriculture in Total Output

A. Developed and Transition Economies



B. Developing Economies

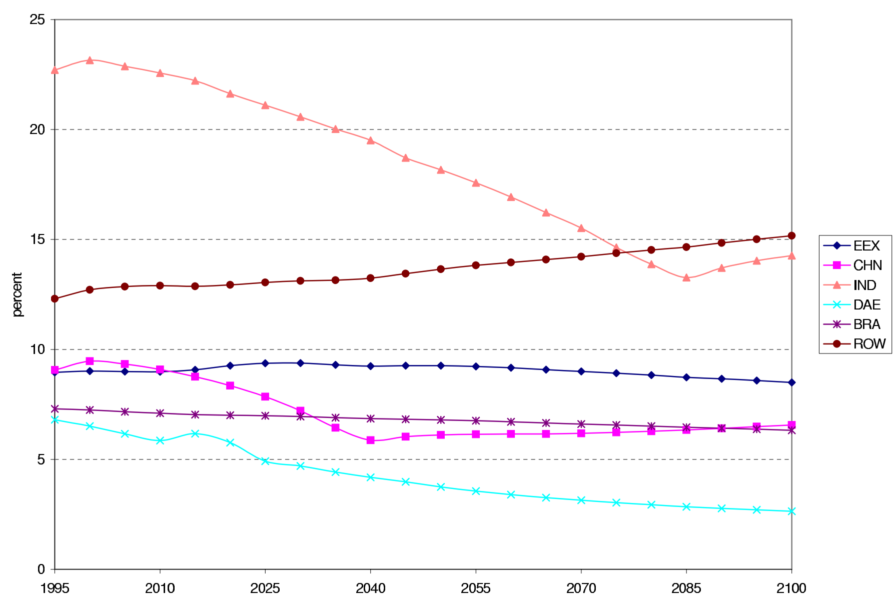
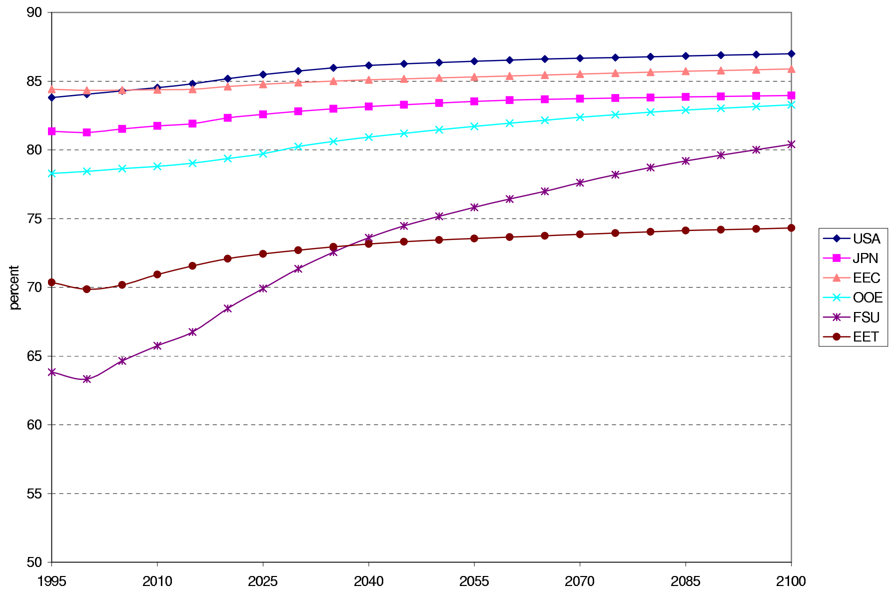
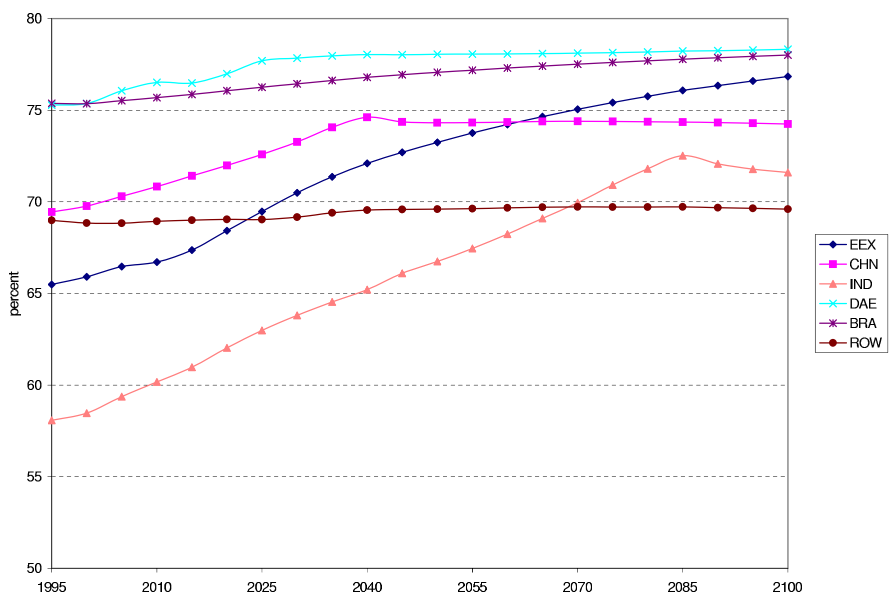


Figure 16: Share of Other Industry in Total Output

A. Developed and Transition Economies



B. Developing Economies



economies over time. The changes in the agricultural share are essentially mirrored in the other industry share (Figure 16) as the remaining industries (energy producing industries and energy intensive industry) are small shares of the economies of these regions.

Another aggregate economic indicator is the capital/labor price ratio (Figure 17). In general, these show rising capital prices relative to labor prices, particularly in the period through 2030. These patterns largely result from the pattern of labor productivity growth. Labor productivity growth is modeled as an increase in the effective labor force, essentially an increase in number of workers. The result is effective labor force grows rapidly in early years and labor supply growth is rapid compared with growth in capital. The result is that labor prices per effective unit of labor falls relative to capital. This convention for labor price does not allow direct comparison to wage rates as normally measured in the economy (i.e. per hour of work). For example, a fall in the labor price as measured in EPPA of 25 percent as productivity doubled would mean that the hourly wage of an worker would actually increase by 75 percent because that worker is now able to do two hours of work in one hour. This would appear as a 75 percent increase in wage income.

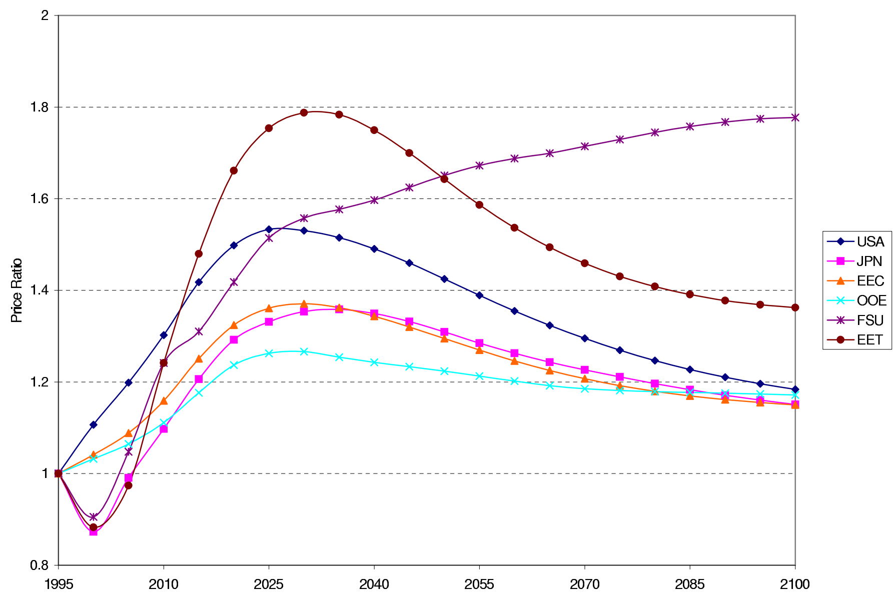
5.2 Energy Consumption and Energy Prices

The growth rates of energy consumption in the model are shown in Figure 18. The EPPA projections show a slowing of rate of growth of energy consumption in developed and developing regions from historical rates, the slowing is more pronounced in the developing regions. Energy consumption growth recovers in the FSU and EET from the large declines in the 1990s and then exhibits a pattern similar to the developed regions. Energy consumption patterns are the result of many separate effects. GNP growth is an important determinant and the slowing growth in energy consumption thus reflects the pattern of growth in GNP. Exogenous growth in energy efficiency is also important and, thus, it is not surprising that the growth rates of energy consumption are lower than the growth rates of GNP.

Energy prices are another important factor. In EPPA, energy prices generally rise over time. In EPPA energy prices, along with all other prices, are market-clearing prices and thus reflect changes in supply and demand. Rising prices mean, however, that demand is growing more rapidly than supply and, thus, energy consumption is lower than it would have been without the rise in prices. The generally rising prices are thus another reason why energy consumption grows slower than GNP. Figure 19 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. The price path is specified for the period through 2010. After 2010, the resource depletion model takes over, resulting in a rapid rise in prices through 2030. After

Figure 17: Baseline Ratio of the Capital Rental Rate to the Wage, Relative to 1995

A. Developed and Transition Economies



B. Developing Economies

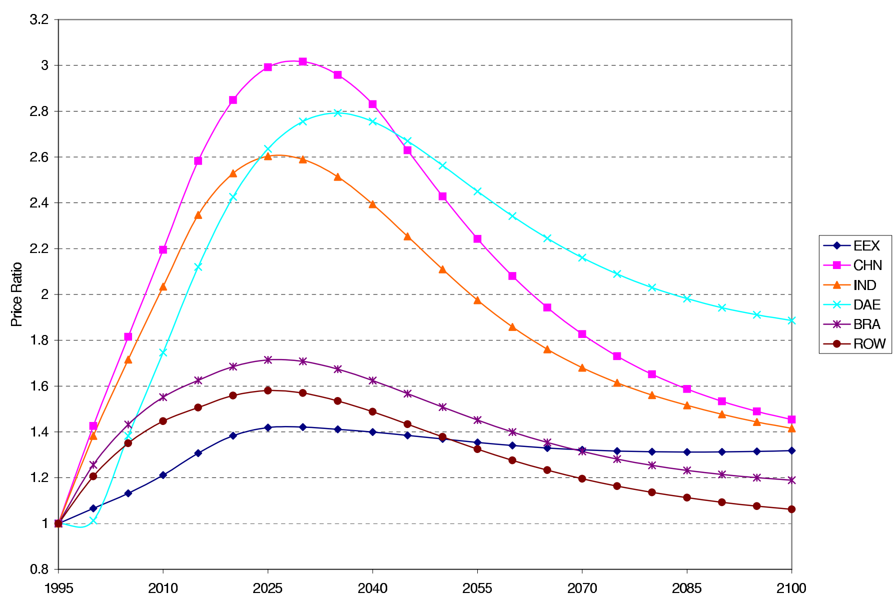
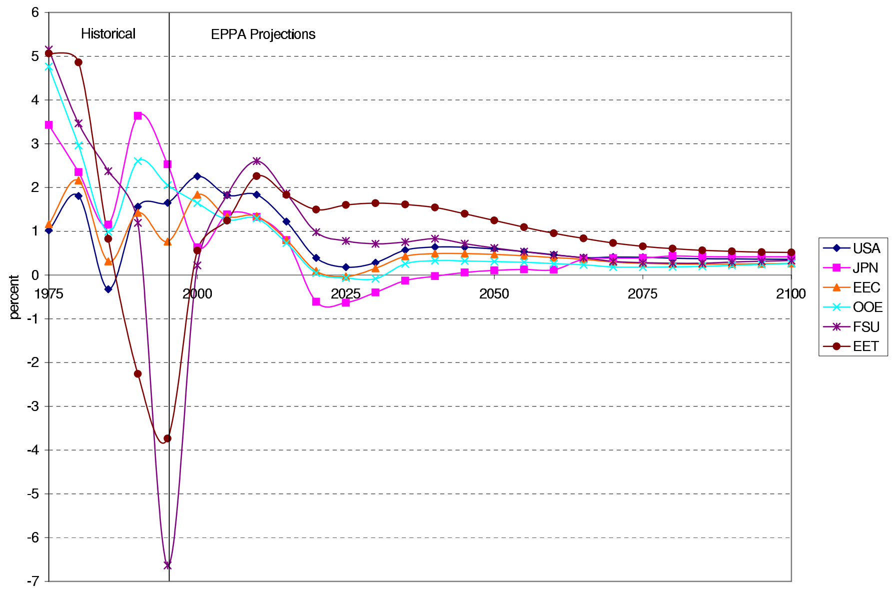


Figure 18: Assumed Rates of Growth of Energy Consumption

A. Developed and Transition Economies



B. Developing Economies

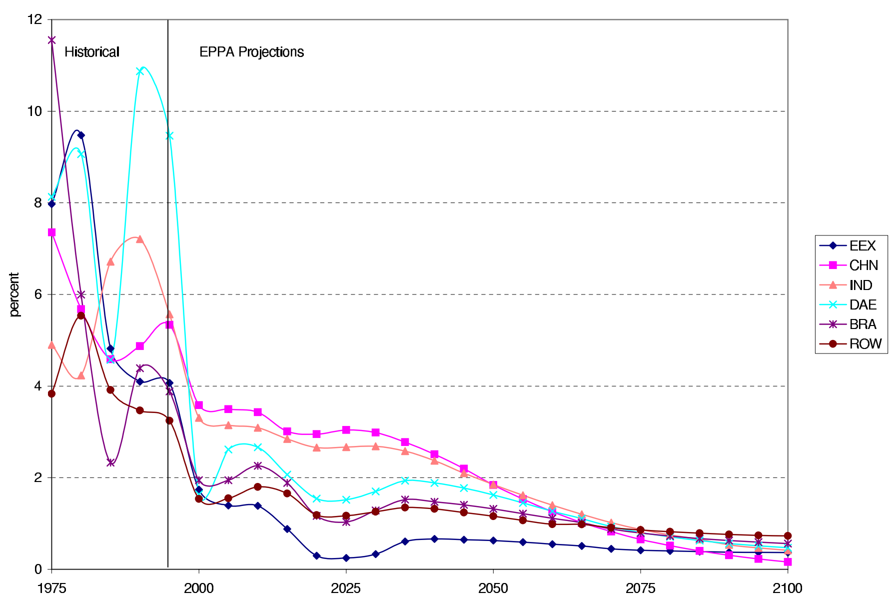
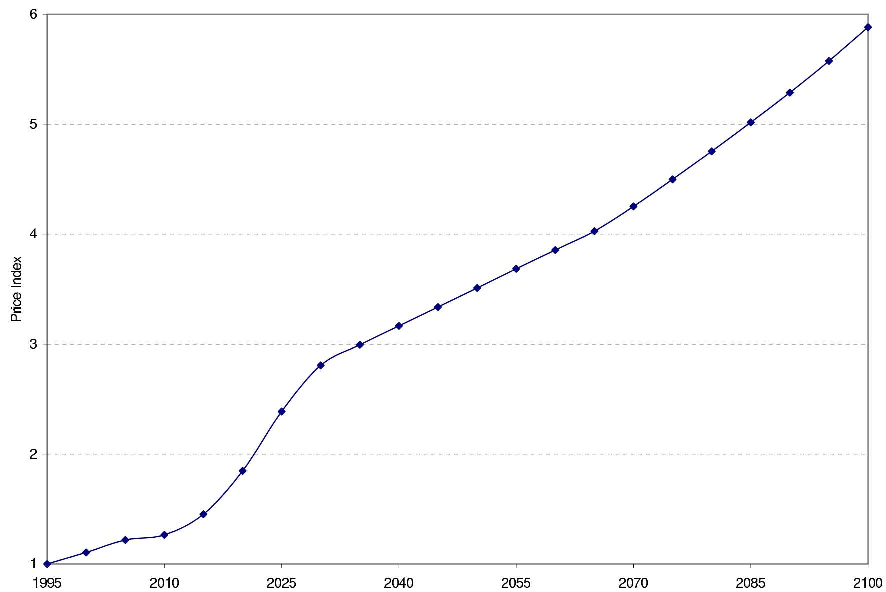


Figure 19: Evolution of the World Oil Price

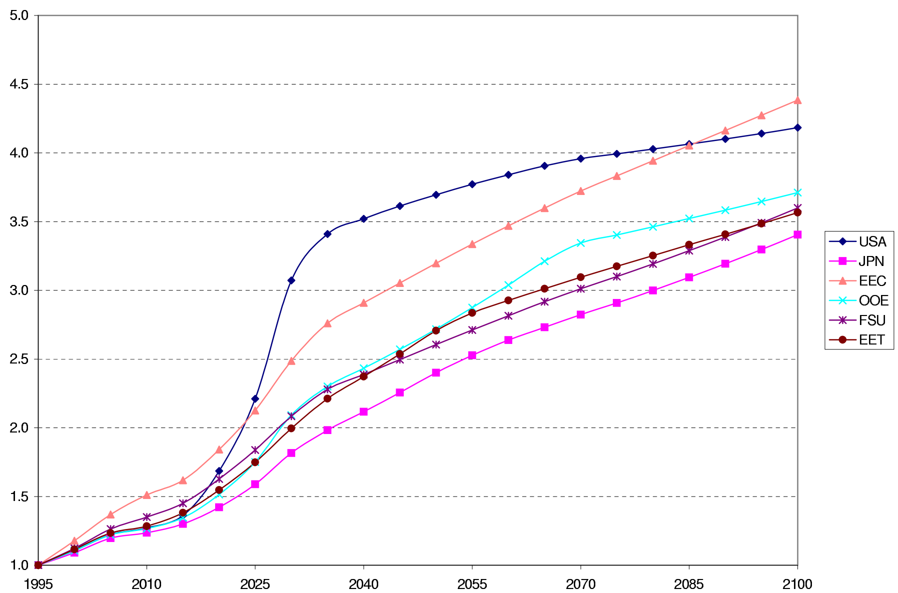


2030 this rapid increase is partially mitigated by the availability and entry into the market of shale oil backstop technology. The continued rise in the oil price over the remainder of the simulation is driven by the depletion of the shale oil resource, for which other inputs are assumed to have limited substitutability (Figure 11, Panel A). Gas and coal price trends differ among regions (Figures 20 and 21, respectively) because gas and coal are modeled as Armington goods. Foreign and domestic sources are close substitutes, however, and thus the overall trend is similar among regions. Gas prices also increase somewhat more rapidly after the resource depletion model is activated after 2010. In later years, price increases are moderated somewhat by the availability and introduction of coal gasification.

Coal price increases are much smaller than for oil or gas because depletion is not a significant factor for coal. Price increases accelerate somewhat in late years as coal gasification places greater demand on coal resources. The pattern for India stands out from other regions. This result is due to several factors. GNP and energy demand growth is rapid and in comparison domestic resources are relatively limited. In addition, a feature of the Armington specification is that it tends to preserve the initial share of foreign versus domestic goods and limit the ability to substitute foreign goods for domestic goods particularly if in the base year the share foreign goods is very small. This is the case for India for coal and gas. The limited ability to substitute foreign for domestic goods may not be realistic over the longer term. The implications are that India shifts more toward imported oil (a Heckscher-Ohlin

Figure 20: Evolution of Regional Gas Prices

A. Developed and Transition Economies



B. Developing Economies

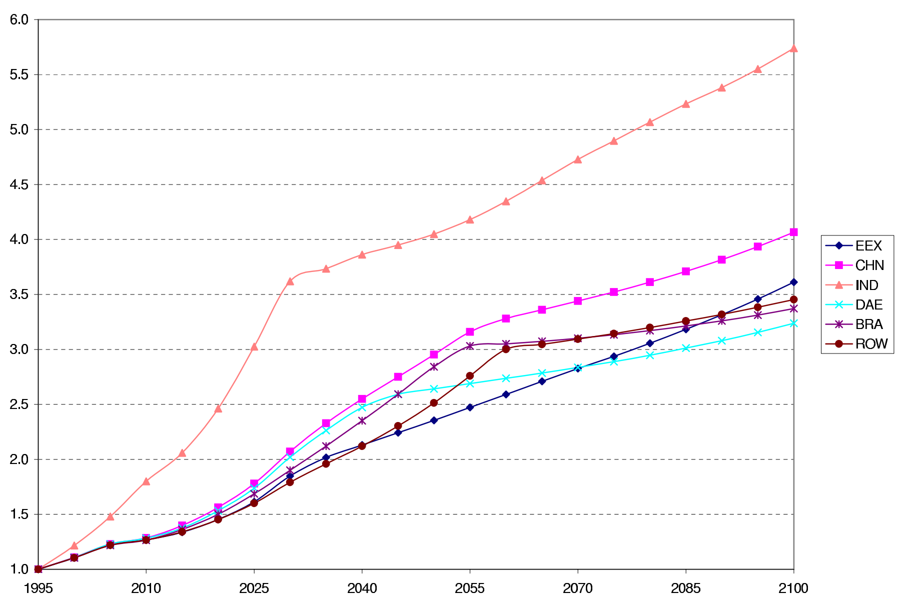
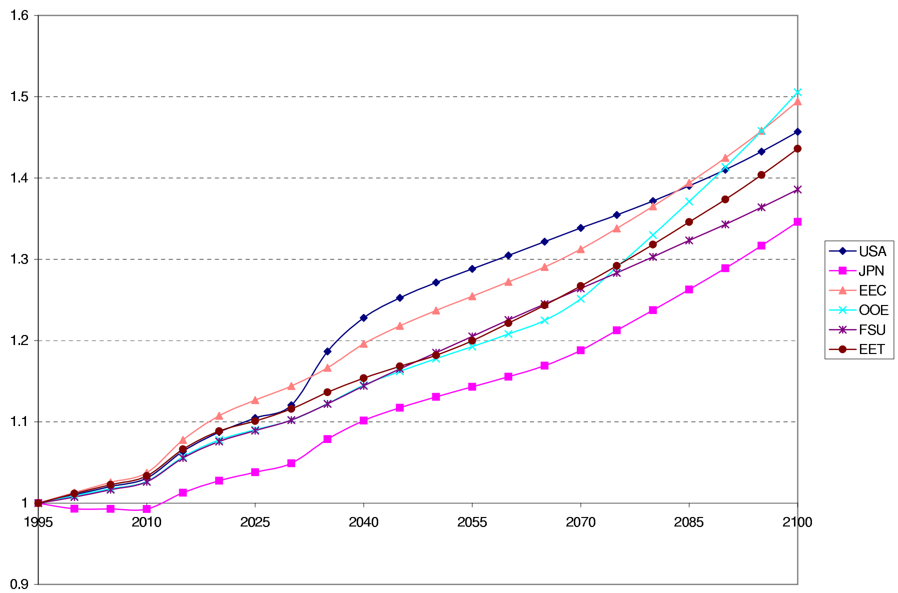


Figure 21: Evolution of Regional Coal Prices

A. Developed and Transition Economies



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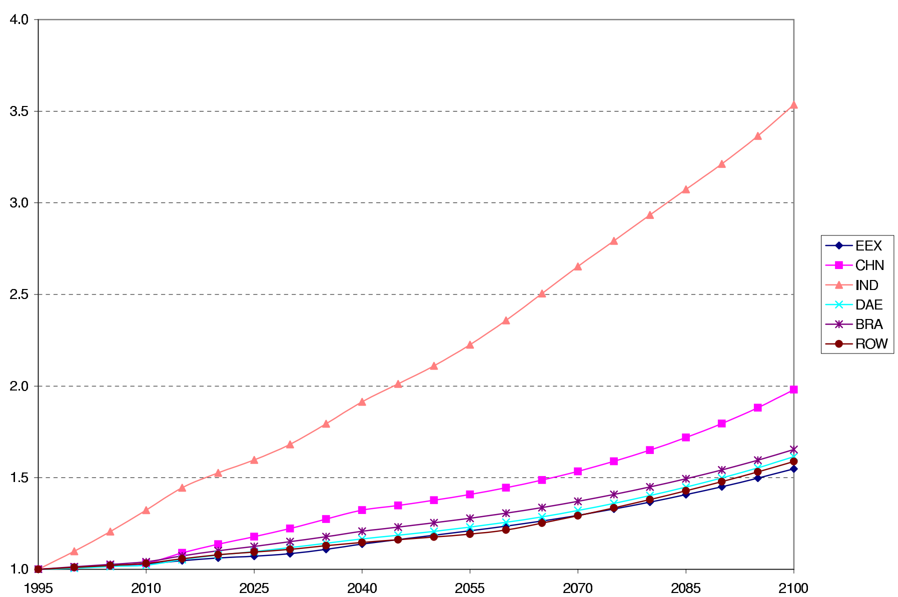


good) and less toward imported coal and gas. While accurate projections for energy use in India would require further investigation of the reasonableness the Armington shares, the substitution of oil (with carbon emissions per unit of energy midway between gas and coal) for a combination of coal and gas would not be expected to substantially alter the overall carbon and energy projections for the world.

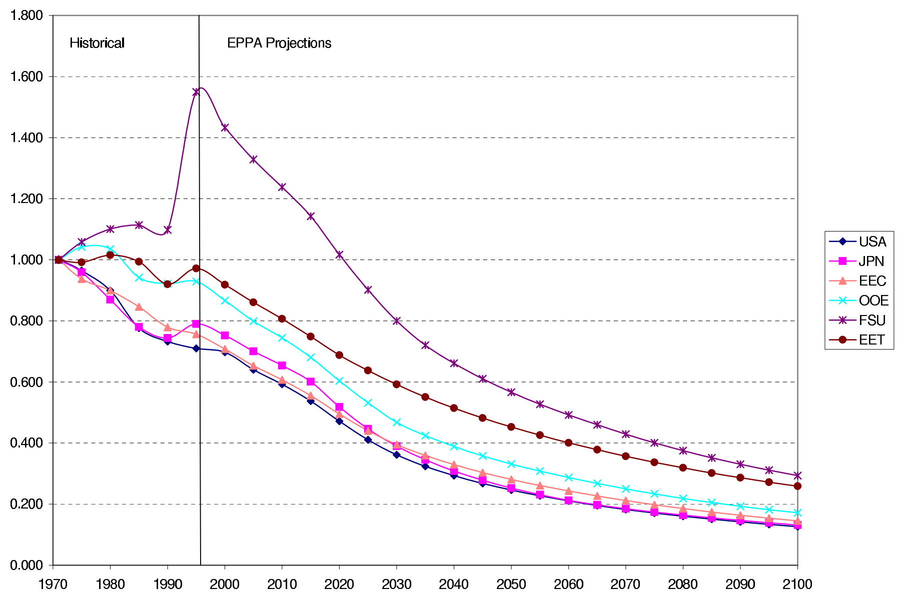
The overall pattern of energy prices, with particularly rapid increases in the 2015 to 2040 periods, are reflected in the pattern of energy consumption growth rates that are particularly low (and even negative in Japan) over this period. Even with this unevenness in consumption growth, the projected rates do not exhibit as much period-to-period variability as historical rates. Again, EPPA does not project business cycles or the types of shocks to energy markets that can produce wide year-to-year changes.

5.3 Energy Intensity of GNP and Energy/GNP Elasticities

Energy intensity of GNP and the energy/GNP elasticity are two closely related measures that summarize the relationship between energy and GNP in an economy. Energy intensity is simply energy consumption in heat units divided by GNP. Changes in energy intensity over time, including the historical period since 1970 and EPPA projections through 2100, are presented in Figure 22. 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 GNP to comparable units (e.g. US dollars) and this, to be an accurate indicator, requires use of purchasing power parity indices. To avoid a misdirected comparison of absolute levels we report the value as an index equal to 1.0 in 1970 in all regions. Panel A of Figure 22 shows that for the developed and transition economies energy intensity has generally declined over the period 1970 to 1995 and EPPA projects continued declines through 2100. The exception is FSU. The substantial rise for 1990 to 1995 reflects the fact that GDP fell far more than energy use over that period. For most developing countries regions there was a small increase in energy intensity between 1970 and 1995 (Figure 22, Panel B). The two exceptions are EEX—where the intensity nearly doubled, and China—where intensity has halved. China's pattern of historical energy intensity of GDP is due to economic restructuring that has progressively ameliorated sources of inefficiency since the 1980s. The EEX regional grouping is an aggregate encompassing some of the poorest developing countries of Africa. In the early stages of development that these countries currently find themselves, energy intensity of output is traditionally high and is likely to rise over time, being reinforced by industrialization through energy intensive production activities that take advantage of abundant energy supplies and low prices. EPPA projections show a

Figure 22: Evolution of Regional Energy-Intensity of GNP

A. Developed and Transition Economies



B. Developing Economies

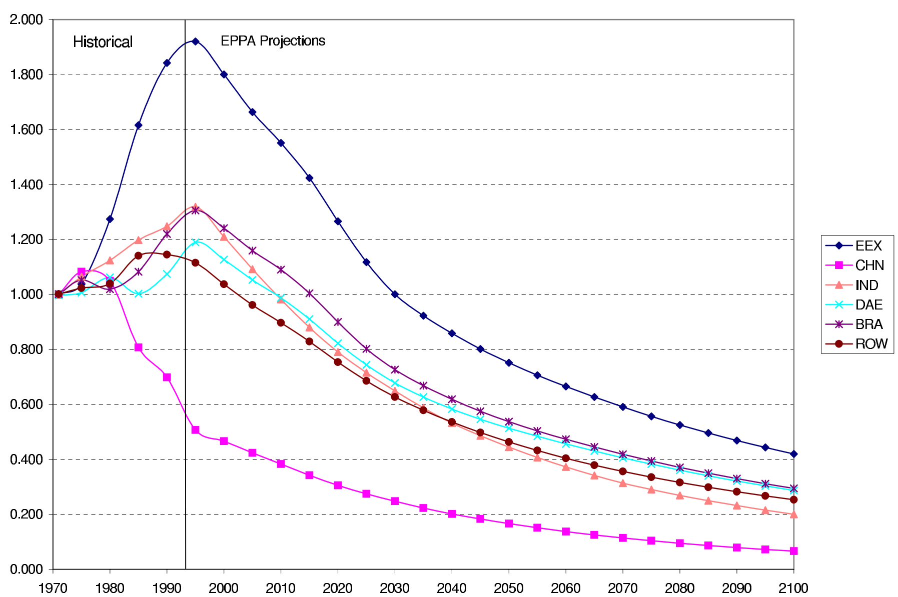
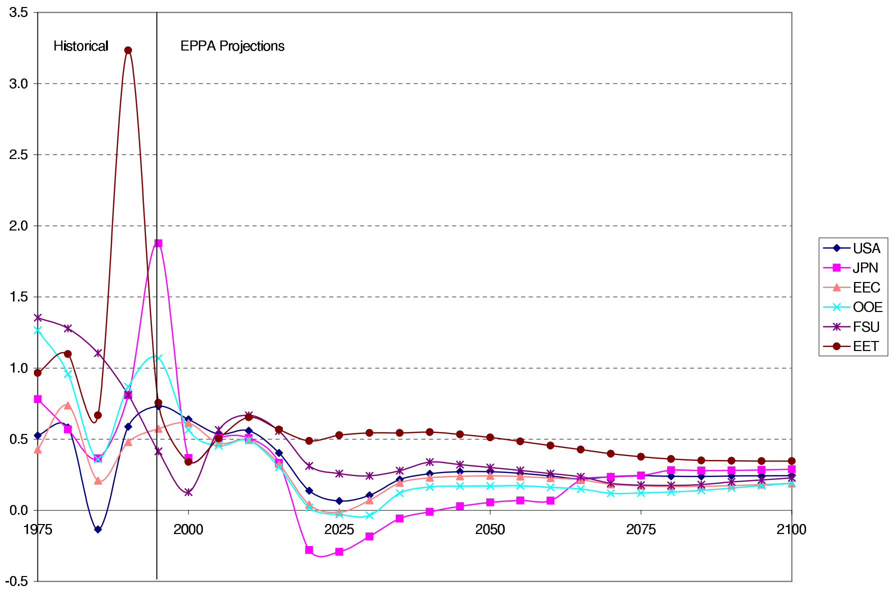
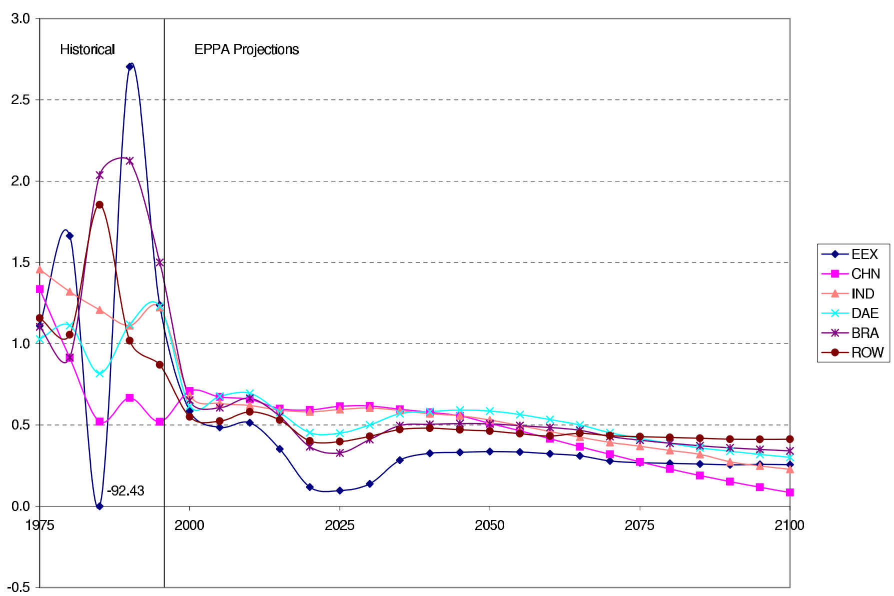


Figure 23: Energy-GNP Elasticities

A. Developed and Transition Economies



B. Developing Economies



declining energy intensity of GNP for all developing regions after 1995.

The energy/GNP elasticity is the percentage change in energy use divided by the percentage change in GNP. Elasticities are unitless and thus directly comparable across economies. These are essentially the rate of change of the energy intensity and are thus far more variable than the energy intensity itself. Historical energy/GNP elasticities were particularly variable but were generally above one for developing countries and below one in developed countries (Figure 23). This pattern must necessarily be observed given the observations on energy intensity (decreasing in developed economies and increasing in developing regions). EPPA projections exhibit energy/GNP elasticities that are very comparable across regions (developed, transition, developing) starting out at just above 0.5 for all regions and declining to a value on the order of 0.25, with some variation among regions, by 2100. These projections reflect a significant decoupling of energy use and economic growth that shows no precedent, with the exception of a single 5-year period for some regions, in the 1970-1995 data. While we have not attempted a formal attribution of the source of this decoupling, the consistent and substantial rise in fossil energy prices projected as part of the reference combined with the assumption about exogenous energy efficiency improvement are likely the major factors behind these low elasticities. The low energy/GNP elasticities are not in themselves an indicator that the relationship between energy use, energy prices, and economic growth in EPPA are different than that observed in the past, at least for the developed countries, but rather the break from the past is the consistent and substantial rise in energy prices. The break is more substantial in developing countries where they converge almost immediately to elasticities seen in the developed countries. The projection is, thus, a relatively optimistic assessment that developing country economic growth in the future can be achieved with less growth in energy demand than in the past.

5.4 Emissions of Climatically Important Substances

The emissions of all climatically important substances projected by EPPA under the reference case parameters and assumptions are shown in Figure 24. We show emissions for each substance aggregated across sectors and for three regional groupings—developed countries(DCs), economies in transition (EIT), and less-developed countries (LDCs)—that are aggregations of actual EPPA regions. The wide range of sources of these emissions and the varying emissions coefficients and economic structure across regions and over time give rise to widely different patterns of emissions among regions and among climatically important substances. Thus, few generalizations are possible but the basic results can be traced to assumptions about parameters and the evolution of economies over time. Among the generalizations that are possible, the developing countries show more rapid growth in emissions whereas developed countries and economies in transition show slower growth or declines in emissions. Developed countries are projected to be the largest source of those pollutants related mainly to production of advanced industrial products (e.g. HFCs, PFCs, SF6) through the early part of the century but developing countries are projected in this reference case to become the largest source of emissions of all the climatically important substances we project. Perhaps more remarkably but already apparent in the emissions inventory data presented in previous sections, the developing countries are already the largest source by far of many of these pollutants.

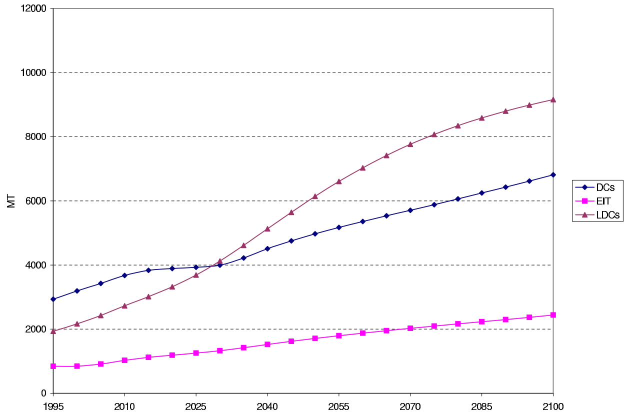
The high level of emissions from developing countries reflects to a large degree the inventory data for 1995. Land use, agriculture, and biomass burning are largely responsible for large emissions of these gases from developing countries, whereas in the developed countries we associate many of these pollutants with industrial and energy using-activities concentrated in the urban areas. This is due to the fact that, in part, there are more of these activities (rice production, livestock) in developing countries. It is also due to the fact combustion of agricultural waste, residues from land clearing, and biomass for energy use in developing countries is very inefficient and leads to high levels of pollutant emissions per unit of material combusted. The EPPA model includes structural change in the economy that reduces the agricultural share of output and that reduce emissions coefficients of many of these gases as per capita income increases. These relationships were based on cross-section observation of emissions coefficients and income per capita. But, despite these relationships that by themselves would reduce emissions we still get rapidly growing emissions because of growth in the economy driven both by larger populations and increased productivity growth. Thus, to avoid high levels of emissions of these gases developing countries will need to achieve greater reductions of emissions at lower per capita income levels than is currently observed in cross-section evidence.

By comparison, emissions of many of these pollutants from developed countries and economies in transition grow little or decline over the next century. This reflects less rapid population and economic growth, less growth in activities that emit these gases, and continuing declines in emissions coefficients.

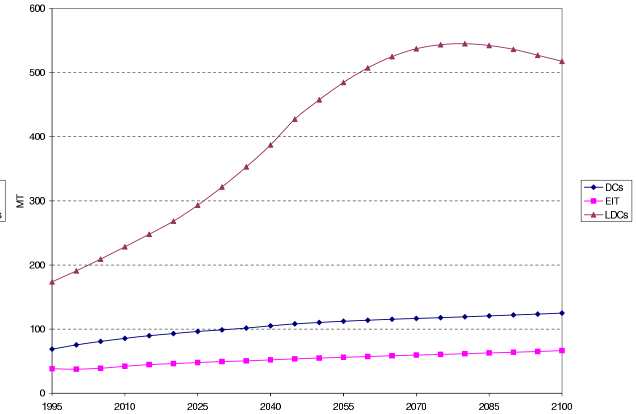
These trends and results are the result of a careful assessment of existing data and projections of economic growth. They are, however, highly uncertain. The relationship between per capita income and pollution emissions is subject to considerable error bounds in the cross section data. There are also many reasons why developing countries may exhibit different behavior than the developed countries so that the cross-section evidence may not apply in the future. Because more efficient combustion technologies and pollution control technologies have already been developed in the advanced countries, their adoption may occur at lower levels of per capita income. Further, the health, agriculture and environmental damage created by pollution depends on the density of emissions over a geographic area and the density of population and agriculture activities affected by the pollution as well as other climatic and geographic factors. Thus, countries that are much more densely populated and where much pollution is upwind from activities that might be affected by the pollution might well have an incentive to control pollution at relatively low per capita income levels. The converse might be true for more sparsely settled areas or where the pollution emitted by one country blows downwind to affect activities in another country. In this latter case, control efforts might well require regional multilateral negotiations and agreements. Uncertainties exist for all aspects of projecting human activities far into the future but probably more so in the case of many of these substances where there have been very few attempts to do so. Our reference case is a starting point for exploring the implications of remaining more-or-less on the path of economic development and attendant emissions of various pollutants that we have observed in the past.

Figure 24: Reference Scenario Emission Projections for Kyoto Greenhouse Gases

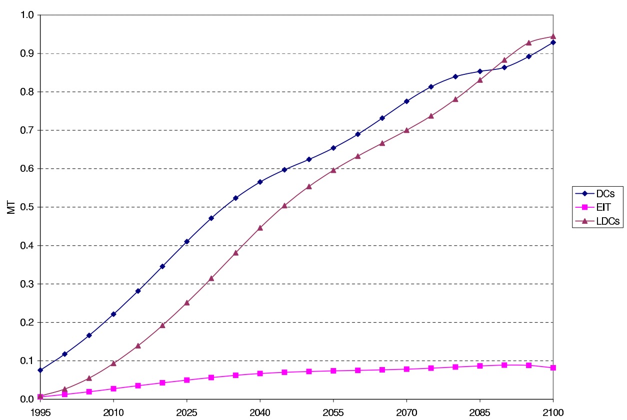
CO_2



CH_4

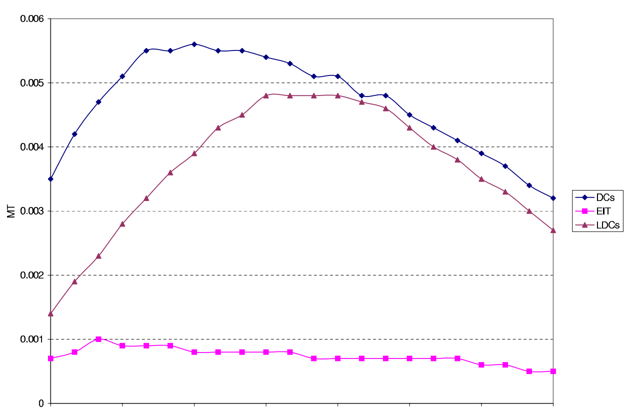


HFCs



PFCs

SF_6



N_2O

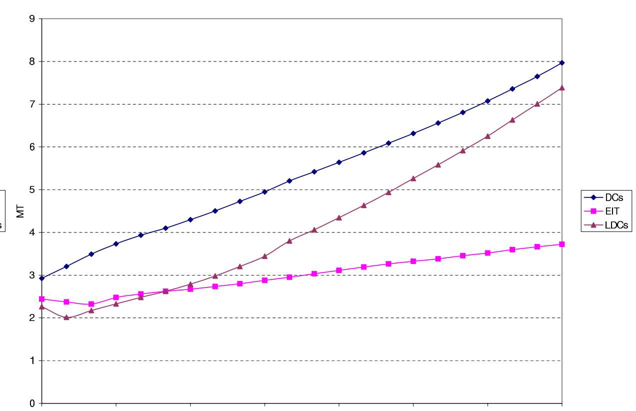
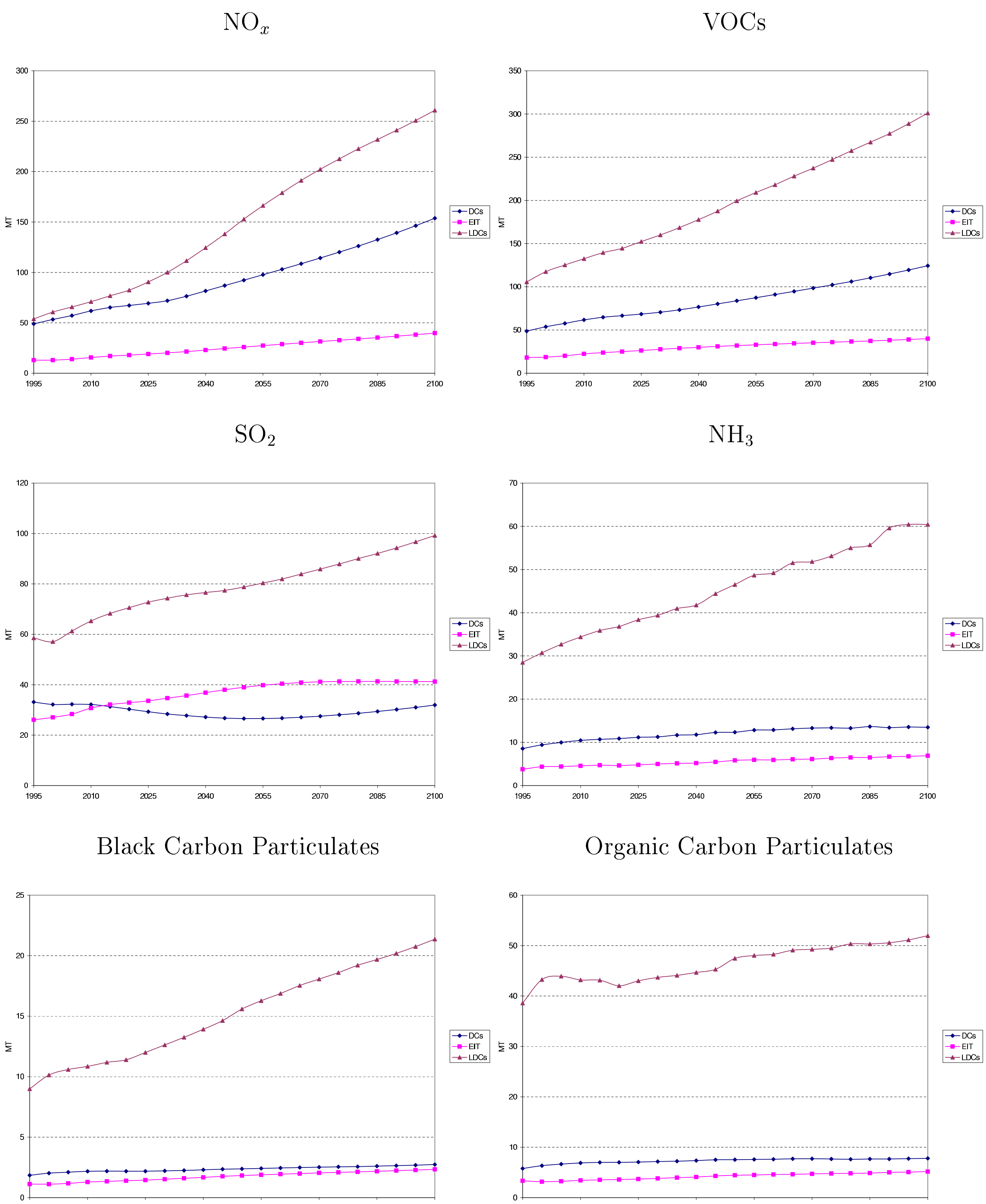


Figure 25: Reference Scenario Emission Projections for Criteria Pollutants



6 Conclusion

The purpose of this paper was to provide documentation of the structure and parameters of the MIT EPPA model, version 3.0, a major revision of earlier versions of the model (Yang, Eckaus, Ellerman and Jacoby, 1996). It is constructed on a set of 1995 social accounting matrices (SAMs) available from the Global Trade and Analysis Project (GTAP). In this version of EPPA, revisions were made in the structure of the production and consumptions sectors, the resource model, and in savings and investment. Nuclear power was added as a separate electricity production sector and backstop technologies producing shale oil and gas from coal were added. We also reconsidered the value of nearly all the parameters in the model including elasticities of substitution among inputs, energy efficiency improvement, and labor productivity growth. We added time and region dependent substitution and share parameters in the consumption function to better treat the structural change that occurs in an economy over long periods of time. We developed completely new 1995 inventories of non-CO_2 greenhouse gases and other climatically important substances based on the most recent data on emissions. In many cases, estimates of emissions from human activities have changed substantially over the past few years as more attention has focused on these gases. It was necessary, therefore, to reflect these changes in EPPA emissions coefficients even though there remains considerable uncertainty in them. We also added a new set of gases that, while not included in current climate policy control efforts, are important in understanding climate change and the atmospheric lifetime of controlled greenhouse gases.

There are many areas of the model where more detail and improvements could increase the accuracy of our projections, represent economic processes more realistically, and expand the types of problems that can readily be analyzed with the model. In any modeling exercise of this sort, by the time a report documenting the model is produced and printed, it is almost certain that revisions and improvements of some sort have already been made in the model. In that regard, it seems useful to conclude by noting some of the improvements and changes underway.

Perhaps one of the more important features of the GTAP data set is that it contains much greater country and sector detail than does the EPPA model. We have created and produced studies with other versions of EPPA that include greater regional detail, in one case focusing on disaggregating developing countries and in an ongoing effort, disaggregating the European Union and the transportation sector. The regional and sector detail in the GTAP data set means that we can be quite flexible in creating versions of EPPA with greater disaggregation. We are, however, limited when disaggregating below the level of the standard version of EPPA by data additions we have made beyond the standard GTAP data set. For example, the nuclear sector breakout is not in the standard GTAP data set. Similarly, our inventory of the non-CO_2 emissions is based on the standard regional aggregation reported here. Transportation, as important as it is for energy use and carbon emissions, is not a separate sector in GTAP, and the standard version of EPPA reported here does not contain an explicit transportation sector. We are developing a version of EPPA with transportation broken out for important regions. Energy resources are also not a standard part of the GTAP data set. A disaggregated version of EPPA that contains these features thus requires considerable effort to go back and augment the GTAP data set if all of these features are to be retained in the disaggregated version.

In this version of EPPA we changed the way we represented all emissions of non-CO_2 greenhouse gases and criteria pollutants, introducing them directly into the production and consumption structure of EPPA to facilitate eventual endogenous calculation of the costs of controlling costs these substances. The development of parameters that will allow us to realistically estimate control costs of these gases endogenously is well underway and we expect the next update of EPPA to include this feature. We are also developing a test version of EPPA that includes carbon sequestration technologies in the electric power sector and expanded and revised electric power generation options.

In another development project we are working on a fully dynamic, forward-looking version of EPPA that includes the structural detail of this version of EPPA. Such a model will allow a more consistent treatment of investment and savings behavior and consideration of such issues as how will the economy respond in anticipation of change in carbon policy or the option to bank and borrow permits.

As science and economic understanding of the climate issue changes and as new and wide ranging 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. While grounded in the best data available and sound economic modeling methods, we remain humble about our ability to accurately project the changing economic fortunes—and resulting greenhouse gas emissions—of the world's economies.

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