MIT Joint Program on the Science and Policy of Global Change

The MIT Emissions Prediction and Policy Analysis (EPPA) Model

Z. Yang, R.S. Eckaus, A.D. Ellerman and H.D. Jacoby

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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.

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THE MIT EMISSIONS PREDICTION AND POLICY ANALYSIS (EPPA) MODEL

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by

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1. INTRODUCTION

The Emissions Prediction and Policy Analysis (EPPA) model is a component of an Integrated Framework of natural and social science models being developed by the MIT Joint Program on the Science and Policy of Global Change. It is a detailed, global, computable general equilibrium (CGE) model with a long time horizon and regional as well as sectoral detail. The EPPA model can be used to project economic activity, energy use and greenhouse gas (GHG) emissions for each of 12 regions through the year 2100. The model can also be used to simulate different GHG mitigation policy scenarios and to analyze the impacts and consequences of these policies. Within the Joint Program's Integrated Framework, the EPPA projections of anthropogenic GHG emissions are inputs to a coupled chemistry-climate model. It thereby forms the first link in an integrated analysis of global climate change.

The EPPA model is derived from the GeneRal Equilibrium EnviroNmental model (GREEN), which was developed by the OECD (Burniaux et al., 1992).[1] The evolution of EPPA from GREEN can be described by the several steps that have been taken in adapting the model to the requirements of the Joint Program's integrated analysis. For the most part, the benchmark data set of the GREEN model remains unchanged, as do the basic features of the production, consumption and international trade specifications. The main departure from GREEN has been

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[1] We are greatly indebted to colleagues at the OECD Economics Directorate for their generous assistance in the early stages of our model development, both in providing the original code and in helping us to understand GREEN.

the re-coding of the model in the GAMS language, using a software system designed for general equilibrium problems (Rutherford, 1994). This change was made to facilitate the testing of alternative model features and policies. The first step in implementing EPPA within this new system was to create a "Cousin" version that mimics the original GREEN model. Further development, including a number of changes in the economic structure of the model, have led to EPPA Version 1.6, which is reported here. The processes of improving and extending the model are continuing.

This paper is organized as follows. Section 2 describes the basic structure of the EPPA model, and Section 3 outlines the way that assumptions about technology and growth are used in defining alternative simulations. Section 4 is a brief discussion of the solution algorithm. Section 5 introduces the policy instruments now implemented in the model. Section 6 presents simulation results, to illustrate the capabilities and behavior of the model. Finally, in Section 7, anticipated future developments of the EPPA model are summarized.

2. MODEL STRUCTURE

2.1 Model Overview

The EPPA model is a multi-region, multi-sector, recursive-dynamic computable general equilibrium (CGE) model.[2] The current Version 1.6 covers the period 1985 to 2100 in five year steps. The world is divided into the 12 regions shown in Table 1, which are linked by bilateral trade. The economic structure in each region consists of eight production sectors and four consumption sectors, all shown in Table 1, plus one government and one investment sector. In addition to these production sectors, there are two future energy supply or "backstop" sectors that produce perfect substitutes for refined oil and electricity.

Each of the eight production sectors has a multi-layer constant elasticity of substitution (CES) nesting structure that combines the output of other sectors as material or energy inputs, and uses labor and capital as primary factors. Natural resources constitute an additional primary "fixed factor" input in all production sectors except Refined Oil, Energy Intensive Industries, and Other Industries and Services. Each of the backstop energy production sectors has a linear

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[2] For detailed information about CGE modeling, see Shoven and Whally (1992).

$Xi_{i,r,t}$ = an imported output within the Armington bundle;

$Xd_{i,r,t}$ = Domestic output within the Armington bundle;[4]

$Y_{c,r,t}$ = a consumption good.

Then there are the three primary input factors:

L = labor;

K = capital;

FF_i = sectoral fixed factor.

And finally,

P = price.

All assumed parameters and coefficients in the model are denoted by Greek letters; all calibrated parameters and coefficients are denoted by lowercase Roman letters. The definitions of other variables and parameters will be introduced when needed.

2.3 Production Structure

The EPPA model, in a modification of the original GREEN version, permits a choice among ways to represent factor substitutability within production sectors, with either putty-putty, mixed vintage, or fully-vintaged specifications for capital inputs. The "putty" portion of the production structure is a multi-layer CES function calibrated with the 1985 SAM tables for the 12 regions. Equations 2.2 to 2.7 are EPPA's CES production functions in the order of top-down nesting, where the ρs indicate the CES substitution parameters. The corresponding substitution elasticities are shown in Table A1 of Appendix 2.[5] The structure is shown in Figure 1.

Equation 2.1 is the top-layer of the production function. It states that sectoral output X is a linear function of intermediate inputs Xa and an interim quantity variable, Z, comprised of labor, energy, capital and fixed factor,

$$X_i = \sum_{ne} a_{ne,i} Xa_{ne,i} + a_{lkef,i} Z_{lkef,i} \; . \tag{2.1}$$

Equation 2.2 expresses one of the branches at the next layer of the nesting. The input bundle $Z_{lkef,i}$

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[4] X and Xd represent the same variable. Xd is used only in the context of Armington specification.

[5] The Allen elasticity of substitution is related to the CES substitution parameter by the equation $\sigma = \frac{1}{1-\rho}$.

technology employing capital and labor. A linear transformation matrix maps non-energy production sectors into the material inputs of the consumption sectors. Energy inputs of the consumption sectors are CES aggregates.

The EPPA model is calibrated with 1985 data. The data set consists of Social Accounting Matrices for each of the 12 regions, and a bilateral trade matrix.[3] As an example, Table 2 shows the SAM for the United States. The units of the SAM tables are 1985 US dollars, based on official exchange rates. The SAM dimensions are consistent with the sectoral break-down of the EPPA model. The data set was collected and compiled by the OECD (1993b).

The model is myopic. It solves for a sequence of new equilibria for future periods, based on assumptions about exogenous trends in the rate of population and labor productivity growth and technology change, as well as endogenous changes in capital stocks and fixed factor supplies.

2.2 Notation

For clarity and consistency in the description of the production structure and other parts of EPPA, the following notation is employed. (A full list of variables and definitions is provided in Appendix 1.) Key indices are:

$I=\{i\}$ indexing production sectors;
$R=\{r\}$ indexing regions;
$C=\{c\}$ indexing consumption sectors and
$T=\{t\}$ indexing periods;
l, k, e, f = indices identifying labor, capital, energy, and fixed factors.

For convenience, we also define $\{e\}$, which contains all energy sectors (4 through 8 in Table 1), and $\{ne\}$, which contains all non-energy sectors (sectors 1, 2 and 3), as subsets of i.

There are a set of flow aggregates, with precise definitions indicated by the subscripts above:

$X_{i,r,t}$ = sectoral gross output;
$Xa_{i,r,t}$ = an Armington output, which is a CES aggregate variable using domestic and imported goods as two arguments;

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[3] A social accounting matrix for a region is an extended input-out table in value terms. It describes value-added composition of production sectors and the total demand for each production sector, the latter being made up of demands by other production sectors, consumption, government, investment and export.

is, in turn, a CES function of labor and a bundle comprised of energy, capital and the fixed factor,

$$Z_{lkef,i} = \left[a_{l,i} L_i^{\rho_{lkef}} + a_{kef,i} Z_{kef,i}^{\rho_{lkef}}\right]^{\frac{1}{\rho_{lkef}}} . \tag{2.2}$$

Proceeding down the nesting, the $Z_{kef,i}$ bundle is a function of an energy bundle and a bundle comprised of capital and fixed factor, as Equation 2.3 shows:

$$Z_{kef,i} = \left[a_{e,i} E_i^{\rho_{kef}} + a_{kf,i} Z_{kf,i}^{\rho_{kef}}\right]^{\frac{1}{\rho_{kef}}} \tag{2.3}$$

At the bottom of the nesting, the $Z_{kf,i}$ bundle is a CES function of its capital and fixed factor components, as in Equation 2.4, and the energy bundle is a CES function of Armington goods made up of domestic outputs and imports of energy, shown in Equation 2.5.

$$Z_{kf,i} = \left[a_{k,i} K_i^{\rho_{kf}} + a_{f,i} FF_i^{\rho_{kf}}\right]^{\frac{1}{\rho_{kf}}} \tag{2.4}$$

$$E_i = \left[\sum_e a_{i,e} Xa_{e,i}^{\rho_e}\right]^{\frac{1}{\rho_e}} \tag{2.5}$$

The Armington specification treats imported goods as imperfect substitutes for their domestic counterparts. Equations 2.6 and 2.7 describe the other branch at the top level Armington specification for production, combining imported and domestic components of non-energy intermediate goods, and the Armington specification inside the energy bundle. In Equation 2.6, the Armington good, *Xa*, used in domestic production and consumption, is a CES function of a domestic good *Xd* and an imported compound good *Xi*.

$$Xa_{j,i} = \left[a_{i,j} Xi_{j,i}^{\rho_{i,\alpha_2}} + a_{d,j} Xd_{j,i}^{\rho_{i,\alpha_2}}\right]^{\frac{1}{\rho_{i,\alpha_2}}} \qquad j \in ne,e \tag{2.6}$$

The imported compound good *Xi* is a CES function of Armington goods imported from other regions.

$$Xi_{j,i} = \left[\sum_r a_{r,j} Xa_{r,i,j}^{\rho_{j,\alpha_1}}\right]^{\frac{1}{\rho_{j,\alpha_1}}} \qquad j \in I \tag{2.7}$$

Equilibrium factor demands, by sector and region, and prices for factors and sectoral outputs, can be derived in the usual manner from the primary and dual solutions of the cost minimization problem with the above technology.[6]

The three capital vintaging specifications in EPPA differ in the extent to which the factor proportions can change after the initial investment in a capital good is made. In all three cases, current technology and input prices determine the factor proportions of new investment. In the putty-putty case, there is no distinction between old and new capital: the inherited capital stock adjusts its factor proportions and technical efficiency to changes in relative prices and technology as fully as does new capital. By comparison, in both the vintaged cases, the factor proportions and technical efficiency of the inherited capital stock are frozen for all periods subsequent to its initial creation. In effect, each vintage of the surviving capital stock is Leontief, with technical coefficients determined initially by the CES functions described above and the input prices and level of technology in the initial period. In addition to the differing assumptions about the malleability of the inherited capital stock, the fully vintaged specification makes a different assumption about the survival of the capital stock. In the mixed vintage specification, "old" capital is one composite aggregate for which the technical coefficients are the average of the Leontief coefficients of the constituent vintages weighted by the depreciated quantity of each vintage. In the fully vintaged specification, each depreciated vintage is identified separately for five succeeding periods and then eliminated. As a result of this truncation, the quantity of "old" capital is somewhat less than in either the putty-putty or mixed vintage specifications.

2.4 The Demand for Crude Oil and Natural Gas

The demand for crude oil and natural gas differ from the demand for other energy inputs and intermediate inputs in that, for each, domestic production and imports are perfect substitutes. Furthermore, each is traded inter-regionally with perfect substitutability, as Heckscher-Ohlin goods, instead of as Armington goods. Within each region, therefore, the production sectors--as well as the consumption sectors, government, and investment--treat crude oil and natural gas from domestic output and from imports as the same good. It is assumed that trade barriers for oil and natural gas are non-existent, except for taxes or subsidies that may cause the domestic prices for these two goods to differ among regions. Instead of the usual definition for Armington goods

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[6] For details on how to derive the factor demand functions and equilibrium prices, see Varian (1995), or Mas-Colell *et al.* (1995).

(Equations 2.6 and 2.7), the aggregate demand for oil and gas takes the following form:

$$Xa_j = (\sum_r a_{r,j} Xi_{r,j}) + a_{d,j} Xd_j \qquad j \in (oil,\ gas) \tag{2.8}$$

Equivalently, we can assume that for oil and gas $\rho_{\alpha 1} = +1.0$ and $\rho_{\alpha 2} = +1.0$ in Equations 2.6 and 2.7.

2.5 Emissions of Greenhouse-Relevant Gases

Estimates of emissions of greenhouse gases, and other gases which produce scattering aerosols or otherwise influence the atmospheric chemistry, are driven by various activity levels within the model. With the exception of emissions from deforestation and some components of biomass burning, CO_2 emissions are calculated directly from the period-to-period levels of energy sector activities. The prediction of trace gases begins with base-level emissions in 1985, and the emissions in subsequent periods are related to changing levels of energy and non-energy activities using elasticity factors, as detailed by Liu *et al.* (1996).

Emissions are denoted *EE*, with the particular gas and sector of origin indicated by subscript indices. Recall that *i* indicates a production sector, *e* is a subset of *i* indicating an energy sectors, and that *b* is a backstop sector. These sectors are listed in Table 1. To these we add two new indices:

$G = \{g\}$, indexing types of gases, also listed in Table 1, and

$S = \{s\}$, indexing subsectors of origin of emissions.

With these definitions we can describe how emissions are calculated. Sample results for CO_2 emissions are shown in Figures 2 and 3; corresponding results for the trace gases are shown in Figure 4.

Carbon Dioxide. Aside from emissions from deforestation, all CO_2 emissions are ascribed to the region where they are generated. For each region, emissions are calculated as

$$EE_{g,t} = \sum_e Xa_{e,t} TJ85_e \varepsilon_e + X_{b,t} \lambda TJ85_{refoil} \varepsilon_{refoil} \ , \tag{2.9}$$

where

e = natural gas, refined oil, coal, and

b = carbon liquids backstop.

The first term in the expression is the emissions at the point of consumption, where Xa is the Armington aggregate of energy type e, $TJ85$ is the coefficient converting the dollar value of energy of type e, expressed in millions of 1985 U.S. dollars, into heat units (exajoules), and ε is the coefficient converting heat units into CO_2 emissions. The values of $TJ85$ and ε are provided in Tables A2 and A3 of Appendix 2. The second term in Equation 2.9 is the emissions at the point of production of the carbon liquids backstop, which is available in only the USA, the Other OECD (representing Canadian and Australian resources) and the Energy Exporting LDCs (representing Venezuela among others). (The backstop technologies are described in Section 3.5.) This technology is assumed to produce refined oil after extensive processing, and the release of CO_2 at the point of production is expressed as a fraction, λ, of the CO_2 emitted by the corresponding refined oil at the point of consumption. In the sample calculations shown below, λ is set at 0.8.

Emissions from deforestation are exogenously determined, and are added to the emissions driven by the activity levels generated by the EPPA model. In the results shown below, these emissions are assumed constant at estimated 1985 values from 1985 to 2000, and thereafter to decline linearly to zero in 2050.

Methane. Total methane emissions are the sum of the emissions from a number of sources. First are emissions from agricultural activities, which are driven by activities in the aggregate agricultural sector:

$$EE^{s}_{g,t} = EE^{s}_{g,t-1}\left(1+\alpha_{g,s}\frac{Xd_{i,t}-Xd_{i,t-1}}{Xd_{i,t-1}}\right) \quad , \quad i = agr \ , \tag{2.10}$$

where s = rice paddies, enteric fermentation and animal waste,.and Xd_i is production in agriculture (agr). Components of energy sector methane are estimated as

$$EE^{e}_{g,t} = EE^{e}_{g,t-1}\left(1+\alpha_{g,e}\frac{Xd_{e,t}-Xd_{e,t-1}}{Xd_{e,t-1}}\right) \ , \ e = coal, \ nat. \ gas \ . \tag{2.11}$$

Landfills and domestic sewage are modeled in the same fashion, with landfill emissions driven by per-capita GDP and emissions from domestic sewage related to population itself. Methane also is emitted from biomass burning, which is covered below.

Nitrous Oxide. Emissions of N_2O result from a number of agricultural, industrial, and energy-sector activities, and from biomass burning (this last source also treated separately below). The estimates of emissions from fertilizer use and nitric acid production are of the form of Equation 2.10, with appropriate values of $\alpha_{g,s}$. Adipic acid production is the same, only related to the Xd_i for i = Other Industries and Services. Emissions from fossil fuel combustion takes the form of Equation 2.11 for e = refined oil, with an appropriate value of $\alpha_{g,e}$ applied. Emissions from the extension of cultivated land are based on a simple growth rate applied to emissions as estimated in 1985. Parameter values are given in Table A4 of Appendix 2.

Nitrogen Oxides. The main anthropogenic source of NO_x is fossil fuel combustion from stationary and mobile sources, with additional emissions from petroleum refining, cement manufacture, nitric acid production, and biomass burning. At present, the prediction of NO_x emissions from all sources but biomass burning is modeled by an equation of the form of Equation 2.10, with Xd_i from Energy Intensive Industries, and appropriate values of $\alpha_{g,s}$.

Chloroflurocarbons. Chloroflurocarbons are assumed to follow the phase-out schedule of the London Amendments to the Montreal Protocol.

Carbon Monoxide and Sulfur Oxides. Anthropogenic sources of CO include fossil fuel combustion, the production of steel, pig iron, and ammonia, and the burning of refuse and agricultural waste, sewage, and biomass. The sources of SO_x include coal and petroleum use, smelting of non-ferrous ores, production of sulfuric acid, pulp and paper, incineration of wastes, and biomass burning. (As with other gases, emissions from biomass burning are treated separately.) For each region, emissions of these two gases are modeled by two equations each, one representing energy use and the other covering industrial activity.

For CO, the emissions from fossil fuel use are projected as resulting from the use of coal and refined oil:

$$EE_{g,t} = EE_{g,t-1}\left(1+\alpha_g\left\{\lambda_g\frac{Xd_{e1,t}-Xd_{e1,t-1}}{Xd_{e1,t-1}}+(1-\lambda_g)\frac{Xd_{e2,t}-Xd_{e2,t-1}}{Xd_{e2,t-1}}\right\}\right) \quad ,(2.12)$$

where $e1$ denotes coal and $e2$ is refined oil, and λ_g is 0.2. Emissions from industrial sources are modeled as

$$EE_{g,t} = EE_{g,t-1}\left(1 + \alpha_g \frac{Xd_{i,t} - Xd_{i,t-1}}{Xd_{i,t-1}}\right) , \tag{2.13}$$

where Xd_i is the activity level of energy-intensive industries. For SO_x the equations are the same, with λ_g set to 0.66 and appropriate values of the elasticity, as described in Table A4 of Appendix 2.

Biomass Burning. Biomass burning encompasses a variety of activities, which can be roughly classified into the five categories: (1) the burning of the world's forests for land clearing and agricultural use (including both shifting agriculture and permanent agriculture), (2) the annual burning of savannas to control pests, weeds, and brush accumulation, (3) prescribed burning in temperate and boreal forests, (4) the annual burning of agricultural stubble and waste after harvest, and (5) the burning of wood for energy production. These processes emit CO_2 and the trace gases CH_4, N_2O, NO_x, SO_x, and CO.

In the case of CO_2, annual burning of savannas, brushland, and agricultural wastes does not contribute net emissions into the atmosphere, since the CO_2 released is re-absorbed by re-growth the following year. Only deforestation with burning of the wood represents a significant net CO_2 emission into the atmosphere, as long-term stores of carbon are released with no possibility for re-absorption in the short term. For all other greenhouse-relevant gases, however, all biomass burning yields net releases since they are not re-absorbed by plant growth. With the exception of prescribed fires in temperate forests, biomass burning takes place almost exclusively in the tropical and subtropical regions of the world. Since EPPA does not aggregate into tropical and other regions, we compute emissions from biomass burning as a global value. Agricultural sources of trace gases (category 4 above) are estimated using a relation of the form of Equation 2.10, with Xd_i from aggregated global agriculture, and appropriate values of $\alpha_{g,s}$. Other sources (categories 1, 2,3 and 5 above) are assumed to follow the same pattern as the exogenous assumption for CO_2 from deforestation.

Annual burning of savannas for control of pests and brush accumulation, prescribed forest fires, and burning due to shifting agriculture is treated as constant over time at their 1985 levels. Shifting agriculture is not expected to grow much, but permanent conversion of forests to land for agriculture or pasture is growing. The harvesting of wood for energy also contributes to deforestation. Emissions from permanent deforestation and fuelwood harvesting grow at the rate of deforestation, which is exogenous as noted above. Burning of agricultural wastes is assumed to increase as agricultural production increases, and is modeled by a relation like Equation 2.10, with appropriate parameters.

Distribution by Latitude. Emissions of all gases are needed by 7.8° latitude band, for inclusion in the MIT coupled chemistry-climate model, because the atmospheric chemistry is influenced by the geographical distribution of emissions as well as their global amount. Global emissions of the long-lived gases (CO_2, N_2O, CH_4 and the CFCs) are distributed by a function that remains constant over time. Emissions of the short-lived gases (CO, NO_x, SO_x) are distributed within each region according to population distribution, and the latitudinal totals are simply the sum of the 12 regions. Thus with differential growth and emissions among the 12 regions, the latitudinal distribution shifts over time.

2.6 Consumption, Investment and Government Expenditure

Each region has a representative consumer who maximizes a utility function in consumption Y_c and a minimum consumption level, θ_c:

$$\prod_c (Y_c - \theta_c)^{\mu_c} , \tag{2.14}$$

subject to the budget constraint on disposable income *Id*. Disposable income is defined as the sum of returns to all primary factors, plus government transfers (G_{tr}), minus savings (S_h) and household taxes (T_h). Namely,

$$Id = wL^s + rK^s + \sum_i pf_i FF_i^s - S_h + G_{tr} - T_h \tag{2.15}$$

where L^s, K^s and FF^s are total regional supplies of labor (specified in efficiency units as described in Section 3.1) capital and fixed factor, respectively, and

w = equilibrium wage rate,

r = equilibrium return to capital service, and

pf_i = equilibrium fixed factor price.

On the supply side, consumer goods are produced using inputs from the three non-energy production sectors plus energy inputs for two of the consumer goods, fuel and power and transport and communication.

$$Y_c = \sum_{ne} a_{ne,c} Xa_{ne,c} + a_{e,c} E_c \ , \tag{2.16}$$

where the energy inputs are CES aggregates of the various energy sectors:

$$E_c = \left[\sum_{e} a_{e,c} Xa_{e,c}^{\rho_e} \right]^{\frac{1}{\rho_e}} . \tag{2.17}$$

As with the production sectors, the prices of consumer goods, and consumer demand functions for those goods, can be derived from the corresponding optimization problem.

The demand for production goods by the investment sector is defined in the same manner as for consumption:

$$I = \sum_{ne} a_{ne,I} Xa_{ne,I} + a_{e,I} E_I \ , \tag{2.18}$$

where

$$E_I = \left[\sum_{e} a_{e,I} Xa_{e,I}^{\rho_e} \right]^{\frac{1}{\rho_e}} . \tag{2.19}$$

Note that investment, like consumption, does not require direct primary factor inputs.

Government expenditure includes two parts. One is for the direct transfers to the consumer; another is expenditure for inputs required for the production of government services. Government revenue comes from taxes on household and production sectors. The difference between government expenditure and revenue is government savings (S_g). The production function of the government good takes the following form:

$$G = \sum_{ne} a_{ne,g} Xa_{ne,g} + a_{e,g} E_g + a_{l,g} L_g + a_{k,g} K_g \tag{2.20}$$

where

$$E_g = \left[\sum_{e} a_{e,g} Xa_{e,g}^{\rho_e} \right]^{\frac{1}{\rho_e}} \tag{2.21}$$

Finally, in the EPPA model, stock-building entries in the 1985 SAM tables are treated as residuals that are added to or subtracted from the endowment of the consumer. Therefore, no stock building relationships are specified.

2.7 Closure Rules and Market-Clearing Conditions

The levels of government expenditures, both production and transfers, are exogenous. The tax revenues, both from household taxes and from indirect taxes on production, are also exogenous. For each region, both expenditure and revenue are set as a fixed share of total GNP. These assumptions imply that the initial government deficits or surpluses remain fixed at the initial (1985) share of GNP.

Initial current account imbalances among the regions are phased out over time. The absolute values of the imbalances decline gradually during the first four periods, and are eliminated completely in the fifth period. Initial inventory and exogenous investment (i.e., the differences between total investment and household saving in the SAMs) are treated in a similar way. They are reduced gradually in the first four periods, and disappear completely in the fifth period.

Finally, based on the above closure rules, the EPPA model solves for an overall equilibrium in which the following market clearance conditions are met:

$$L^s = \sum_i L_i + L_g \tag{2.22}$$

$$K^s = \sum_i K_i + K_g \tag{2.23}$$

$$F_i^s = F_i \tag{2.24}$$

$$X_i = \sum_j Xd_{i,j} + \sum_c Xd_{i,c} + Xd_{i,J} + Xd_{i,g} + EX_i \tag{2.25}$$

where EX_i = exported output. Equations 2.22, 2.23 and 2.24 are clearing conditions for primary factor markets. Equation 2.25 is a commodity market clearing condition. It states that the production of sectoral output is equal to domestically produced intermediate goods demanded by other sectors plus domestically produced "final goods" including exports.

3. ASSUMPTIONS ABOUT GROWTH AND TECHNICAL CHANGE

3.1 Labor Supply

Labor supply in the EPPA model is measured in efficiency units or "effective" labor input. Thus the labor supply can be decomposed into two parts: numbers of people in the labor force and levels of productivity. An increase of effective labor supply over time implies either population growth or labor productivity improvement, or both. Rates of change in population and labor productivity are specified exogenously. The equilibrium condition of the solution requires that the sum of all sectoral demands for labor equal labor supply in each region.

The exogenous rates of population growth in different regions over the next century are based on United Nations' estimates (Bulatao *et al.*, 1990). In general, the UN estimates anticipate moderate population growth in developed countries and rapid population growth in developing countries in the near future. The population growth rates in both regions slow down over time. Based on United Nations estimates, we calibrated $Pop_r(t)$, the population growth trend in region *r*, to fit the following formula:

$$Pop_r(t) = Pop_r(0)\, e^{\alpha_{p,r}\left(1 - e^{-\beta_{p,r} t}\right)} \tag{3.1}$$

$$\alpha_{p,r} = \ln(g_{\infty,r})\ ; \qquad \beta_{p,r} = -\ln\left[1 - \frac{\ln(g_{1,r})}{\ln(g_{\infty,r})}\right] \tag{3.2}$$

The coefficients, g_∞ and g_1 are the ratios of asymptotic level and the second period level of population relative to the base year, respectively. The initial population and coefficient values are given in Tables A2, A3 and A4 in Appendix 2.

Labor productivity improvement in region *r* is expressed as an index over time. It is assumed that all regions start with relatively high, though different, labor productivity growth rates, but converge to some common, lower annual labor productivity growth rate by the year 2100. In the reference runs shown below, this target is 1.0% for OECD regions (USA, JPN, EEC and OOE) and EEX. All other regions converge to 2.0% per annum by the year 2100. Based on the above assumption, $Lp_r(t)$, the labor productivity level, is:

$$Pl_r(t) = e^{\alpha_{l,r}\left(1 - e^{-\beta_{l,r}t}\right)} \qquad (3.3)$$

$$\alpha_{l,r} = \left[\frac{\ln(1 + g_{0,r})}{1 - e^{-\beta_{l,r}}}\right]; \qquad \beta_{l,r} = \ln\left[\frac{\ln(1 + g_{0,r})}{\ln(1 + g_{n,r})}\right] \Big/ \; Hoz \qquad (3.4)$$

Here g_0 is the initial labor productivity growth rate; g_n is the terminal labor productivity growth rate (set at 1% or 2% in the runs below); *Hoz* is the time horizon of the model and is 115 years (from 1985 to 2100). The values of g_0 are given in Table A8 of Appendix 2.

Finally, $L_r\,(t)$, total labor supply is defined as:

$$L_r(t) = Pop_r(t)\, Pl_r(t) \; . \qquad (3.5)$$

3.2 Capital Formation

In the EPPA model, the mechanism of capital formation has been changed significantly from that in GREEN. The capital supply in region *r* at period *t*, *K(t)*, is given by the following relationships:

$$K_r(t) = (1 - \delta_r)K_r(t-1) + S_{h,r}(t-1) \; , \qquad (3.6)$$

$$S_{h,r}(t) = \left[\frac{r_r(t)}{w_r(t)}\right]^{\sigma} s_r Y_r(t), \qquad \sigma < 1, \qquad s_r < 1 \; , \qquad (3.7)$$

where $S_{h,\,r}$ is household saving, Y_r is GDP;[7] r_r is the return to capital; w_r is the wage rate; δ_r is the benchmark capital depreciation rate derived from the SAM table; s_r is the initial saving share and σ is a damping factor. In the actual programming, the time differences are compounded for each five year step based on annual data. Several small adjustments which are made to insure that initial inventory and trade imbalances are properly incorporated into the $S = I$ identity are not shown in equations 3.6 and 3.7. These imbalances and the corresponding adjustments are zeroed out by the fourth period.

The treatment of capital formation in EPPA brings neoclassical investment theory into the

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[7] Disposable income is defined after savings and is fully consumed (cf. Eq. 2.15 supra).

empirical CGE model environment by making savings a function of the shadow price of capital.[8] This is in contrast to GREEN, which adopts a balanced growth assumption, determines savings exogenously, and adjusts capital productivity (usually negatively) to maintain balanced growth on a pre-determined growth path. In the EPPA model, household savings adjust according to the relative scarcity of capital in the economy. Both r and w are set to 1.0 in the base year. Therefore, if r/w is subsequently greater than one, capital is in short supply, relative to the labor supply in efficiency units, and vice versa. In response to the short supply of capital, household savings are increased as a share of total GDP. Because r/w deviates significantly from 1.0 in a few initial periods, a damping factor is applied to reduce the fluctuation in saving levels. The damping factor σ in equation 3.7 is set at 0.25 in the current version of the model; and the values of s_r are given in Table A9 of Appendix 2.

3.3 Fixed Factor Supply

Five of the eight production sectors require fixed factor inputs. These five sectors and their fixed factors are Agriculture and land, Coal and coal reserves, Crude Oil and Natural Gas and their reserves, which are depletable, and Electricity, Gas and Water Distribution for which hydro and nuclear power capacity are represented as fixed factor endowments. The units of fixed factor supply are in 1985 US dollars and are measured as fixed factor remunerations.

Within the time horizon of the model, the potential supplies of fixed factors in agriculture, coal and electricity are assumed to have no upper bound. The actual supplies in these sectors are functions of their own prices and previous period's supply level. In fact, $FF_{i,r}(t)$, the fixed factor supply of sector i, region r and period t, is:

$$FF_{i,r,t} = FF_{i,r,t-1}\left[\frac{pf_{i,r,t}/pu_{r,t}}{pf_{i,r,t-1}/pu_{r,t-1}}\right]^{\sigma_{f,i}}, \quad i \in (Agric,\ Coal,\ Elec) \qquad (3.8)$$

Here pf is the fixed factor price, pu is the price of consumer's utility and σ_f is price elasticity of fixed factor supply.

Fixed factor supplies in the oil and gas sectors are exhaustible within the time horizon of the model. In these sectors, the fixed factor supply is proportional to the sectoral and regional

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[8] For theoretical background on investment, see O.J. Blanchard and S. Fischer (1989).

resource depletion profiles which are functions of discovered and yet-to-find reserves, an exogenously specified depletion rate and output prices. The determination of resource depletion profiles for oil and gas in the EPPA model is similar to that in GREEN.[9]

3.4 Energy and Fixed Factor Productivity Improvement

The EPPA model introduces productivity improvements in the input requirements for energy in the non-energy sectors and for the fixed factors in oil and natural gas, similar to that described above for labor. Like GREEN, EPPA adopts an assumption of autonomous energy efficiency improvement (AEEI) to reflect the observed long-run historical trend of reduced energy requirement per unit of output. For three non-energy production sectors, four consumption sectors, government and investment sectors, the input energy bundles have the following feature to reflect the AEEI:

$$E_{i,t}^{e} = (1+\gamma_{e,i})^{t} E_{i,t} \qquad i \in (ne, c, gov, inv) \qquad (3.9)$$

where E^e is effective energy input in sector i; γ_e is AEEI rate. In the current EPPA reference, γ_e is set at an annual rate of 0.0075 for all sectors and across all regions.

In order to reflect the parallel effect of technological progress on the supply of oil and natural gas, it is also assumed that the fixed factor input requirements for oil and natural gas are reduced over time. The fixed factor improvement rate is set at 1% per year for all regions.

3.5 Backstop Technologies

The EPPA model allows for the introduction of backstop technologies which produce perfect substitutes for conventional energy. In Version 1.6 of this model, two backstop technologies are implemented: (1) a carbon-free electricity production backstop, representing opportunities such as solar or advanced nuclear technology, and (2) a relatively carbon-intensive substitute for refined oil, based on world resources of heavy oils, tar sands and oil shale. This carbon backstop emits CO_2 in the production process of the fuel, as well as from the consumption of the final product, refined oil. The carbon-free electric backstop is assumed to be available to all regions. The carbon backstop is assumed producible only in USA, OOE, and EEX, which have large reserves of oil shale and tar sands. The liquid fuel output is traded internationally as refined

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[9] See OECD (1993a) for an analytical exposition of resource depletion profiles for oil and natural gas.

oil (an Armington good).

Backstop technologies in the EPPA model have linear production structures with two inputs, labor and capital, which reflect the assumed infinitely reproducible nature of this output. Thus, we have:

$$X_{b,i} = \alpha_{b,i} L_{b,i} + \beta_{b,i} K_{b,i} \ , \tag{3.10}$$

and

$$\alpha_{b,i} + \beta_{b,i} = c_{b,i} > 1.0 \tag{3.11}$$

$$X_i = X_{c,i} + X_{b,i} \ . \tag{3.12}$$

where, subscript *b* represents backstop production, subscript *c* represents conventional production; and α and β are the Leontief coefficients. The initial period or benchmark unit cost of the backstop technology, $c_{b,i}$ is the sum of the Leontief coefficients. By definition, the backstop technologies are not economic in the initial period, and thus the sum of these coefficients is greater than 1.0, which is the initial price of the conventional fuel for which the backstop can substitute.[10] The values of $c_{b,i}$ are in Table 10 of Appendix 2.

In the EPPA model, backstop technologies are introduced when

$$\alpha_{b,i} w + \beta_{b,i} r \le p_i \ . \tag{3.13}$$

Of course, by the Kuhn-Tucker theorem, in the final equilibrium:

$$X_{b,i} > 0 \quad \Leftrightarrow \quad \alpha_{b,i} w + \beta_{b,i} r = p_i \ . \tag{3.14}$$

In the model, we also restrict the entry of backstop technology to occur no earlier than the year 2000.

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[10] The prices of the factors are set equal to unity in the initial period. In the case of conventional production, unit cost is also initially 1.0 which implies that the sum of the technical coefficients is unity. Thereafter, unit cost evolves according to changes in input prices and the technical coefficients. For the backstops, the technical coefficients are fixed and such that the initial unit cost must be greater than 1.0, else the technology would be economically competitive in the first period and not a backstop. For example, if the backstop and the conventional fuel both require an identical quantity of labor per unit of output, the backstop must require more capital. It may become economic later, however, if the price of capital becomes sufficiently cheap relative to the wage rate or the price of fixed factor for the conventional fuel.

4. THE SOLUTION CONCEPT

4.1 Algorithm

The EPPA model is programmed in GAMS language (Brooke *et al.*, 1992). Under the GAMS platform, the static structure of the EPPA model is written in MPSGE (Rutherford, 1994), which is an abstract, high-level language for formulating CGE models. The equilibrium prices and quantities of the EPPA model are solved by using the PATH solver, a generic algorithm for solving MCP (Mixed Complementary Programming) problems.[11]

The main advantage of programming in MPSGE/GAMS is that the solution algorithm and the economic model can be separated. This separation makes it possible for users to make changes in model structure, and to introduce new assumptions, without extensive re-programming and debugging. A professional division of labor is allowed, in which the implementation of a robust solution algorithm for CGE models is left to mathematicians and computer scientists, so the modelers can focus on the economic structure of the model.

4.2 Sequential Equilibria

Most CGE models are static models. Benchmark data are calibrated to fit the designed economic structure, and an equilibrium solution is obtained. Then "counter-factual" scenarios are imposed on the model to explore the impacts of potential policies or shocks. The EPPA model operates in this manner.

In the EPPA model, any single solution consists of one assumed equilibrium imposed on the benchmark data for the base year, 1985, and 23 calculated equilibria for five-year intervals through 2100. Each new equilibrium of supply, demand and relative prices is calculated based on exogenous changes in population, labor productivity and the AEEI rate and endogenous changes in saving levels and fixed factor availability. Since the model is myopic, no consideration is given to potential changes in future prices or resource availability in determining each period's equilibrium.

When CO_2 reduction policies are imposed, the EPPA model generates a set of new sequential equilibria that are consistent with policy constraints. An entire path with 24 periods

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[11] A computable general equilibrium (CGE) problem is a specific case of much more broadly defined MCP problem. See Stephen P. Dirkee and Michael C. Ferris, "The PATH Solver for Complementary Problems," in Rutherford (1994).

generated from policy shocks is a "counter-factual" scenario relative to baseline path.

5. POLICY INSTRUMENTS

Policies implemented in the EPPA model may take the form of either price instruments (taxes or subsidies) or quantitative instruments (quotas). The price instruments that have, so far, been specified are *ad valorem* energy taxes levied on unit[12] energy consumption or, *ad valorem* carbon taxes levied on units of carbon content in energy output. The quantitative instruments are CO_2 emission quotas imposed on individual regions or block of regions or all regions. When imposed globally or on a block of regions, quotas can be tradable among regions.

Both energy taxes and carbon quotas depress the demand for output from the energy sectors. The revenues from taxes and quota allowances are assumed to be transferred to the representative consumer as a lump sum. Since the taxes or quotas distort the equilibria in the economy from the no-policy baseline, the imposition of these policy instruments often reduces GDP. It is possible, however, for regional GDP to increase when the tax or quota has the effect of off-setting the distortion from an existing subsidy. In all the solutions the conventional assumption of CGE modeling is maintained that all productive resources are always fully employed.

In policy comparisons, GDP is often used as an approximate measure of general welfare, and a change in GDP is interpreted as a measure of resources foregone as a result of the policy constraint.[13] In EPPA, we do not use real GDP, strictly defined, as our measure of welfare, but rather real household consumption. We do this to avoid problems involved in the definition of real GDP in this type of model, and the response of this variable to policy perturbations. Real GDP is defined on the input side as the inner product of primary factor prices and quantities. When perturbed by policy, factor quantities adjust very little because factors are fully employed. Therefore, typically real GDP changes little. Household consumption provides a more accurate reflection of welfare. Since consumption consists of four goods in EPPA, we are able to capture

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[12] The unit can be either in heat contents of the product or in quantity units of the model, i.e. 1985 US$.

[13] For these comparisons, we do not attempt to measure the value of the environmental or other benefits obtained by the policy measures.

the differential effects of policy measures on the composition of household expenditure (for instance, between energy and non-energy intensive goods) as determined by our specification of consumer utility.

6. SAMPLE RESULTS

In order to illustrate the behavior of the EPPA model, we provide some simulation results based on the parametric values and other assumptions described above. In Section 6.1 we show various features of the model in typical reference run that is unconstrained by policy relative to GHGs. Section 6.2 presents the results of imposing a sample policy prescription.

6.1 Reference Run

Figures 2, 3 and 4 present the basic output of the EPPA model, which is the time path of global emissions of CO_2 and other gases from 1985 through the year 2100. In Figure 2, four cases are presented for CO_2 emissions, in which the effect of two of the improvements incorporated in EPPA are shown, namely, varying assumptions about the presence of backstop technology and the treatment of capital. The closed symbols in Figure 2 represent projections in which the backstop technology is assumed not to be available, and the open symbols denote the presence of backstop technology. Similarly, squares represent the putty-putty assumption of completely flexible capital, and the diamonds denote the fully vintaged specification of the capital stock. The mixed vintage capital specification is not illustrated here. (The emissions of trace gases, in Figure 4, are for the case with backstops and full vintaging.)

As can be seen in Figure 2, the fixity of capital does not matter in the long term because the vintage specification reverts to putty-putty in 2040. The assumptions about backstop technologies do make a discernable difference, however. Given the assumptions incorporated in this EPPA run, the net effect of introducing both carbon-intensive and carbon-free backstop technology is a lower carbon trajectory over the latter half of the 21st century.

The nearer-term effect of the different assumptions about capital fixity is shown by Figure 3, which is an enlargement of Figure 2 for the years 1985-2050. Since there is an assumed tendency toward improved energy efficiency and higher energy prices over time, successive vintages of capital are less energy and carbon-intensive. Global emissions are higher when the energy efficiency of the older vintages is assumed fixed, but by 2025 the initial capital stock has been completely replaced and it is only new technology that matters.

In our reference predictions, the paths of emissions with and without the backstop technologies cross over in the 2040s. Initially, the projections of carbon emissions, when backstop technologies are available, are higher than projections without backstop technologies, because the carbon backstop is used earlier than the carbon-free backstop. However, as the carbon-free backstop is deployed, the emissions path for the backstop scenario turns lower by 2050 and is progressively lower as seen in Figure 2.

The main cause of the projected overall increase in global CO_2 emissions is growth in regional GDP as shown in Table 3,[14] which shows 1985 GDP, average annual rates of growth in subsequent intervals, and 2100 GDP as a multiple of 1985 GDP. The last column shows that regional differences in GDP growth are considerable. With the exception of Japan, the GDP for the OECD regions (the first four rows) increases about five-fold, while regions such as China, India and the Dynamic Asian Economies increase by multiples of 20 to 25 by the year 2100. The differences reflect the effect of assumptions concerning population growth and increases in labor productivity, as well as differences in capital formation.

Figure 5 shows the evolution of CO_2 emissions per unit of GDP for these regions. In general, carbon efficiencies increase over time, due primarily to improving energy efficiency but also due to a shift towards less carbon intensive technologies, chiefly electricity. Regions with particularly notable near-term improvements in carbon efficiency are the Former Soviet Union, China, and Eastern Europe, in which the projections reflect the effect of removing energy subsidies and the movement to more market-based economies. Among the regions with less improvement in carbon efficiency (e.g., EEX and OOE) the emissions trajectories are explained largely by their role as producers of the carbon-intensive backstop. The resulting refined oil, when traded, yields its emissions in the destination region, but production of this backstop generates CO_2 as well.

The net effect of differing regional rates of growth in GDP and carbon efficiency result in shifts in the regional shares of CO_2 output as illustrated in Figure 6. The principal change in

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[14] This table and all subsequent figures assume backstops and full vintaging.

shares between 1985 and 2100 are the reduction in OECD share (-10%) and the FSU and EET shares (-9%) and the increase in EEX share (+15%). The reason for the large shift of carbon emissions to the EEX is that this region becomes the world's primary producer and exporter of the carbon intensive backstop, based on tar sands and oil shales.

The shift of energy shares is presented in Figure 7. The primary shifts in projected global energy use result from the increasing shares of the electric and oil backstops to compensate for fuels which are assumed to be depletable, namely, conventional oil and natural gas. The substitution of backstop oil for conventional oil keeps the aggregate oil share (refined plus crude) relatively constant (36% in 1985 *vs.* 35% in 2100); but carbon-free electricity supplies gain share (13% *vs.* 34%) primarily at the expense of natural gas (21% *vs.* 4%), which in the current data set is assumed to be severely resource constrained. The coal share remains relatively constant (30% *vs.* 28%).

6.2 Sample Policy Run

In this subsection, we present results from a sample policy run. The purpose is not to conduct policy analysis, which will be discussed in subsequent papers, but to reveal the behavior of the model by a comparison of the policy-constrained case with a corresponding baseline run. The particular policy scenario we demonstrate is the proposed AOSIS Protocol (United Nations, 1994), in which OECD regions stabilize their CO_2 emissions at the 1990 level by the year 2000, and then reduce CO_2 emissions to 80% of 1990 level from 2010 onward.[15]

Figure 8 compares the reference run (with full vintaging) with the AOSIS Protocol, both with and without backstop technology (squares and diamonds, respectively). The reference runs are in black; the imposition of the AOSIS constraint results in the carbon trajectories shown by the open symbols. The policy clearly reduces global emissions regardless of backstop assumption.

Figure 9 shows the evolution of regional shares of global emissions under the AOSIS Protocol, in the same manner as Figure 6 did for the reference run. As would be expected, the AOSIS Protocol reduces the projected OECD share in 2100 from 40% to 17%. Figure 10 shows that the AOSIS policy would increase the fuel share of carbon-free electricity in 2100 by 11% at

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[15] The actual AOSIS (Alliance of Oceanic and Small Island States) proposal states 2005 as the timetable for the 20% reduction below 1990 levels, but we impose the 2010 date to facilitate comparison with results from other models which use a decadal time step.

the expense of oil (-6%) and coal (-5%).

One of the principal advantages of a regional model, like EPPA, is that it can show the trade effects of regionally specific policies, such as the AOSIS proposal. Two effects are particularly notable: the depressing effects of the CO_2 constraint, which forces adjustments to less efficient production and a less desirable composition of output, and the changes in patterns of trade, which generate "carbon leakage." Figure 11 shows the cumulative discounted percentage GDP loss for the twelve regions when compared with the reference case. The GDP losses are greater in the OECD regions, but there is GDP loss in all other regions as a result of the reduced demand in the industrialized world and the consequent effects through international trade. Figure 12 shows the associated percentage change in cumulative carbon emissions by region. The reductions in the OECD regions are significant, and, on the average, emissions increase for the non-OECD regions due to leakage effects. The reduction in cumulative carbon emissions corresponding to the reduction of GDP shown in Figure 11 is shown by the white bars. The black bars depict the substitution effects of the restriction in the OECD regions and the leakage effects in the non-OECD regions, and the net change is the sum of the two effects.

A further feature of EPPA that is important for policy purposes is the more accurate representation of the costs of the policy due to capital fixity. Figure 13 contrasts the cumulative percentage GDP loss for the OECD when fully flexible capital (putty-putty) and the fully vintaged approach is adopted for the first thirty years of the century and for the entire 21st Century. As shown, the putty-putty assumption always understates cost, but more so in the earlier decades than over the entire period of the projection.

7. FURTHER DEVELOPMENT OF THE EPPA MODEL

This report describes Version 1.6 of the EPPA model, which is being applied to climate studies using the MIT Integrated Framework, and to assessment of proposed emissions control policies. In addition, work continues to improve the model and to extend its capabilities. Several areas of further development are receiving high priority. One of these concerns the influence within various segments of the model of improvements in productivity. The predicted increase in labor productivity (Section 3.1) is an important determinant of economic growth in each region of the model; the assumption about autonomous improvements in energy efficiency (Section 3.4) has a strong influence on the energy intensity of economic activity; and judgments about the influence of technical progress on the fixed factor inputs to conventional oil and gas production (Section 3.4) have an effect on energy supplies and prices, and thus on energy use and emissions. Research is under way on methods to ensure consistency among these now separate formulations.

Another area of effort concerns sub-sectors of the energy sector. Of particular importance is the imposition, within the model of natural gas, of more realistic costs of (and constraints on) international shipment, and the elaboration of the cost structure of the backstop technologies. In addition, the production structure within the model is being disaggregated, in order to increase the usefulness of the model for policy assessment, and for the prediction of particular gases. In EPPA Version 1.6, for example, as in the parent GREEN model, transport is contained within Other Industries and Services (see Table 1). Transport is being disaggregated, to allow study of policies directed specifically at this sector (e.g., gasoline taxes and vehicle economy standards). Also, we plan to disaggregate the current Agriculture sector, to identify different types of crops, and livestock activity, in order to improve the analysis of emissions of methane and nitrous oxide.

These efforts are accompanied by a continuing effort to improve the estimates of key input parameters, and to update the underlying social accounting matrices. When these various improvements are brought together into a new version of the EPPA model, a revision of this report will be prepared.

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Table 1. Key dimensions of the EPPA model

Production sectors, *i*

- Non Energy
  1. Agriculture
  2. Energy-intensive industries
  3. Other industries and services
- Energy, *e*
  4. Crude oil
  5. Natural gas
  6. Refined oil
  7. Coal
  8. Electricity, gas and water
- Future Supply Technology, *b*
  9. Carbon liquids backstop[1]
  10. Carbon-free electric backstop[2]

Regions

	Name
1. United States	USA
2. Japan	JPN
3. EC	EC
4. Other OECD[3]	OOE
5. Central and Eastern Europe[4]	EET
6. The former Soviet Union	FSU
7. Energy-exporting LDCs[5]	EEX
8. China	CHN
9. India	IND
10. Dynamic Asian Economies[6]	DAE
11. Brazil	BRA
12. Rest of the World	ROW

Consumer sectors, *c*

1. Food and beverages
2. Fuel and power
3. Transport and communication
4. Other goods and services

Primary factors

1. Labor
2. Capital (by vintage)
3. Sector-specific fixed factors for each fuel
4. Land in agriculture

Gases, *g*

	symbol
1. Carbon Dioxide	CO_2
2. Methane	CH_4
3. Nitrous Oxide	N_2O
4. Chloroflurocarbons	CFC
5. Nitrogen Oxides	NO_x
6. Carbon Monoxide	CO
7. Sulfur Oxides	SO_x

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[1] Liquid fuel derived from shale or tar sands.

[2] Carbon-free electricity derived from advanced nuclear, solar or wind.

[3] Australia, Canada, New Zealand, EFTA (excluding Switzerland and Iceland) and Turkey.

[4] Bulgaria, Czechoslovakia, Hungary, Poland, Romania and Yugoslavia.

[5] OPEC countries as well as other oil-exporting, gas-exporting and coal-exporting countries. See OECD (1992).

[6] Hong Kong, Philippines, Singapore, South Korea, Taiwan and Thailand.

Table 2. Sample SAM (USA, 1985, Millions of Dollars)*

		Agric	Coal	Oil	Gas	Refoil	Elec	EnerInt	OtherInd	Agric	Coal	Oil	Gas	Refoil	Elec	EnerInt	OtherInd
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	Agric	40,908	11	3	1	1	19	826	103,635								
2	Coal	27				22	13,476	4,328	4,586								
3	Oil					82,852		3,431									
4	Gas					1,561	32,597		442								
5	Refoil	7,242	649	240	131	9,726	13,384	6,213	55,408								
6	Elec	4,099	839	1,177	644	5,255	44,770	22,170	64,858								
7	EnerInt	8,831	832	873	368	4,788	721	99,842	202,883								
8	OtherInd	51,534	6,592	13,384	7,326	19,648	22,468	101,730	1,919,355								
9	Agric	1,368	0	0	0	0	1	21	3,466								
10	Coal	0				0	46	15	16								
11	Oil					26,561		1,103									
12	Gas					110	2,304		31								
13	Refoil	893	80	30	16	1,200	1,651	767	6,835								
14	Elec	7	1	2	1	9	75	37	109								
15	EnerInt	1,014	73	77	42	550	83	11,482	23,291								
16	OtherInd	3,134	401	814	446	1,195	1,368	6,187	116,730								
17	FoodBev																
18	Energy																
19	TrnspComm																
20	Other																
21	Labour	36,096	9,943	17,177	8,986	6,720	33,752	84,349	2,183,809								
22	Capital	15,858	3,049	30,402	15,905	8,457	28,437	48,143	1,066,187								
23	Fixed Factor	28,403	1,720	15,105	7,903		42,047										
24	Production Taxes	-2,816	2,754	11,321	5,923	13,148	18,825	4,123	256,987								
25	Distortions																
26	Households																
27	Government																
28	Investment																
29	Stock Building																
30	Depreciation																
31	Exports																
32	ROW									6,030	78	28,980	3,321	21,192	430	41,847	346,303
		196,596	26,744	90,405	47,694	181,601	256,020	394,546	6,008,517	6,030	78	28,980	3,321	21,192	430	41,847	346,303

*Source: OECD (1993b)

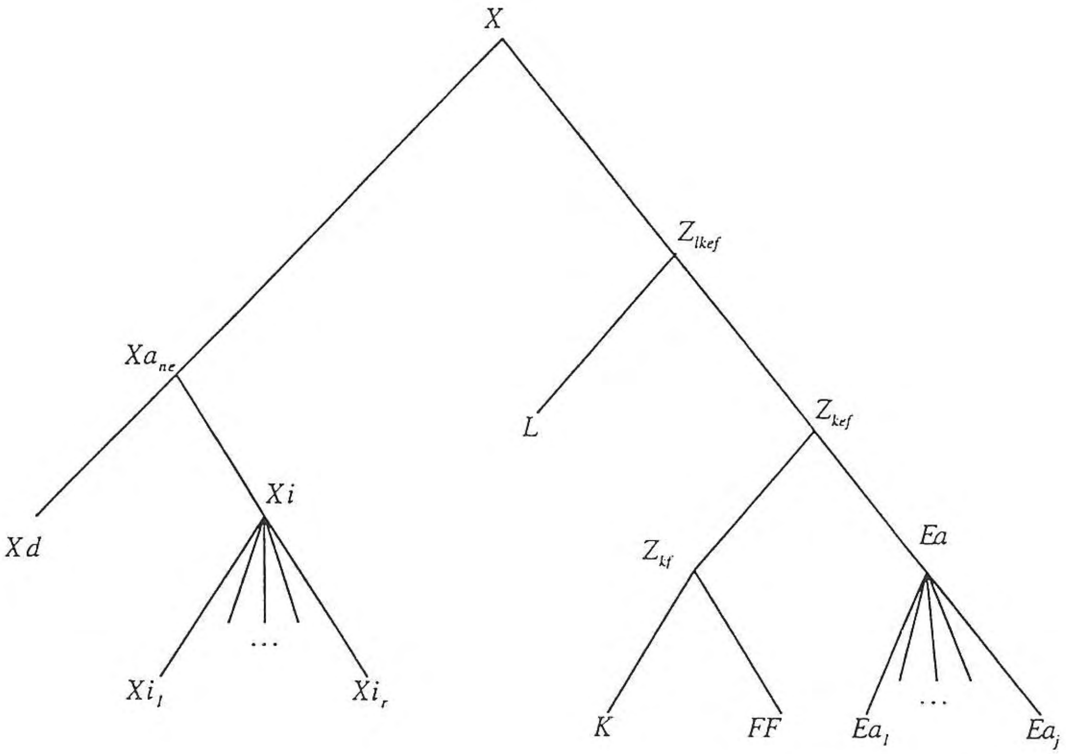
Table 2. Sample SAM, continued

Food & Bev	Energy	Transp & Comm	Other	Labour	Capital	Fixed Factor	Prod Taxes	Distors	House-Holds	Gover-ment	Invest-ment	Stock Buidling	Deprec-iation	Exports	ROW	Total
17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	
15,426	87		5,051							11,596		2,957		16,277		196,596
	275									318		47		3,664		26,744
								3,274		619	203			226		90,405
	11,933									339	111			711		47,694
	15,589	44,483								13,038		5,685		9,815		181,601
	72,954		22,885							16,320				250		256,020
	16	65	45,600							11,547	788	-12,253		30,024		394,546
327,983	49	345,239	1,549,784							719,637	593,898	15,514		314,379		8,008,517
516	3		169							388		99				6,030
	1									1		0				78
								1,052		199	65					28,980
	843									24	8					3,321
	1,923	5,488								1,608		701				21,192
	123		38							27						430
	2	10	5,235							1,326	91	-1,407				41,847
19,947	3	20,997	94,254							43,768	38,119	943				348,303
									363,872							363,872
									103,801							103,801
									416,301							416,301
									1,723,017							1,723,017
																2,380,922
																1,216,437
																95,177
																310,266
										4,326						4,326
				2,380,922	1,216,437	95,177				485,627						4,158,163
							310,268		810,411		170,027					1,290,704
									237,461				503,300		72,835	813,596
											12,286					12,286
									503,300							503,300
															375,346	375,346
																448,181
363,872	103,801	416,301	1,723,017	2,380,922	1,216,437	95,177	310,266	4,326	4,158,163	1,290,704	813,596	12,286	503,300	375,346	448,181	

Table 3. Changes in Regional GDP

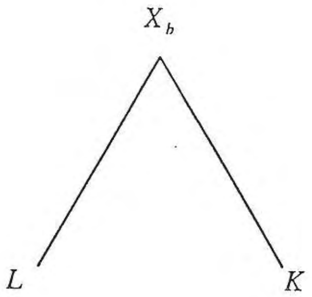
Region	*1985 GDP* (billion 1985 US$)	Growth Rates of Regional GDP					GDP in 2100 as a multiple of 1985
		1985-2000	2000-2025	2025-2050	2050-2075	2075-2100	
USA	3,692.54	3.18%	1.57%	1.30%	1.16%	0.96%	5.524
JPN	1,265.99	4.03%	2.18%	1.70%	1.29%	1.03%	8.398
EEC	2,227.56	3.10%	1.69%	1.23%	0.87%	0.69%	4.811
OOE	787.41	3.96%	1.48%	1.20%	1.02%	0.82%	5.519
EEX	1,047.61	6.25%	1.67%	1.14%	0.63%	0.39%	6.444
CHN	440.90	9.12%	3.33%	2.54%	1.60%	1.10%	30.714
FSU	637.74	7.13%	1.00%	1.76%	1.56%	1.41%	11.620
IND	181.79	7.04%	3.65%	2.66%	1.89%	1.44%	29.901
EET	237.15	6.41%	2.00%	1.88%	1.44%	1.25%	12.934
DAE	261.78	6.59%	4.32%	2.67%	1.43%	0.79%	25.183
BRA	186.31	4.19%	4.48%	2.57%	0.65%	0.06%	12.478
ROW	614.24	4.27%	3.44%	2.46%	1.69%	1.32%	16.934

Figure 1. Production Nesting



* Subscript a represents Armington specification. Below each Ea_i there is a nesting structure similar to *Xa*.

Backstop Technology



Consumption

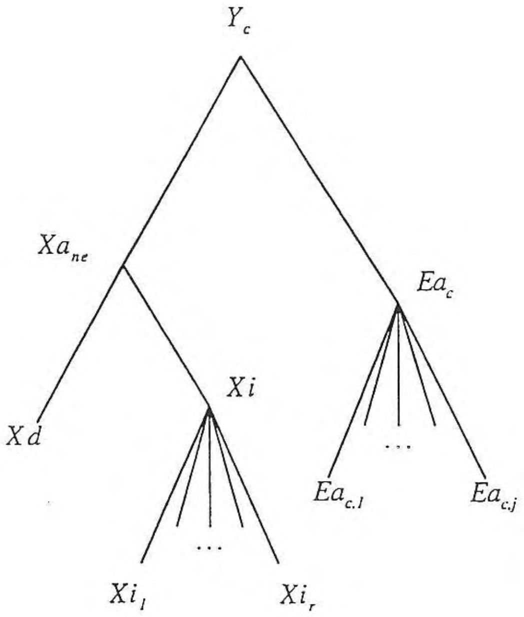


Figure 2. Global Carbon Emissions 1985-2100

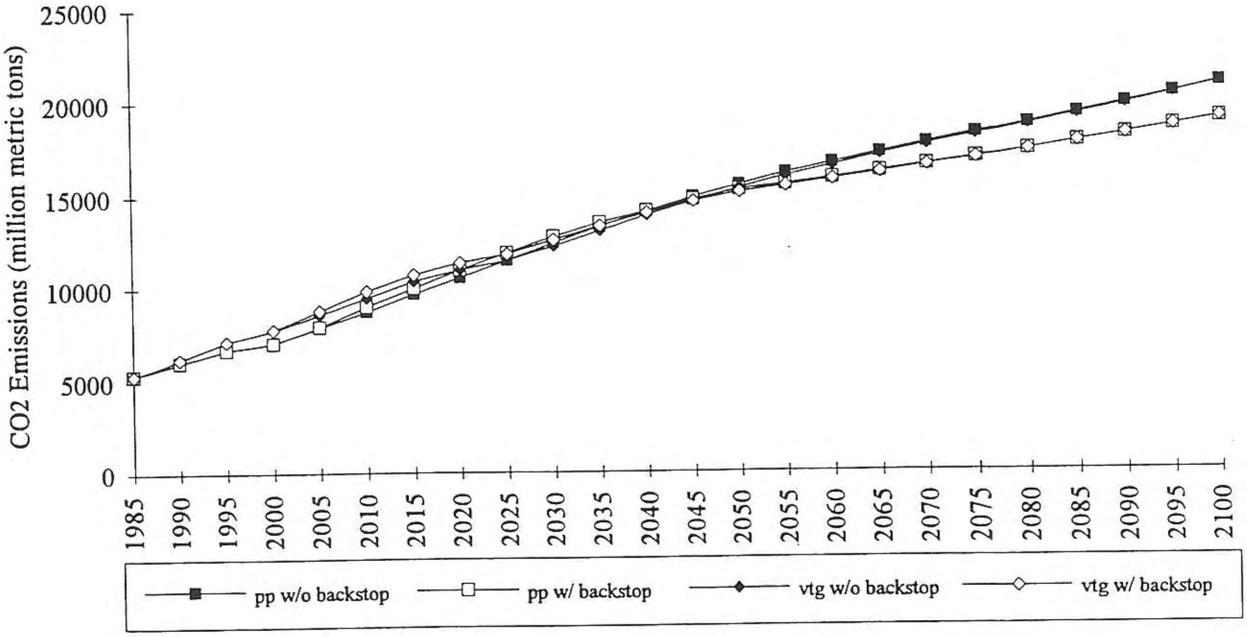


Figure 3. Global Carbon Emissions 1985-2050: The Effects of Vintaging

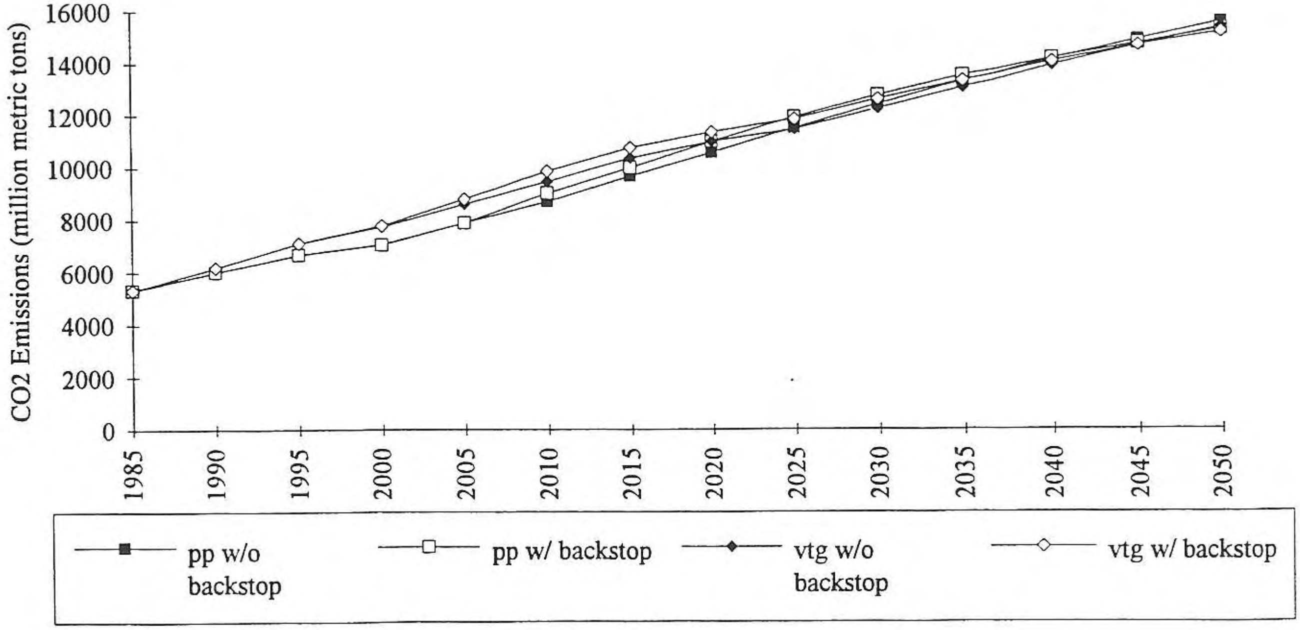


Figure 4. Global Emissions of CO_2 and Trace Gases

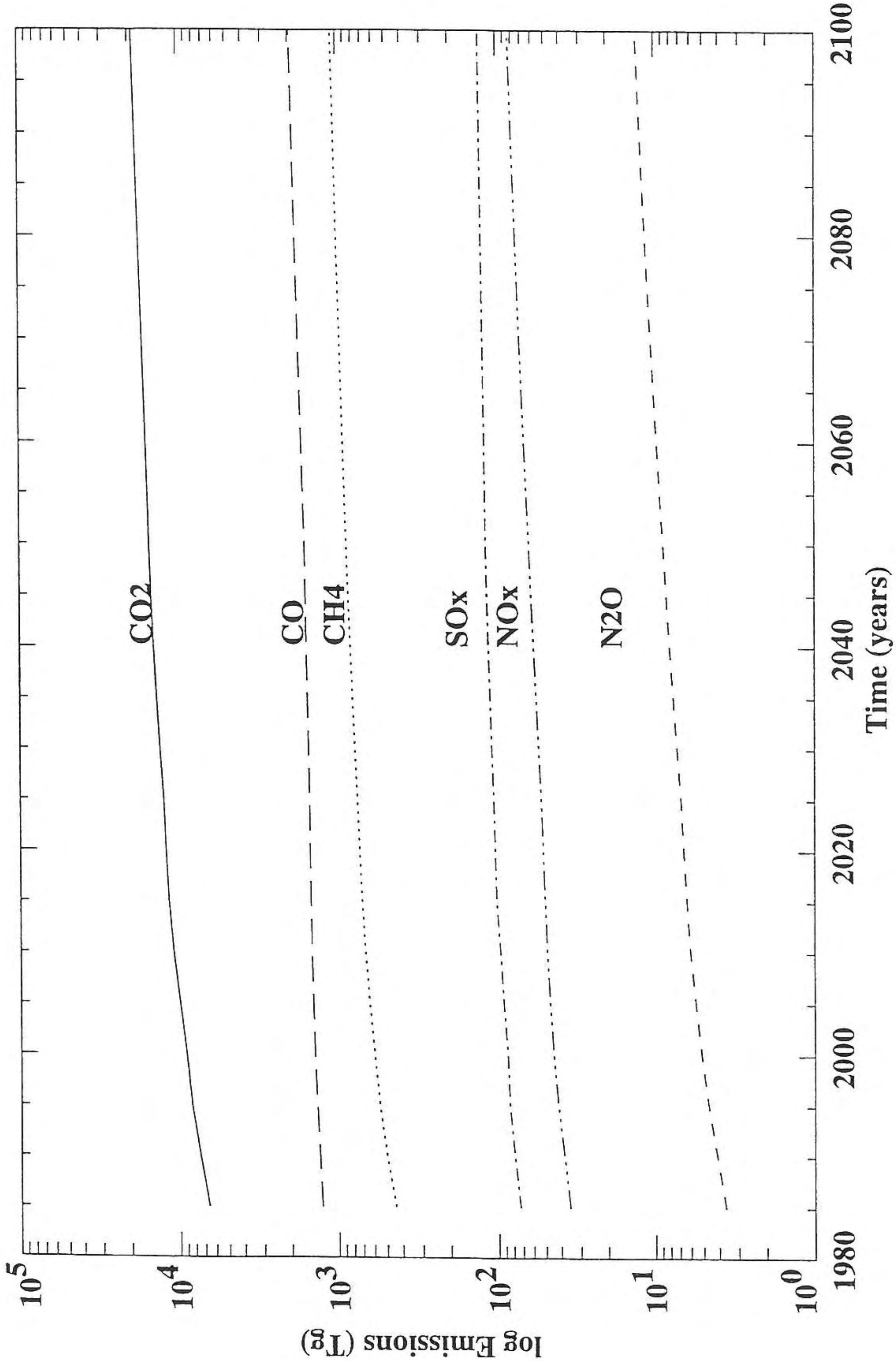


Figure 5. Evolution of the Carbon Intensity of Regional Economies

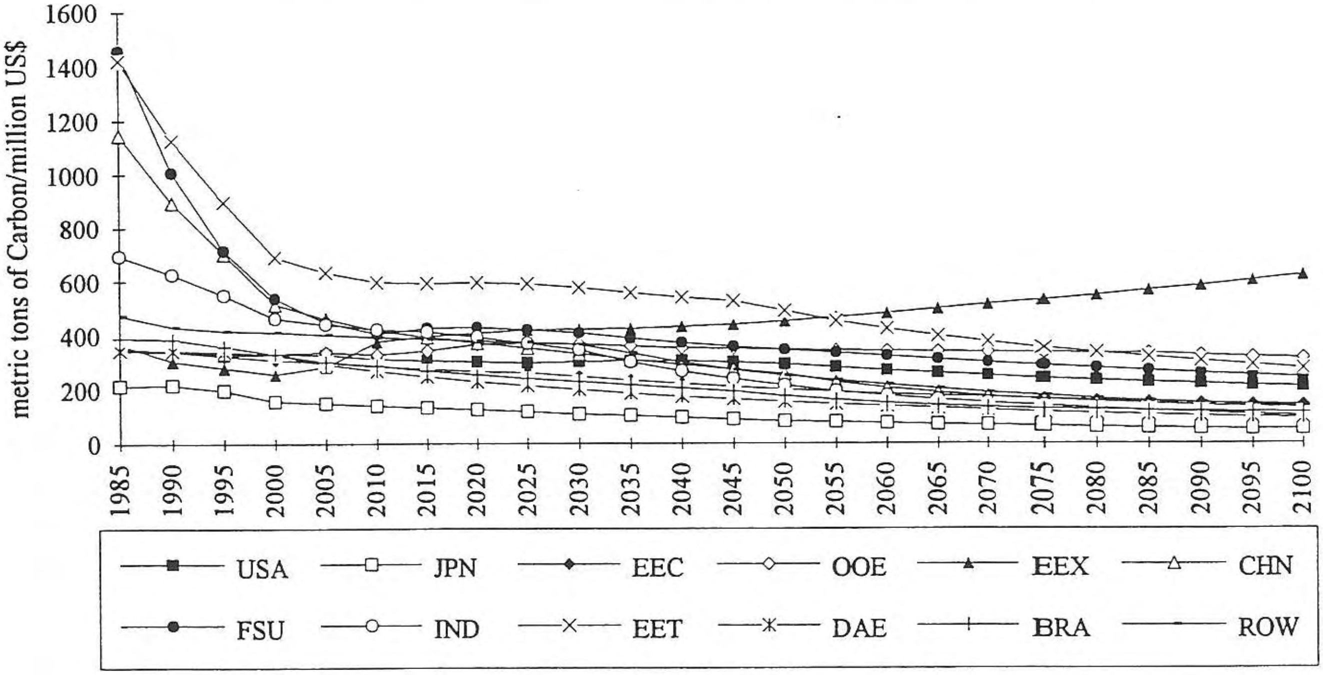


Figure 6. Regional Shares of CO2 Emissions, Reference Case

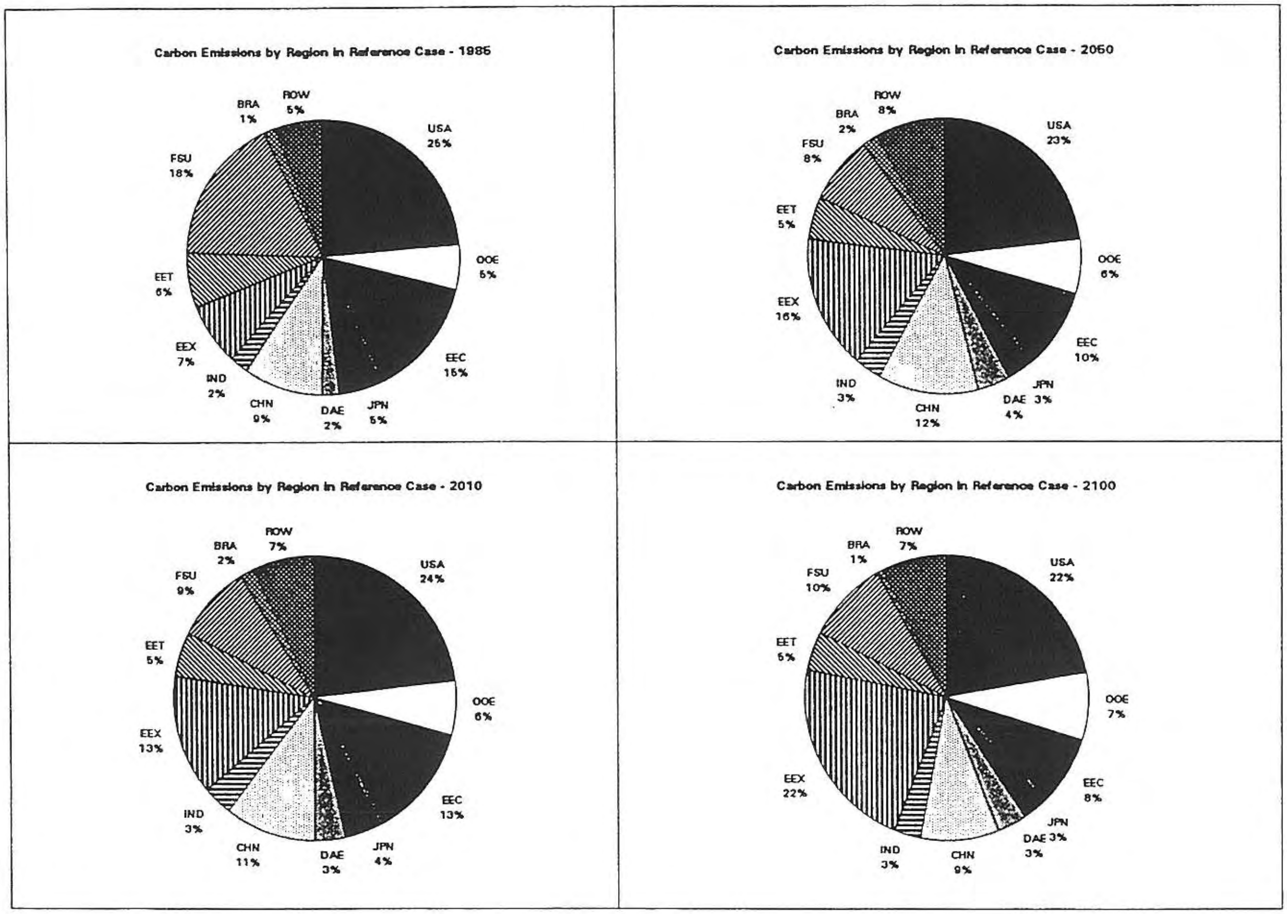


Figure 7. Energy Shares in Consumption, Reference Case

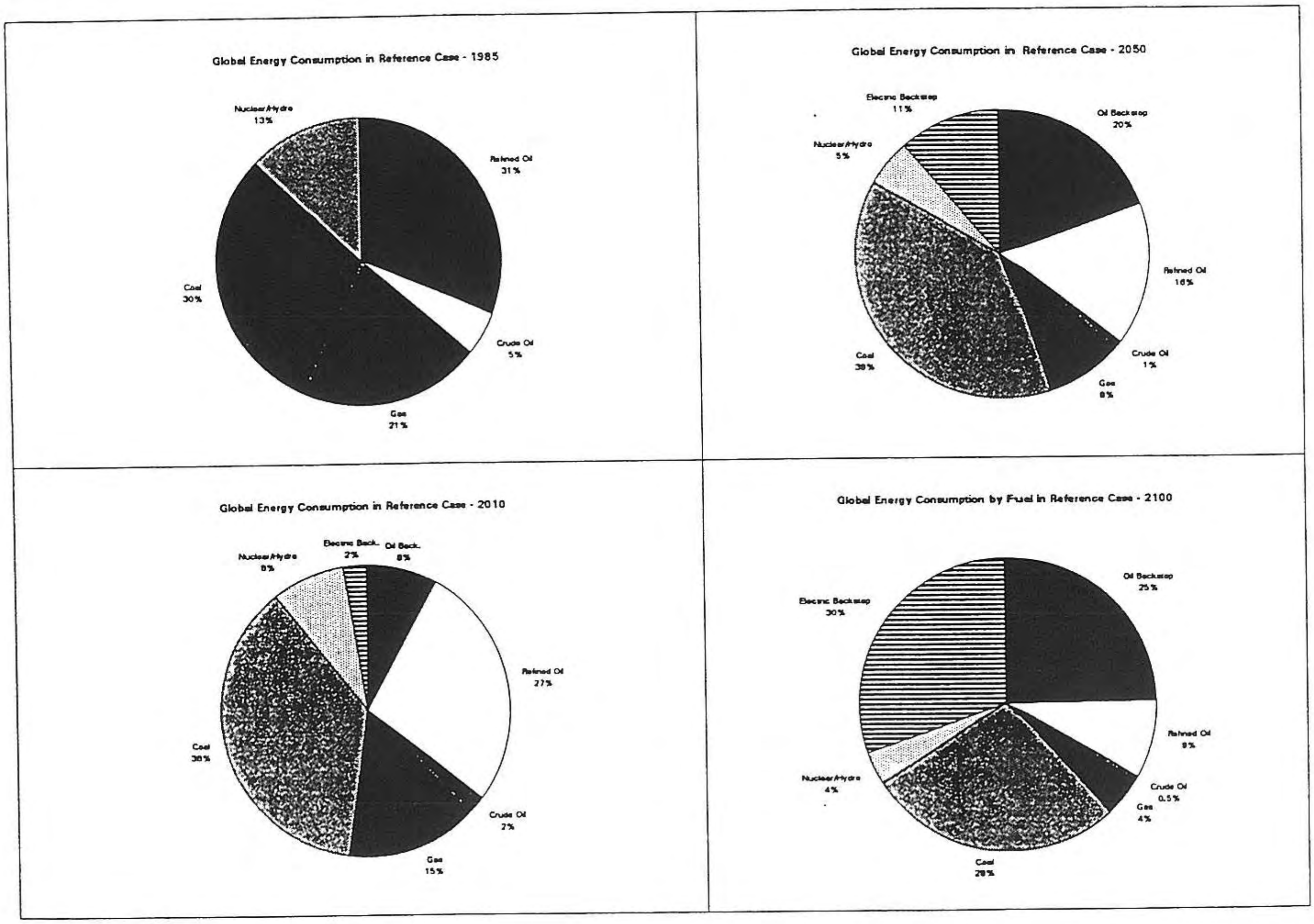


Figure 8. Global Carbon Emissions Under Baseline and AOSIS Cases 1985-2000

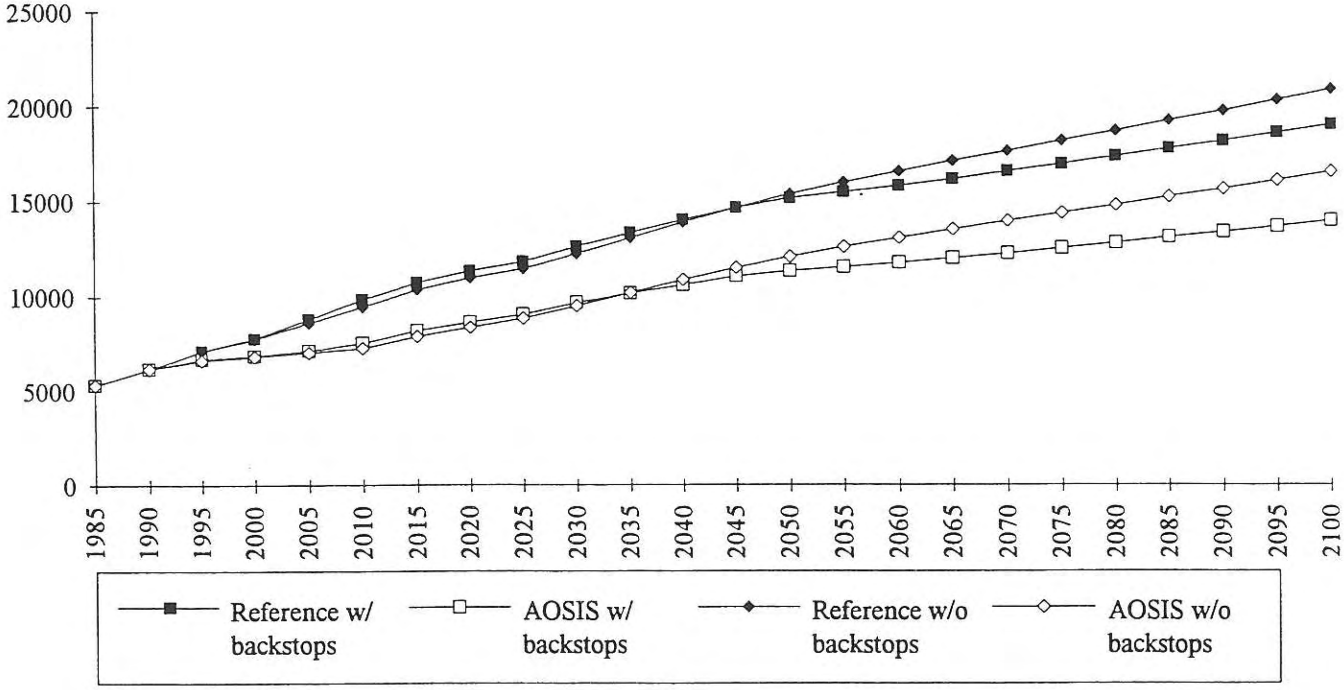


Figure 9. Regional Shares of CO2 Emissions, AOSIS Case

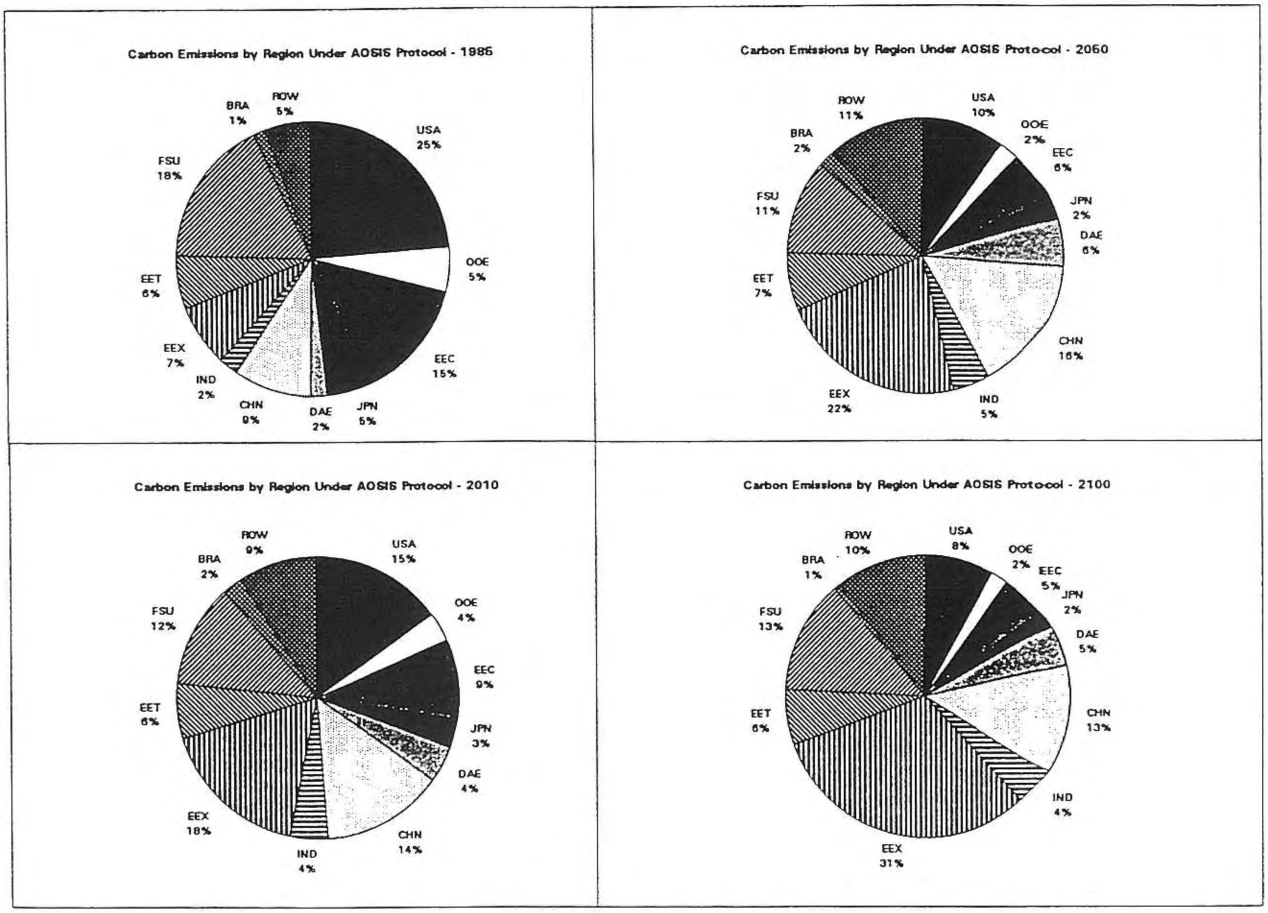


Figure 10. Energy Shares in Consumption, AOSIS Case

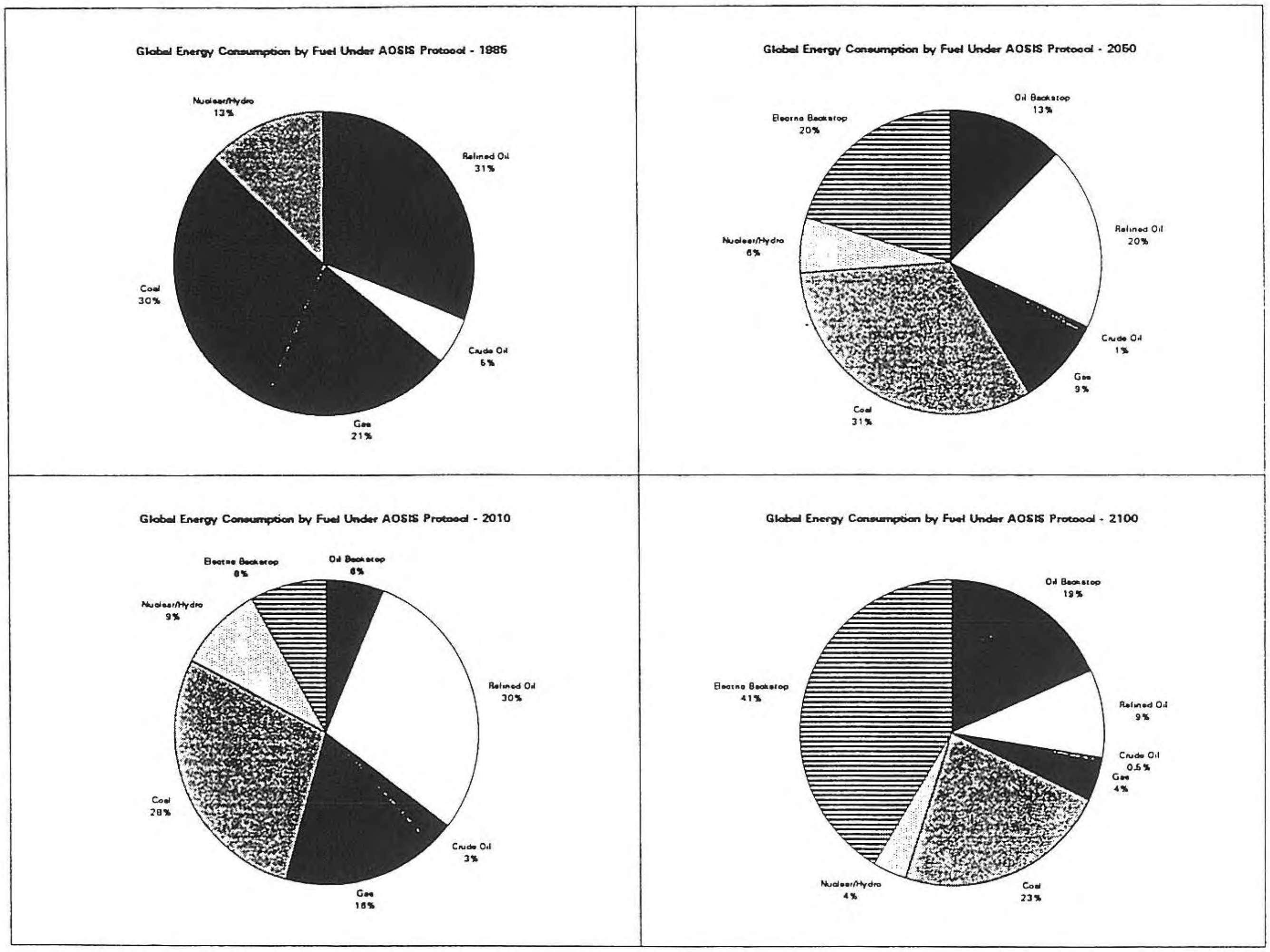


Figure 11. Regional Economic Impacts of AOSIS Protocol (1990-2100, discounted at 5%)

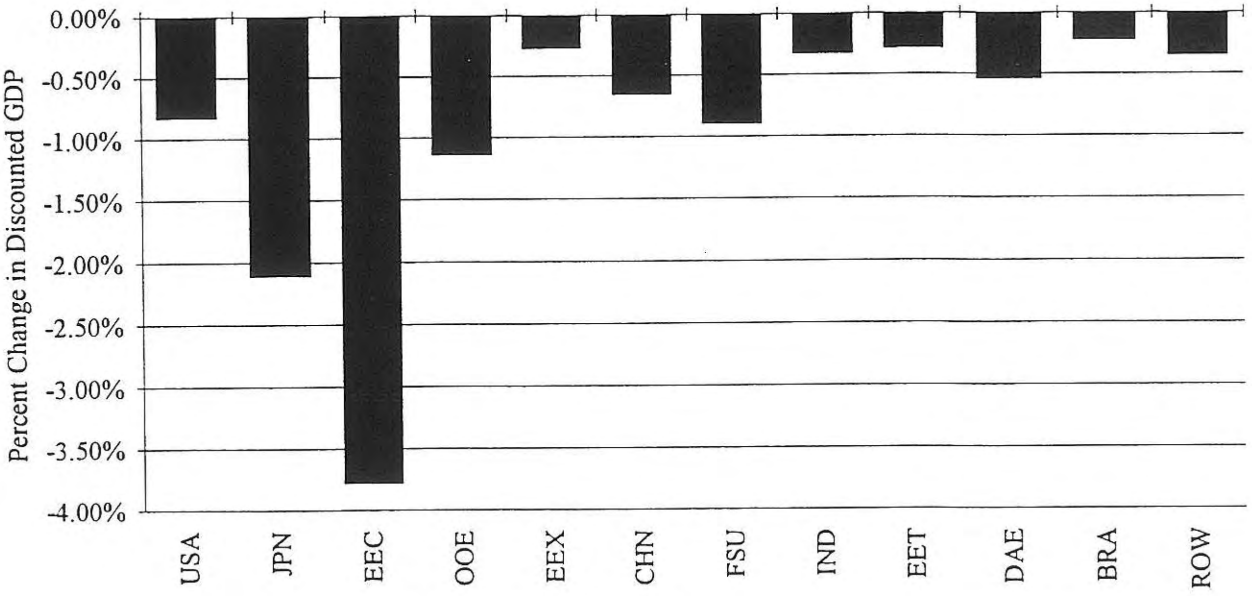


Figure 12. Change in Carbon Emissions Due to Substitution Effects and GDP Loss Resulting from AOSIS Protocol

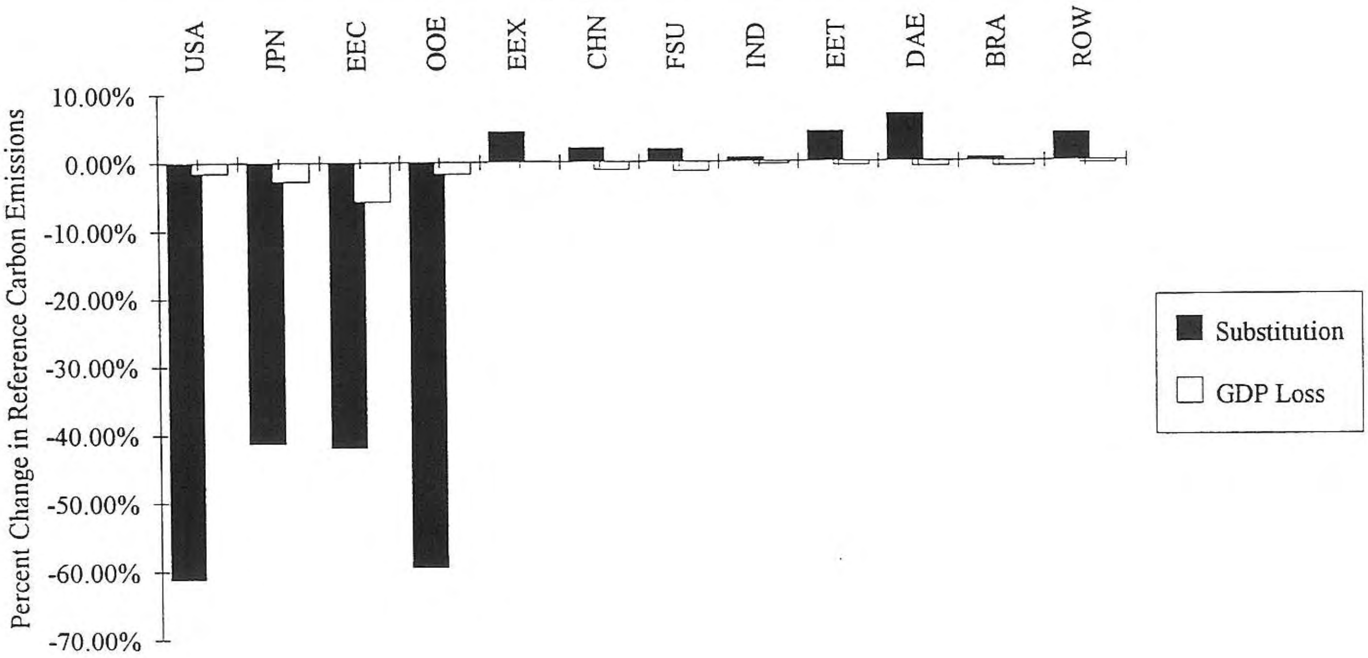
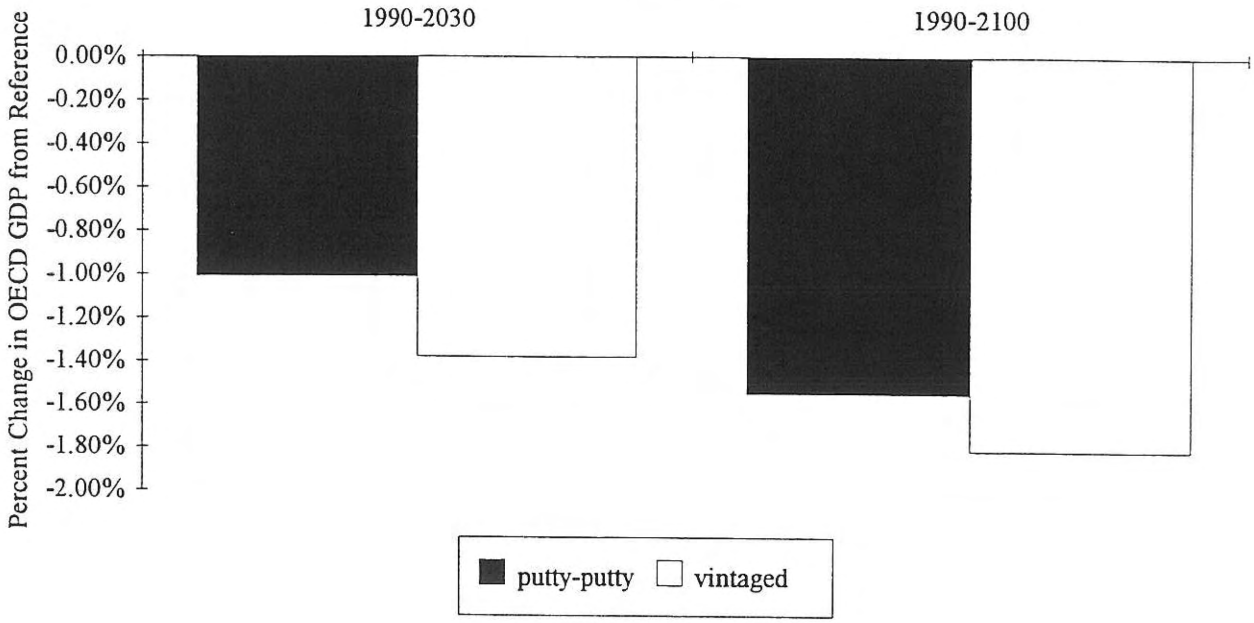


Figure 13. Impact of Capital Fixity Assumptions on Costs to OECD of the AOSIS Protocol



APPENDIX 1. LIST OF VARIABLES AND PARAMETERS

1. Variables[1]:

X_i :	Gross output of sector *i*
Xa_i :	Armington output of sector *i*
Xd_i :	Gross domestic output of sector *i*
Xi_i :	Imported output of sector *i*
Z_{lkef} :	Aggregate of labor, capital, energy and fixed factor bundle
Z_{kef} :	Aggregate of capital, energy and fixed factor bundle
Z_{kf} :	Aggregate of capital and fixed factor bundle
E_i :	Aggregate of energy bundle
FF_i :	Demand for fixed factor in sector *i*
K_i :	Demand for capital in sector *i*
L_i :	Demand for labor in sector *i*

Y_c :	Consumption of good *c*
$Xa_{i,c}$:	Armington good *i* demanded by consumer good *c*
E_c :	Energy bundle demanded by consumer good *c*
Id :	Disposable income
L^s :	Total labor supply (in efficiency units)
K^s :	Total capital supply (capital service)
FF^s_i :	Total fixed factor supply of sector *i*
S_h :	Household saving
G_{tr} :	Government transfers to household
T_h :	Household income tax

i :	Gross investment
$Xa_{i,i}$:	Armington good of sector *i* demanded by investment
E_I :	Energy bundle demanded by investment
G :	Government sector
$Xa_{i,g}$:	Armington good of sector *i* demanded by government
E_g :	Energy bundle demanded by government
L_g :	Labor demanded by government
K_g :	Capital demanded by government

Pop_r :	Population of region *r*
Pl_r :	Labor productivity of region *r*
L_r :	Labor supply (in efficiency unit) of region *r*

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[1] For simplicity, we omit subscript of region in the list of variables and parameters whenever it does not cause confusions.

$X_{b,i}$:	Output of backstop technology b substituting output of sector *i*
$X_{c,i}$:	Output of sector *i* from conventional technology

2. Parameters

$a_{ne,i}$:	Share coefficient of non-energy inputs in CES production function of sector *i*
$a_{lkef,i}$:	Share coefficient of labor, capital, fixed factor and energy bundle inputs in CES production function of sector *i*
$a_{l,i}$:	Share coefficient of labor inputs in CES production function of sector *i*
$a_{kef,i}$:	Share coefficient of capital, fixed factor and energy bundle inputs in CES production function of sector *i*
$a_{e,i}$:	Share coefficient of energy bundle inputs in CES production function of sector *i*
$a_{i,e}$	Share coefficient of individual input in energy bundle.
$a_{kf,i}$:	Share coefficient of capital and fixed factor bundle inputs in CES production function of sector *i*
$a_{k,i}$:	Share coefficient of capital inputs in CES production function of sector *i*
$a_{f,i}$:	Share coefficient of fixed factor inputs in CES production function of sector *i*
$a_{i,j}$:	Share coefficient of imported intermediate inputs of sector *j* in CES production function of sector *i*
$a_{d,j}$:	Share coefficient of domestic intermediate inputs of sector *j* in CES production function of sector *i*
$a_{r,j}$:	Share coefficient of imported intermediate inputs of sector *j* from region *r* in CES production function of sector *i*
$a_{i,c}$:	Share coefficient of inputs from sector *i* in consumption of good *c*
$a_{i,i}$:	Share coefficient of inputs from sector *i* in investment
$a_{i,g}$:	Share coefficient of inputs from sector *i* in government production
$a_{k,g}$:	Share coefficient of capital inputs in government production
$a_{l,g}$:	Share coefficient of labor inputs in government production
ρ_{lkef} :	Substitution elasticity between labor and bundle of capital, fixed factor and energy in CES production function
ρ_{kef} :	Substitution elasticity between energy bundle and bundle of capital, fixed factor in CES production function

ρ_{kf} : Substitution elasticity between capital and fixed factor in CES production function
ρ_e : Substitution elasticity between components in energy bundle in CES production function
$\rho_{i,\alpha 2}$: Substitution elasticity between imported and domestic intermediate inputs in CES production function (top layer Armington elasticity)
$\rho_{j,\alpha 1}$: Substitution elasticity between imported intermediate inputs from different regions in CES production function (bottom layer Armington elasticity)

θ_c : Subsistence consumption of good *c*
μ_c : Share of good *c* in utility function
w: Wage rate
r: Return to capital service

pf_i : Return to fixed factor service

$g_{1,r}$: Initial growth rate of population in region *r*
$g_{\infty,r}$: Asymptotic growth rate of population in region *r*
$g_{0,r}$: Initial growth rate of labor productivity in region *r*
$g_{n,r}$: Terminal growth rate of labor productivity in region *r*
$\alpha_{p,r}$: Auxiliary parameter in determining population growth path in region *r*
$\beta_{p,r}$: Another auxiliary parameter in determining population growth path
$\alpha_{l,r}$: Auxiliary parameter in determining labor productivity growth path in region *r*
$\beta_{l,r}$: Another auxiliary parameter in determining labor productivity growth path

s_r : Initial saving rate in region *r*
δ_r : Benchmark capital depreciation rate in region *r*
σ: Saving rate adjustment damping factor

$\sigma_{f,i}$: Fixed factor supply elasticity in sector *i*
γ_{ej} : Annual AEEI rate in sector *j*

$\alpha_{b,i}$: Labor share in backstop technology for substituting sector *i*
$\beta_{b,i}$: Capital share in backstop technology for substituting sector *i*

$c_{b,i}$: Benchmark unit cost of backstop technology for substituting sector *i*

APPENDIX 2. VALUES OF SELECTED PARAMETERS AND INPUT DATA

Table A1. Substitution Elasticity

	ρ_{lkef}	ρ_{kef}	ρ_{kf}	ρ_e	$\rho_{i,\alpha 2}$	$\rho_{j,\alpha 1}$
AGRIC	1.0	0.7	0.2	2	2	3
COAL	1.0	0.7	0.2	2	3	4
OIL	1.0	0.7	0.2	2	3	4
GAS	1.0	0.7	0.2	2	3	4
REFOIL	1.0	0.7	0.2	2	3	4
ELEC	1.0	0.7	0.2	2	0.3	0.5
ENERINT	1.0	0.7	0.2	2	2	3
OTHERIND	1.0	0.7	0.2	2	2	3

Table A2. Coefficients of Energy Contents (Exajoule per million 85 US$) (*TJ85*)

	Coal	Oil	Gas	RefOil	Elec
USA	0.77392863	0.21500844	0.35049142	0.14487117	0.03666328
JPN	0.18333706	0.19020428	0.20264218	0.11774523	0.02878860
EEC	0.44055759	0.20084558	0.21657994	0.12084787	0.03611633
OOE	0.87697120	0.24021348	0.36637941	0.13963108	0.06265089
EEX	1.09960583	0.32586471	0.34825090	0.13934171	0.04533677
CHN	1.56175400	0.21069774	0.31063511	0.13201714	0.13791845
FSU	1.59455539	1.18700000	2.36671885	1.18697639	0.29648470
IND	1.20249187	0.35550614	0.55303922	0.16871833	0.07785827
EET	1.17001266	0.33892263	0.64022308	0.13810134	0.08988690
DAE	0.46830608	0.25073499	0.20418787	0.09398377	0.04111171
BRA	0.30533072	0.27395807	0.47145186	0.12541675	0.08605055
ROW	1.26048079	0.22679826	0.14891489	0.10603939	0.04468788

Table A3. Coefficients of Carbon Contents (million ton per exajoule) (ε_e)

COAL	24.686
OIL	20.730
GAS	13.473
REFOIL	20.730
ELEC	0

Table A4. Values the Parameter $\alpha_{g,s}$ Used in the Trace Gas Estimates

Gas, *g*	Source, *s*	α
CH_4	Rice Paddies	0.3
CH_4	Enteric Fermentation	0.5
CH_4	Animal Wastes	0.6
CH_4	Landfills	0.05 or 0.5[a]
CH_4	Domestic Sewage	1.0
CH_4	Coal Mining	1.0
CH_4	Natural Gas	1.0
N_2O	Fertilizer Use	0.8
N_2O	Nitric Acid	0.8
N_2O	Gain of Cultivated Land	0.03
N_2O	Adipic Acid	1.0
N_2O	Fossil Fuel Combustion	1.0
NO_x	Fossil Fuel Combustion	0.3, 0.5, 1.0[b]
CO	Fossil Fuel Combustion	0.15, 0.50[c]
CO	Industrial Sources	0.5
SO_x	Fossil Fuel Combustion	0.3, 0.5, 1.0[b]
SO_x	Industrial Sources	0.5
all	Agricultural Source Biomass	0.25

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[a] 0.05 for OECD, 0.5 for non-OECD.

[b] 0.3 for USA, 0.5 for OECD, 1.0 for non-OECD.

[c] 0.15 for OECD, 0.50 for non-OECD.

Table A5. Base Year Population (millions)

USA	239.279
JPN	120.837
EEC	321.902
OOE	118.435
EEX	655.067
CHN	1040.264
FSU	277.537
IND	750.859
EET	118.160
DAE	174.429
BRA	135.564
ROW	869.011

Table A6. Initial Population Growth Rate (% annum) (g_l)

USA	0.20722
JPN	0.03418
EEC	0.09542
OOE	0.14010
EEX	1.54756
CHN	0.48222
FSU	0.28184
IND	0.95412
EET	0.24764
DAE	0.66783
BRA	0.80859
ROW	1.87180

Table A7. Asymptotic level of population (g_{∞})

USA	1.23
JPN	1.03
EEC	1.10
OOE	1.15
EEX	4.70
CHN	1.62
FSU	1.32
IND	2.60
EET	1.28
DAE	1.95
BRA	2.24
ROW	6.49

Table A8. Initial Labor Productivity Growth Rate (g_0)

	PRD %
USA	2.000
JPN	2.500
EEC	2.000
OOE	2.000
EEX	1.500
CHN	6.000
FSU	3.000
IND	5.000
EET	2.500
DAE	5.500
BRA	3.000
ROW	2.100

Table A9. Initial Saving Rate

USA	0.13
JPN	0.25
EEC	0.25
OOE	0.25
EEX	0.30
CHN	0.30
FSU	0.35
IND	0.15
EET	0.30
DAE	0.25
BRA	0.15
ROW	0.15

Table A10. Benchmark Cost of Backstop Technologies ($C_{b,i}$)

	Electricity	Refined Oil
USA	1.540	1.4
JPN	1.209	0
EEC	1.517	0
OOE	2.631	1.4
EEX	1.904	1.4
CHN	7.723	0
FSU	12.452	0
IND	4.360	0
EET	3.775	0
DAE	1.727	0
BRA	3.614	0
ROW	1.877	0