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GREEN a Multi-Sector, Multi-Region General Equilibrium Model for Quantifying the Costs of Curbing CO2 Emissions: A Technical Manual

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by
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GREEN -- A MULTI-SECTOR, MULTI-REGION DYNAMIC GENERAL EQUILIBRIUM MODEL FOR QUANTIFYING THE COSTS OF CURBING CO_2 EMISSIONS: A TECHNICAL MANUAL

The OECD Secretariat has developed a multi-region, multi-sector, dynamic applied general equilibrium (AGE) model to quantify the economy-wide and global costs of policies to curb emissions of carbon dioxide (CO_2). The project is called the GeneRal Equilibrium ENvironment model, hereafter referred to as GREEN. The purpose of this paper is to provide a full technical description of the GREEN model, its data base and parametrisation as of April 1992. It replaces the previous version of the GREEN Technical Manual which was issued in June 1991 as Working Paper No. 104.

* * *

Le Secrétariat de l'OCDE a construit un modèle d'équilibre général dynamique, multi-sectoriel et multi-régional afin de quantifier les coûts induits aux niveaux macroéconomique et mondial par les politiques visant à réduire les émissions de dioxide de carbone (CO_2). Le nom du projet est GREEN, par référence à "GeneRal Equilibrium ENvironmental model". L'objet de cette publication est de fournir une documentation technique complète du modèle GREEN, des données et de la paramétrisation dans la version disponible en avril 1992. La présente note remplace la version précédente du manuel technique de GREEN qui a été diffusée en juin 1991 sous la forme du document de travail n° 104.

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GREEN -- A MULTI-SECTOR, MULTI-REGION DYNAMIC GENERAL EQUILIBRIUM MODEL FOR QUANTIFYING THE COSTS OF CURBING CO_2 EMISSIONS: A TECHNICAL MANUAL

by

Jean-Marc Burniaux, John P. Martin, Giuseppe Nicoletti and Joaquim Oliveira Martins[1]

I. INTRODUCTION

The OECD Economics and Statistics Department has developed a global applied general equilibrium (AGE) model, covering four OECD regions and eight non-OECD regions, with the objective of quantifying the economic effects of policies aimed at reducing emissions of carbon dioxide (CO_2) in the atmosphere. The project is called the GeneRal Equilibrium ENvironmental model, hereafter referred to as GREEN.

This paper updates the technical documentation provided in Burniaux, Martin, Nicoletti and Oliveira Martins (1991) and describes the version of the model that was operational by Spring 1992. With respect to the previous version of GREEN, the current model has an extended time horizon, a complete world closure with a finer regional disaggregation and incorporates a putty/semi-putty production structure, backstop technologies, endogenous oil price determination and a treatment of energy price distortions.

The structure of the paper is as follows. A brief non-technical overview of the model precedes a more complete description of its specification. The construction of the benchmark data sets is described in Section IV. The key parameters of GREEN are identified in Section V and values are assigned to them, drawing partly on a review of the relevant economic literature. The final section discusses the calibration of the model.

II. MODEL OVERVIEW

GREEN is a multi-sector, multi-region, dynamic AGE model for evaluating the costs of policies to reduce CO_2 emissions. It currently includes twelve regional sub-models: four OECD countries/regions -- United States, Japan, the EC and the other OECD countries -- and eight non-OECD regions -- the former Soviet Union, China, the energy-exporting LDCs (mainly OPEC), the Central and Eastern European Countries (CEECs), the Dynamic Asian Economies (DAEs), India, Brazil and the Rest of the World (RoW). All regions are linked together by bilateral world trade matrices.

The model highlights the relationships between depletion of fossil fuels, energy production, energy use and CO_2 emissions. Therefore, the main focus is on the energy sector.

Three sources of fossil fuels -- oil, natural gas and coal -- and one source of non-fossil energy, the electricity sector, are distinguished. In addition, non-conventional energy sources -- the so-called "backstop technologies"-- are assumed to become available in the course of the simulation period. The production side of each regional model describes in a detailed way the supply of fossil fuels and the use of fossil and non-fossil energy inputs in the productive process. Some allowance is also made for shifts in the composition of production by treating agriculture as a separate sector and by distinguishing between two broad aggregates, energy-intensive industries and other industries and services.

The current version of GREEN has a simple recursive dynamic structure, in which saving decisions affect future economic outcomes through the accumulation of productive capital. Firm's investment decisions are not modelled and investment is computed residually. The model includes factor-market rigidities, which make capital (partially) sector-specific and imply a distinction between "old" and "new" capital vintages.

GREEN is currently simulated over the 1985-2050 period, in five steps of five-year intervals up to 2010 and two further steps of twenty-year intervals. In each region, the base model is calibrated on exogenous growth rates of GDP and population and on neutral technical progress in energy use.

Given the recursive structure of the model, the evolution over time of the economy can be described as a sequence of single-period static temporary equilibria. The characteristics of these equilibria are examined next.

A. Single-period equilibrium

(i) Production

The production block includes eleven sectors[2]. Five of them -- coal mining, crude oil, natural gas, refined oil products and electricity, gas and water distribution -- concern the supply and distribution of conventional energy. Three additional energy sectors describe the supply of non-conventional energy sources. The remaining three sectors -- agriculture, energy-intensive industries and non-energy intensive industries and services -- relate to the production of goods and services.

Each of the four primary sources of energy -- coal, oil, natural gas and electricity -- can be replaced at some future date by alternative technologies, called "backstop". In GREEN, backstop technologies are defined by three characteristics: (i) they become available at a given identical time period in all regions; (ii) the backstop product is produced at a constant marginal cost and in unlimited quantities; and (iii) its price is exogenous and identical across regions. For each of the three fossil fuels, two alternative backstop technologies are assumed to exist: a carbon-based backstop which produces a synthetic fuel with a higher carbon content than the conventional technology and a carbon-free backstop fuel. A single carbon-free backstop technology is also available for producing electricity. The carbon-based and carbon-free backstop technologies are identical for coal, oil and natural gas. Table 1 provides the list of the eleven conventional and backstop production sectors of GREEN.

In each conventional sector, gross output is produced using the four primary energy sources or their backstop alternatives, refined oil products, a fixed factor (land, a fossil fuel or a carbon-free resource), capital, labour and intermediate goods and services[3]. Due to GREEN's dynamic structure, in each period two kinds of capital goods coexist, "old" capital, which was installed in previous periods, and "new" capital, which results from current-period investment. Finally, it is assumed that conventional energy and intermediate inputs can be obtained either from domestic or foreign suppliers. Backstop products are produced using only capital and labour and are not traded, since by assumption their supply is unlimited and their price is constant and identical across regions[4].

In each period, the supply of primary factors is usually predetermined. However, there are important exceptions. First, while the supply of new capital is predetermined, old capital available to each sector is partially dependent on its own rental value. The structure of second-hand capital markets will be described below. Second, land, the conventional carbon-free resource, crude oil, natural gas and coal are all assumed to be sensitive to their contemporaneous prices.

The upward-sloping supply curve for land accounts for the possibility of bringing marginal land into exploitation. Own-price sensitivity of the carbon-free resource is a proxy for time-to-build adjustment costs in the nuclear sector. Crude oil and natural gas are assumed to become sensitive to their prices only when potential supply (whose determination is described below) exceeds demand. In this latter case, the supply curves for oil and gas account for pressures due to extraction costs. Finally, the elasticity of coal to its price is assumed to be finite but large.

Over time, the potential supply of fossil fuels is assumed to be resource-based. While coal reserves are assumed to be infinite, supplies of crude oil and natural gas are described by a resource depletion submodel, which is part of the dynamic structure of the model. However, the depletion sub-model allows for some price-sensitivity of potential supply or, alternatively, of ultimate resources.

In summary, two output concepts can be distinguished for crude oil and gas. *Potential* output is determined by the depletion mechanism, which may be sensitive to the prices of the exhaustible resources. *Actual* output is determined by the supply curve for the fixed factor, which also depends on prices, but is bounded above by the potential supply profile. At each point in time, oil and gas producers can supply less than potential output at the given market prices[5]. In this case, future reserves and the time profile of potential supply are affected.

All sectors are assumed to operate at constant returns to scale and share a common production structure, which is depicted in Figure 1. The quantities of all inputs are optimally chosen by producers in order to minimise production costs given the level of sectoral demand and relative after-tax prices. Simplifying assumptions on the available technology make it possible to separate the decisions of producers into several stages[6]. First, producers are assumed to choose the mix between intermediate inputs and a composite input including all primary factors (capital, labour and the fixed factor) and energy. Second, the subdivision of this composite input among labour and the other primary factors is decided. Third, the mix between energy and the capital/fixed factor bundle is chosen. Fourth, the energy bundle is allocated among coal, oil, gas, refined oil products and electricity. Fifth, the optimal mix between conventional and backstop technologies is determined for each of these energy sources. Sixth, the mix between capital and the fixed factor is determined. Finally, demand for traded intermediate and energy inputs is allocated among domestic supply and imports.

Other simplifying assumptions restrict the range of substitution opportunities among inputs at each stage of the production process. In all sectors, it is assumed that intermediate inputs per unit of gross output are fixed. Similarly, the per-unit input structure of the capital/fixed factor bundle is assumed to be fixed. Finally, all inputs are assumed to be used in fixed proportions in the production of conventional and backstop fuels, petroleum products and backstop electricity.

An important feature of production in GREEN is the distinction between old and new capital goods. This depends on the presence of adjustment costs, which reflect the economic irreversibility of capital formation when markets for second-hand and new capital goods are incomplete. Costs associated with the dismantling or building of plants are proxied by two assumptions: the production technology is putty/semi-putty and the beginning-of-period capital stock is partially mobile across sectors[7].

The putty/semi-putty assumption implies that, at all stages of production, substitution among inputs using old vintages of capital is smaller than substitution among inputs using new vintages. Under this assumption, the way sectors adjust to relative price changes partly depends on the relative proportions of new and old vintages in the capital stock.

Partial mobility of old capital reflects differences in the marketability of capital goods across sectors. Goods such as oil rigs have few alternative uses while trucks and warehouses can be easily diverted from their original, sector-specific uses. In GREEN, costs related to lack of marketability are proxied by sector-specific supply elasticities for existing capital, which restrict mobility of old capital across sectors. This approach has two implications. First, equilibrium rental values for old capital may be lower than for new capital goods and may differ across sectors. Second, in each sector (and in the aggregate), the supply of old capital i.e. disinvestment, is not predetermined, but depends on the ratio of rental values of old and new capital.

For simplicity, it is assumed that old capital goods supplied in second-hand markets and new capital goods are homogeneous. Therefore, in each period, the demand for new capital vintages is equal to the sum of gross investment and aggregate disinvestment and a single rental value is determined for the new vintage of capital. This formulation makes it possible to introduce downward rigidities in the adjustment of capital without excessively increasing the number of equilibrium prices to be determined by the model[8]. At the same time, the possibility is left open to introduce imperfect substitution between old and new capital in some sectors, therefore allowing for sector-specific rigidities (e.g. in the electricity sector).

The final element in the production sub-model concerns the determination of producer prices. Once the optimal combination of inputs is determined, sectoral output prices are calculated assuming competitive supply (zero-profit) conditions in all markets. There is a single real world price of crude oil in the model, reflecting the assumption that oil is an homogeneous commodity in world markets. This price is determined by competitive behaviour of suppliers in the energy-exporting LDCs region[9]. As mentioned above, there are also single world prices for each of the backstop products and these prices are exogeneous. Since each sector supplies inputs to other sectors, output prices -- which are the cost of inputs for other sectors -- and the optimal combination of inputs are determined simultaneously in all sectors, conditional on the exogenous backstop prices.

(ii) Consumption

A single representative consumer is assumed to allocate optimally her/his disposable income among four broad consumer goods -- food and beverages, fuels and power, transport and communication, other goods and services -- and saving. Consumption aggregates differ from the outputs of the eight production sectors and were chosen in order to highlight the principal components of final demand for energy. A matrix of fixed coefficients -- a so-called "transition matrix" -- is used to convert demand for consumer goods and services into demand for energy and other producer goods, and to compute prices of consumer goods from producer prices. While the energy intensity of consumer goods is a technical datum given by the transition matrix, their fuel composition is assumed to be optimally chosen by consumers[10]. Finally, it is assumed that consumer demand can be satisfied by either domestic or foreign suppliers.

The structure of household demand is depicted in Figure 2. The consumption/saving decision is completely static. Saving is treated as a fifth "good" and its amount is determined simultaneously with the demands for other goods. The price of saving is set arbitrarily equal to the average price of consumer goods[11].

Appropriate assumptions on consumer preferences make it possible to separate consumption decisions into three stages. First, given their disposable income and prices of consumer goods, consumers make an optimal allocation of income among saving and the four consumer goods. At this stage, the model of consumer demand allows for different income elasticities across consumer goods[12]. Demands for consumer goods are translated into demands for producer goods and energy by the transition matrix. Second, given the energy intensity of each good and the prices of the various fuels, consumers choose an optimal mix of fuels. Third, the demand for each good is allocated optimally to domestic and foreign markets, as a function of domestic and import prices.

All income generated by economic activity is assumed to be distributed to consumers. Therefore, consumers make their choices based on (i) income from labour and capital (old and new); (ii) rents from fixed factors and other rents associated with crude oil and back-stop products; and (iii) government transfers net of taxes. Saving is assumed to take the form of purchases of investment goods, since no financial intermediation is incorporated in the model.

(iii) Government

The government collects carbon taxes, income taxes and indirect taxes on intermediate inputs, outputs and consumer expenditures. These taxes influence the decisions of economic agents by changing relative prices and/or disposable income. Existing distortions in the relative prices of energy inputs are explicitly modelled as taxes or subsidies on intermediate and final demand for energy. Tax revenues are endogenous in the model, since they depend on the level of economic activity. In addition, under the closure typically used in GREEN (see below), the income-tax rate is adjusted to compensate for variations in the budget caused by changes in carbon tax revenues.

Government expenditures are allocated among transfer and non-transfer expenditures. Both types of expenditures are exogenous in real terms, with real expenditures growing at the same rate as GDP. Total non-transfer expenditures are allocated among primary factors and intermediate goods in order to minimise government costs.

(iv) Policy instruments

(a) **Carbon tax**

The carbon tax is an excise tax, which is expressed as a fixed absolute amount of US$ per ton of carbon emitted. Therefore, in contrast with *ad valorem* taxes, its level per unit of energy does not vary with shocks to energy prices. The tax is fuel-specific, since it varies directly with the CO_2-emission coefficients of oil, coal, natural gas and the carbon-based backstop. It is applied at the level of consumers of *primary* fuels only, i.e. the tax is applied equally on domestic and imported uses of primary fossil fuels. Thus, for example, refineries are taxed on their use of crude oil, but firms using domestically refined petroleum products are not taxed. On the other hand, imports of refined oil products are taxed. The tax is applied prior to any indirect taxation of refined oil products. The distinction between a production- and a consumption-based carbon tax would affect assessments of international incidence[13].

Technically, in each region, the tax can be imposed or computed as the equilibrium shadow price that would be paid for an additional ton of CO_2 emissions when a given constraint on total emissions is imposed. The resulting tax level is then converted into fuel-specific taxes, based on the emission rate of each type of fossil fuel.

(b) **Energy tax**

The energy tax is an excise tax, which is expressed as a fixed absolute amount of US$ per Terajoule. It is a tax on the energy content of energy demand which is applied at the level of consumers of *all* primary energy sources, including the carbon-free electric energy[14]. Since each primary energy source has a specific carbon content, an energy tax equalise the marginal cost of reducing CO2 emissions across sectors. As with a carbon tax, the energy tax can be imposed or computed as an equilibrium price associated with a given constraint on total emissions.

The energy and carbon taxes can be combined to yield a mixed carbon *cum* energy tax. The range of taxation instruments in GREEN for curbing CO2 emissions is described below:

	Carbon tax	Energy tax	Energy *cum* carbon tax
Equilibrium tax	Defined in 1985 US$ per ton of carbon. Shadow price of a carbon emission constraint.	Defined in 1985 US$ per Terajoule. Equilibrium price resulting from a carbon emission constraint.	Weighted average of a carbon tax and an energy tax, with exogenous weights. Equilibrium price resulting from a carbon emission constraint.
Exogenous tax	Defined in 1985 US$ per ton of carbon.	Defined in 1985 US$ per Terajoule.	Weighted average of a carbon tax and an energy tax, with exogenous weights.

(c) **Trade in emission rights**

GREEN allows for the possibility that any global agreement to curb CO_2 emissions could include a provision allowing countries to trade rights to carbon emissions. In this case, a single constraint on carbon emissions is imposed at the world level. Countries are endowed with initial quotas of emission rights. In principle, this initial allocation is arbitrary and could be designed to achieve a range of international distributional objectives. In the current version of the model, the initial distribution is made equal to the upper bounds on emissions imposed in the no-trade situation. A single world price of emissions is determined as the carbon tax level associated with the world emission constraint, and countries can trade emissions rights freely in world markets at this price[15]. As a result, countries for which the world carbon tax is higher than its pre-trade level will sell rights, while countries which find themselves in the opposite situation will be net purchasers of rights.

In GREEN, trade in emission rights corresponds to exchanging a special kind of commodity across countries. It generates a monetary counterpart, which is reflected in a net inflow or outflow of income in countries that sell or buy emission rights. It is assumed that these income flows affect government revenues.

(v) <u>Foreign trade</u>

The world trade block is based on a set of bilateral matrices that describe how price and quantity changes in national economies affect world markets. Trade flows depend on both country supplies and foreign import demands. For each tradeable good, imports are derived from demands of producers and consumers. As explained above, given agents' optimising behaviour, import demand depends on the relationship between domestic and world prices, the latter being composite prices based on (gross-of-tax) export prices of trading partners.

The basic assumption is that imports originating in different countries are imperfect substitutes. Therefore, in each country, total import demand for each good is allocated across trading partners according to the relationship between their export prices. On the other hand, exports and domestically-sold goods are treated as perfect substitutes. This specification of imports -- commonly referred to as the Armington specification -- implies that each country faces downward-sloping demand curves for its exports. In the Armington specification, export prices for any commodity may differ from world prices and a country may both export and import goods in a given sector. In this way, the model captures the phenomenon of intra-industry trade.

The Armington specification is implemented for all goods except crude oil, which is assumed to be a homogeneous commodity[16]. The world price of oil is determined by marginal costs of production in the energy-exporting LDCs region, given the world demand for oil. At this price, the other regions competitively allocate their demand for oil among domestic supply and imports. Real domestic prices of oil may vary across countries, reflecting real exchange rate changes[17]. Oil-trade flows and market shares result from the balance between domestic demand and supply of oil at given real world prices.

Countries can, in principle, run current-account surpluses or deficits in the model. The counterpart of these imbalances is a net outflow or inflow, respectively, of capital, which is subtracted from or added to the domestic flow of saving. No account is taken of international income flows associated with changes in stocks of net foreign assets.

(vi) Closure

In each period, the model equates gross investment to net saving. Net saving is the sum of saving by households, the depreciation of capital, the net budget position of the government and foreign capital inflows, which result from the current account balance. In the current version of the model, the government budget and the current account are fixed in real terms at their benchmark-year values[18].

As mentioned above, changes in the government budget induced by carbon tax revenues are compensated by offsetting changes in the marginal income tax rate.This approximates revenue-neutrality, which is considered the appropriate closure to apply to the government sector for long-term simulations. Since government and foreign trade imbalances are exogenous, investment is almost entirely savings driven.

B. Dynamics

GREEN is a recursive model. The flow of time is expressed by growth or contraction of base-year stocks of resources. Agents are assumed to be myopic, basing their decisions on static expectations about prices and quantities[19]. Therefore, the development of the economy over time is characterised by a sequence of period-related, but intertemporally uncoordinated, flow equilibria[20]. The dynamics in GREEN originate from two sources, depletion of exhaustible resources and capital accumulation.

A resource depletion submodel is specified for oil and natural gas. The submodel determines *potential* supply of these exhaustible resources as opposed to *actual* output, which is determined by the supply function for the corresponding fixed factors. Potential supply is assumed to depend on the initial levels of proven and unproven (so-called "yet-to-find") reserves, the rate of reserve discovery and the rate of extraction. It is assumed that ultimate reserves, i.e. the sum of proven and unproven reserves, are predetermined in each period. The rate of reserve discovery is the rate at which unproven reserves are converted into proven reserves, while the rate of extraction is the rate at which proven reserves are converted into potential supply. Whether potential supply increases or decreases over time depends on whether extracted resources are balanced by newly discovered resources. However, given a *fixed* resource stock, long-run supply necessarily declines as resources are exhausted. For given rates of extraction, this decline is faster the larger are the rates of discovery and the ratio of proven to unproven reserves.

An important feature of the resource base sub-model is that the rate of reserve discovery or, alternatively, the level of unproven reserves may be sensitive to the prices of oil and gas. Therefore, changes of these prices over time, such as would be expected after the introduction of carbon taxes, may affect the pattern of resource depletion.

In the aggregate, the basic capital accumulation function equates the current capital stock to the depreciated stock inherited from the previous period plus gross investment. However, at the sectoral level, the accumulation function may be different because industries are allowed to disinvest faster than their (sector-specific) depreciation rates.

Sectors are assumed to disinvest when their demand for capital in any period is less than their depreciated stock of old capital. As explained above, the extent of disinvestment is determined by the ratio of the sector-specific rental of old capital to the economy-wide rental of new capital, within the restrictions imposed by sector-specific disinvestment elasticities. Moreover, in disinvesting sectors, gross investment is zero since -- due to the assumption of homogeneity in demand between second-hand and new capital -- industries cannot both disinvest and invest at the same time. Therefore, these sectors contract over time releasing old capital resources that are acquired by expanding sectors as part of their new capital vintage. In each period, the new capital vintage available to expanding industries is equal to the sum of disinvested capital in contracting industries and total saving generated by the economy, consistent with the closure rule of the model.

C. Dimensionality and dynamic calibration

In each region and in each period, equilibrium is characterised as a set of prices of goods and primary factors that equate supply and demand in all corresponding markets. The basic equilibrium prices searched for by the solution algorithm in simulations are: (i) the rental values of new and old capital goods[21]; (ii) the real wage; (iii) the prices of coal, gas and the carbon-free resource; and (iv) the price of land; and (v) the world price of oil. In counterfactual simulations, the solution algorithm computes, in addition, the carbon or energy tax needed to satisfy the constraint on carbon emissions. With trade in emission rights, a single carbon tax is computed for the regions involved in trade, while one tax level per region is computed when there is no trade is emission rights.

In simulations, model dynamics are calibrated in each region on exogenous GDP and population growth rates and on given Autonomous Energy Efficiency Improvements (AEEI), which are rates of neutral technical progress in energy use. Under the maintained hypothesis of balanced growth, these exogenous growth rates imply rates of neutral technical progress in the capital/labour/fixed factor bundle[22]. In counterfactual simulations, population growth, AEEI, and technical progress associated with the capital/labour/fixed factor bundle are exogenous and GDP growth rates become endogenous.

III. TECHNICAL SPECIFICATION[23]

A. Prices

All supply and demand functions are assumed to be homogeneous of degree zero in their arguments. As a consequence, only relative prices are important for the determination of the quantities of goods supplied and demanded. All prices are deflated by a *numéraire*, which is the price of labour in the United States. In addition, it is assumed for simplicity that all prices are equal to one in the base year. In this way, the benchmark data set may be assembled in value terms, with no need to specify underlying volumes.

The assumption that the price of a factor is the same across sectors in each period is in contradiction with the reality of a dispersion of wage and rental rates for labour and other primary factors. However, quantities are implicitly measured in "efficiency" units that differ from observed physical ones. Given this assumption, any difference in factor quantities across sectors corresponds to differences in **adjusted** magnitudes. In making this adjustment, the implicit assumption is that observed differences in relative factor prices reflect differences in efficiencies[24].

In each region, the basic prices to be determined in equilibrium are the following:

r^{K^N} and $r_i^{K^O}$	:	rental rate of new capital and sector-specific rental rates of old capital in declining sectors;
w	:	wage rate;
r^f	:	rental rates of fixed factors (f = land, coal, natural gas, carbon-free resource);
T^C	:	carbon tax in US$/ton of CO_2 emissions;
or		
T^{TJ}	:	energy tax in US$/Terajoule[25].

In addition, bilateral world trade patterns determine the import price of each commodity in each region except the prices of backstop products. These products are assumed to be non-traded and their prices are crucial exogenous variables in the model. In each region, the world import price of commodity i (i = 1, 2, 4, 5, 6, 7, 8) is denoted P_i^{WT} and is calculated as a weighted average of the export prices of trading partners [see sub-section III.C.(iv)]. The single real world price of oil is denoted P^{CO}. The exogenous real world prices of the backstop products -- the carbon-based fuel, the carbon-free fuel and the carbon-free electric option -- are denoted $\bar{P}_{b_1}$, $\bar{P}_{b_2}$, $\bar{P}_{b_3}$, respectively[26].

Defining $P = (r^{K^N}, r_i^{K^O}, w, r^l)$; $P^{WT} = [P_j^{WT}]$ $(j \neq 3)$ and $\bar{P}^B = (\bar{P}_{b_1}, \bar{P}_{b_2}, \bar{P}_{b_3})$, equilibrium producer prices in each sector (P_i) ultimately depend on prices of primary factors and imports, the world price of crude oil, the carbon (or energy) tax and the exogenous prices of backstop products:

$$P_i = f(P, P^{WT}, P^{CO}, T^C; \bar{P}^B)$$

GREEN includes a range of distortions such as income taxes, indirect taxes and subsidies. In addition, the main policy simulations involve the introduction of taxes on the consumption of fossil fuels. Since the relevant prices for producer and consumer behaviour are the market prices at which transactions take place, it is necessary to distinguish between before- and after-tax prices.

GREEN's fiscal structure incorporates import tariffs and *ad valorem* taxes or subsidies on all intermediate inputs[27]. In addition, as will be explained below, the excise carbon (or energy) tax T^C translates into fuel-specific *ad valorem* taxes. Denoting by τ^D and τ^I tax rates on domestic and imported intermediate goods, after-tax prices for non-energy goods (i = 1, 7, 8) can be defined as follows:

$$PT_i^D = P_i\,(1 + \tau_i^D)$$

$$PT_i^I = P_i^{WT}\,(1 + \tau_i^I)$$

Denoting by τ_i^{FU} fuel-specific tax rates (i = 2, 3, 4, 5, 6, b_1, b_2,b_3) and by RE the (region-specific) real exchange rate, after-tax prices for fuels can be defined in a similar way[28],

$$PF_i^D = P_i\,(1 + \tau_i^{FU})(1 + \tau_i^D)$$

$$PF_i^I = P_i^{WT}\,(1 + \tau_i^{FU})(1 + \tau_i^I)$$

with $P_i = P_i^{WT} = P^{CO} \cdot RE$ (i = 3), $P_i = P_i^{WT} = \bar{P}_{b_m} \cdot RE$ (i = 2, 3, 4; m = 1, 2) and $P_i = P_i^{WT} = \bar{P}_{b_3} \cdot RE$ (i = 6), reflecting the assumption that crude oil and the backstop products are homogeneous goods across countries[29].

Producer prices are converted into consumer prices (PC_i) using transition matrices for domestic and imported goods -- denoted TR^D and TR^I, respectively [see sub-section III.C. (i) and Figure 4]. The columns of these matrices describe, for each consumer good, their per-unit content in terms of producer goods. Therefore, the after-tax price of each domestic or imported consumer good (PC_j^D and PC_j^I, respectively) is an average of the prices of domestic or imported producer goods, weighted by the column shares from the transition matrices (tr_{ij}^D and tr_{ij}^I, respectively):

$$PC_j^D = \sum_{i=1,7,8} tr_{ij}^D \, PT_i^D + \sum_{i=2}^{6} tr_{ij}^D \, PF_i^D + \sum_{i=b_1,b_2,b_3} tr_{ij}^D \, PF_i^D \qquad (1)$$

$$PC_j^I = \sum_{i=1,7,8} tr_{ij}^I \, PT_i^I + \sum_{i=2}^{6} tr_{ij}^I \, PF_i^I \qquad (2)$$

with $TR^D=[tr_{ij}^D]$, $TR^I=[tr_{ij}^I]$, $\sum_i tr_{ij}^D = \sum_i tr_{ij}^I = 1$.

B. Production: demand for primary factors and intermediate goods

The production side of GREEN includes eight conventional sectors and three backstop sectors (see Table 1). The production structure varies across these eleven sectors. In the production of backstop products, technology is characterised by a Leontief specification. In the other sectors, Leontief and nested-CES specifications are combined at different levels of production. When substitution among inputs is allowed, a putty/semi-putty production technology is assumed, implying that substitutability among inputs at each stage of the production process is different depending on the vintage of the capital stock. Therefore, in each sector, gross output is the sum of outputs from the old and new vintages of capital.

Description of the nested-CES technology applying to output from old and new capital vintages will be simplified by the following short-hand notation, which will be maintained throughout the text. At any stage s of the production process in sector i and for any set of inputs $Z_{1i},...,Z_{ni}$ and output Y_i, the CES aggregator is defined as

$$Y_i = CES\{Z_{1i},..., Z_{ni}, \lambda_i^j; \rho_{si}, \alpha_{si}^1,..., \alpha_{si}^n\} = \{\sum_j^n \alpha_{si}^j \, (\lambda_i^j Z_{ji})^{\frac{1+\rho_{si}}{\rho_{si}}}\}^{\frac{\rho_{si}}{1+\rho_{si}}}$$

where,

λ_i^j = technical progress affecting input j in sector i;

ρ_{si} = elasticity of substitution across inputs in sector i at stage s of the production process ($\rho_{si}<0$);

α_{si}^j = CES distribution parameter associated with input j at stage s of the production process in sector i.

Similarly, given input prices $p_1,...,p_n$, the associated dual unit cost of producing Y_i is defined as[30]:

$$c_i^Y = UC\{p_1,..., p_n, \lambda_i^j; \rho_{si}, \alpha_{si}^1,..., \alpha_{si}^n\} = \{\sum_j^n (\alpha_{si}^j)^{-\rho_{si}} \, (\lambda_i^j p_j)^{1+\rho_{si}}\}^{\frac{1}{1+\rho_{si}}}$$

In backstop sector m ($m = b_1, b_2, b_3$), gross output Q_m is produced using labour L_m and capital K_m. Therefore, the production function for backstop product m is the following,

$$Q_m = \min\{\frac{L_m}{l_m}, \frac{K_m}{k_m}\} \tag{3}$$

In conventional fossil-fuel sector i ($i = 2, 3, 4, 5$), gross output Q_i is produced using fixed proportions of labour L_i, capital K_i, a fixed factor F_i, *non-energy* intermediate inputs X_{ji} ($j = 1, 7, 8$) and the energy bundles FU_{si} ($s = 2, 3, 4, 5, 6$), where X_{ji} and FU_{si} represent quantities sold by sectors j or s and purchased by sector i according to the transactions matrix of the input-output table. A CES technology makes it possible to substitute conventional fuels, denoted FU_{si}^C ($s = 2, 3, 4, 6$), with backstop inputs, denoted FU_{si}^B ($s = b_1, b_2, b_3$), in the production of coal, oil, gas and petroleum products. Fixed factors are allocated among fossil-fuel sectors as follows: F_2 is coal, F_3 is crude oil and F_4 is natural gas. It is assumed that no fixed factor is used in the production of petroleum products. Denoting by lower-case letters the ratios of inputs to sectoral gross output and using the notation introduced above, the production function for fossil-fuel sector i can be expressed as follows,

$$Q_i = \min\{(\frac{X_{1i}}{x_{1i}}, \frac{X_{7i}}{x_{7i}}, \frac{X_{8i}}{x_{8i}}), (\frac{FU_{2i}}{fu_{2i}}, ..., \frac{FU_{6i}}{fu_{6i}}), \frac{L_i}{l_i}, \frac{K_i}{k_i}, \frac{F_i}{f_i}\}$$

$$FU_{si} = CES\{FU_{si}^C, FU_{b_1i}^B, FU_{b_2i}^B; \rho_{4i}^s, \alpha_{4i}^s, \alpha_{4i}^{b_1}, \alpha_{4i}^{b_2}\} \tag{4}$$

$$FU_{6i} = CES\{FU_{6i}^C, FU_{b_3i}^B; \rho_{4i}^6, \alpha_{4i}^6, \alpha_{4i}^{b_3}\}$$

with $s = 2, 3, 4$ and $F_i = 0$ for $i = 5$.

In agriculture, electricity production, energy-intensive industries and other industries and services ($i = 1, 6, 7, 8$), *non-energy* intermediate goods remain fixed at benchmark-year levels per unit of gross output. Similarly, a Leontief specification is maintained for the capital/fixed factor bundle. However, in these sectors the production technology allows for substitution between labour, capital and the various energy sources through a nested-CES specification. Nesting is obtained by assuming weak separability between subsets of primary inputs. As in the fossil-fuel sectors, the nesting hierarchy bundles together in the innermost nest the conventional *primary* sources of energy FU_{si}^C ($s = 2, 3, 4, 6$) and their backstop substitutes FU_{mi}^B ($m = b_1, b_2, b_3$) into fuel aggregates denoted FU_{si} ($s = 2, 3, 4, 6$). Next, these fuel aggregates and petroleum products -- FU_{si} ($s = 2,..., 6$) -- are bundled into an energy aggregate denoted E_i. In the intermediate nest, the capital/fixed factor composite good

-- denoted KF_i -- is bundled with the energy aggregate, yielding a composite good denoted KEF_i. Finally, this composite good is bundled with labour to yield a composite good denoted $KLEF_i$, which is combined with *non-energy* intermediate inputs to produce gross output. The fixed factors are land for agriculture (F_1) and the carbon-free resource for the conventional electric sector (F_6), while no fixed factors are assumed to be used in the industrial sectors (i = 7, 8).

The mixed CES-Leontief production function for gross output (from old or new vintages of capital) in sector i (i = 1, 6, 7, 8) can be written as follows,

$$Q_i = \min\{(\frac{X_{1i}}{x_{1i}}, \frac{X_{7i}}{x_{7i}}, \frac{X_{8i}}{x_{8i}}), \frac{KLEF_i}{klef_i}\} \tag{5}$$

$$KLEF_i = CES\{L_i, KEF_i, \lambda_i^L; \rho_{1i}, \alpha_{1i}^1, \alpha_{1i}^2\} \tag{6}$$

$$KEF_i = CES\{E_i, KF_i, \lambda_i^E; \rho_{2i}, \alpha_{2i}^1, \alpha_{2i}^2\} \tag{7}$$

$$E_i = CES\{FU_{2i}, \ldots, FU_{6i}; \rho_{3i}, \alpha_{3i}^2, \ldots, \alpha_{3i}^6\} \tag{8}$$

$$FU_{si} = CES\{FU_{si}^C, FU_{b_1 i}^B, FU_{b_2 i}^B; \rho_{4i}^s, \alpha_{4i}^s, \alpha_{4i}^{b_1}, \alpha_{4i}^{b_2}\} \tag{9}$$

$$FU_{6i} = CES\{FU_{6i}^C, FU_{b_3 i}^B; \rho_{4i}^6, \alpha_{4i}^6, \alpha_{4i}^{b_3}\} \tag{10}$$

$$KF_i = \min\{\frac{\lambda_i K_i}{a_i^K}, \frac{\lambda_i F_i}{a_i^F}\} \tag{11}$$

where s = 2, 3, 4, and the parameters $a_i^K = \frac{\lambda_i K_i}{KF_i}$ and $a_i^F = \frac{\lambda_i F_i}{KF_i}$ are fixed at their benchmark-year values[31].

Producers are assumed to minimise their after-tax costs of production, given the technology described by equations (3)-(11). Due to the assumption of weak separability among inputs underlying the nested-CES structure, the optimisation problem of the producer can be formulated in several steps. Denoting the after-tax (composite) price of conventional and backstop fuels by PF_s^C and PF_s^B, respectively, and the unit costs of the bundles KEF, E, FU_s and KF by c^{KEF}, c^E, c_s^{FU} and c^{KF}, respectively, the following first-order conditions characterise the optimal choice of labour, the capital/fixed factor bundle, the energy bundle and fuels in sector i (i = 1, 6, 7, 8):

$$\frac{w}{c_i^{KEF}} = \frac{\alpha_{1i}^1}{\alpha_{1i}^2} \left(\frac{L_i}{KEF_i}\right)^{\frac{1}{\rho_{1i}}} \tag{12}$$

$$\frac{c_i^{KF}}{c_i^E} = \frac{\alpha_{2i}^1}{\alpha_{2i}^2} \left(\frac{KF_i}{E_i}\right)^{\frac{1}{\rho_{2i}}} \tag{13}$$

$$\frac{c_{si}^{FU}}{c_{ri}^{FU}} = \frac{\alpha_{3i}^s}{\alpha_{3i}^r} \left(\frac{FU_{si}}{FU_{ri}}\right)^{\frac{1}{\rho_{3i}}} \tag{14}$$

with r,s = 2, 3, 4, 5, 6 ($r \neq s$); and the following conditions characterise the choice between conventional and backstop inputs in sector i (i = 1,..., 4, 6,..., 8):

$$\frac{PF_l^C}{PF_m^B} = \frac{\alpha_{4i}^l}{\alpha_{4i}^m} \left(\frac{FU_{li}^C}{FU_{mi}^B}\right)^{\frac{1}{\rho_{4i}^l}}$$

(15)

$$\frac{PF_{b_1}^B}{PF_{b_2}^B} = \frac{\alpha_{4i}^{b_1}}{\alpha_{4i}^{b_2}} \left(\frac{FU_{b_1 i}^B}{FU_{b_2 i}^B}\right)^{\frac{1}{\rho_{4i}^l}}$$

with $m = b_1, b_2$ for $l = 2, 3, 4$; and $m = b_3$ for $l = 6$.

The unit costs c^{KEF}, c^E, c_s^{FU}, c^{KF} -- as well as the unit cost of the composite input KLEF -- are the duals of production functions (6)-(11) above:

$$c_i^{KLEF} = UC\{w,\ c_i^{KEF},\ \lambda_i^L;\ \rho_{1i},\ \alpha_{1i}^1,\ \alpha_{1i}^2\} \tag{16}$$

$$c_i^{KEF} = UC\{c_i^E,\ c_i^{KF},\ \lambda_i^E;\ \rho_{2i},\ \alpha_{2i}^1,\ \alpha_{2i}^2\} \tag{17}$$

$$c_i^E = UC\{c_{2i}^{FU},\ldots,\ c_{6i}^{FU};\ \rho_{3i},\ \alpha_{3i}^2,\ldots,\ \alpha_{3i}^6\} \tag{18}$$

$$c_{li}^{FU} = UC\{PF_l^C,\ PF_{b_1}^B,\ PF_{b_2}^B;\ \rho_{4i}^l,\ \alpha_{4i}^l,\ \alpha_{4i}^{b_1},\ \alpha_{4i}^{b_2}\} \tag{19}$$

$$c_{6i}^{FU} = UC\{PF_6^C,\ PF_{b_3}^B;\ \rho_{4i}^6,\ \alpha_{4i}^6,\ \alpha_{4i}^{b_3}\} \tag{20}$$

$$c_i^{KF} = a_i^{K^N} r^{K^N} + a_i^F P_i^f \tag{21}$$

with $l = 2, 3, 4$ and $c_{5i}^{FU} = PF_5^C$, reflecting the assumption that backstop products are substitutes for primary energy sources only.

Substituting the first-order conditions (12)-(15) into equations (4) and (6)-(10) and using the unit costs definitions (16)-(21), it is possible to derive the producer's optimal demands for the composite inputs at each stage of the production process:

$$l_i = klef_i\ (c_i^{KLEF})^{-\rho_{1i}}\ \left(\frac{w}{\alpha_{1i}^1}\right)^{\rho_{1i}} \tag{22}$$

$$kef_i = klef_i\ (c_i^{KLEF})^{-\rho_{1i}}\ \left(\frac{c_i^{KEF}}{\alpha_{1i}^2}\right)^{\rho_{1i}} \tag{23}$$

$$kf_i = (c_i^{KEF})^{-\rho_{2i}}\ \left(\frac{c_i^{KF}}{\alpha_{2i}^2}\right)^{\rho_{2i}} \tag{24}$$

$$e_i = (c_i^{KEF})^{-\rho_{2i}} \left(\frac{c_i^E}{\alpha_{2i}^1}\right)^{\rho_{2i}} \tag{25}$$

$$a_{si}^{fu} = (c_i^E)^{-\rho_{3i}} \left(\frac{c_{si}^{FU}}{\alpha_{3i}^s}\right)^{\rho_{3i}} \tag{26}$$

$$a_{si}^{fu^C} = (c_{si}^{FU})^{-\rho_{4i}^s} \left(\frac{PF_s^C}{\alpha_{4i}^s}\right)^{\rho_{4i}^s} \tag{27}$$

$$a_{mli}^{fu^B} = (c_{li}^{FU})^{-\rho_{4i}^l} \left(\frac{PF_m^B}{\alpha_{4i}^m}\right)^{\rho_{4i}^l} \tag{28}$$

where $l_i = \frac{L_i}{Q_i}$, $kef_i = \frac{KEF_i}{Q_i}$, $kf_i = \frac{KF_i}{KEF_i}$, $e_i = \frac{E_i}{KEF_i}$, $a_{si}^{fu} = \frac{FU_{si}}{E_i}$, $a_{si}^{fu^C} = \frac{FU_{si}^C}{FU_{si}}$ (s = 2,..,6), $a_{mli}^{fu^B} = \frac{FU_{mi}^B}{FU_{li}}$ (m = b_1, b_2 for l = 2, 3, 4; and m = b_3 for l = 6).

Equations (23)-(28) make it possible to compute the optimal capital/output (k_i) and fixed factor/output (f_i) ratios as well as the optimal technical coefficients for the intermediate demands for conventional and backstop fuels (fu_{si}^C, fu_{mi}^B):

$$k_i = kef_i \cdot kf_i \cdot a_i^K$$

$$f_i = kef_i \cdot kf_i \cdot a_i^F$$

$$fu_{si}^C = kef_i \cdot e_i \cdot a_{si}^{fu} \cdot a_{si}^{fu^C} \tag{29}$$

$$fu_{mi}^B = kef_i \cdot e_i \cdot \sum_{l=2,3,4} (a_{li}^{fu} \cdot a_{mli}^{fu^B})$$

$$fu_{b_3i}^B = kef_i \cdot e_i \cdot a_{6i}^{fu} \cdot a_{b_36i}^{fu^B}$$

for s = 2,..,6 and m = b_1, b_2, with $a_{si}^{fu^C} = 1$ for s = 5.

Indicating by a superscript O (N) variables and parameters pertaining to production with old (new) capital vintages, unit-input requirements for gross outputs Q_i^O and Q_i^N are completely determined by equations (22) and (29) -- given the elasticities of substitution ρ_{ji}^O, ρ_{ji}^N ($\rho_{ji}^O < \rho_{ji}^N$), the distribution parameters α_{si}^{jO}, α_{si}^{jN} and technical progress λ_i^{jO}, λ_i^{jN}. Once the input structure of old and new vintage outputs has been determined, ratios of primary inputs and fuels to total output Q_i can be derived as a weighted average of old and new technical coefficients,

$$l_i = \theta_i \cdot l_i^O + (1 - \theta_i) \cdot l_i^N,$$

$$k_i = \theta_i \cdot k_i^O + (1 - \theta_i) \cdot k_i^N,$$

$$f_i = \theta_i \cdot f_i^O + (1 - \theta_i) \cdot f_i^N, \tag{30}$$

$$fu_{si}^C = \theta_i \cdot fu_{si}^{CO} + (1 - \theta_i) \cdot fu_{si}^{CN},$$

$$fu_{mi}^B = \theta_i \cdot fu_{mi}^{BO} + (1 - \theta_i) \cdot fu_{mi}^{BN},$$

where $\theta_i = \dfrac{K_i^O}{Q_i \cdot k_i^O}$, s = 2,...,6 and m = b_1, b_2, b_3.

Given these technical coefficients and the fixed input-output coefficients for *non-energy* intermediate inputs, unit-input requirements for gross output Q_i are completely determined. Given sectoral gross outputs, it is possible to derive sectoral demands for capital, labour, the fixed factors and each of the intermediate goods. Sectoral demand for capital (K_i) is the sum of sectoral demands for old and new capital goods, given the assumption of homogeneity in demand of these types of goods:

$$K_i = K_i^O + K_i^N$$

The final step consists in specifying substitution possibilities between *traded* intermediate inputs. A crucial assumption is that all goods traded in world markets are imperfect substitutes, with the important exception of crude oil[32]. Consistent with this assumption, producers can choose between domestic and imported intermediate goods. Within the given unit requirements of intermediate inputs x_{ji}, fu_{si}^C (j = 1, 7, 8; s = 2, 4, 5, 6), they are assumed to choose the optimal mix between domestic (x_{ji}^D, fu_{si}^D) and imported (x_{ji}^I, fu_{si}^I) components, according to the following CES aggregation functions:

$$x_{ji} = CES\{x_{ji}^D, x_{ji}^I; \rho_{5i}, \alpha_{5ji}^D, \alpha_{5ji}^I\} \tag{31}$$

$$fu_{si}^C = CES\{fu_{si}^D, fu_{si}^I; \rho_{6i}, \alpha_{6si}^D, \alpha_{6si}^I\} \tag{32}$$

It is assumed that, for each intermediate input, the domestic and imported shares are identical across sectors, i.e. $\alpha_{5ji}^D = \alpha_{5jk}^D$, $\alpha_{5ji}^I = \alpha_{5jk}^I$, $\alpha_{6si}^D = \alpha_{6sk}^D$, $\alpha_{6si}^I = \alpha_{6sk}^I$ for $i \neq k$. Therefore, given prices for after-tax domestic and imported intermediate goods and conventional fuels, cost-minimisation by producers, subject to equations (31)-(32), yields the following optimal input-output coefficients:

$$x_{ji}^D = x_{ji} \, (PT_j)^{-\rho_{5j}} \, \left(\frac{PT_j^D}{\alpha_{5j}^D}\right)^{\rho_{5j}} \tag{33}$$

$$x_{ji}^I = x_{ji} \, (PT_j)^{-\rho_{5j}} \, \left(\frac{PT_j^I}{\alpha_{5j}^I}\right)^{\rho_{5j}} \tag{34}$$

for j = 1, 7, 8; and,

$$fu_{si}^{D} = fu_{si}^{C}\ (PF_s^{C})^{-\rho_{6s}}\ (\frac{PF_s^{D}}{\alpha_{6s}^{D}})^{\rho_{6s}} \tag{35}$$

$$fu_{si}^{I} = fu_{si}^{C}\ (PF_s^{C})^{-\rho_{6s}}\ (\frac{PF_s^{I}}{\alpha_{6s}^{I}})^{\rho_{6s}} \tag{36}$$

for s = 2, 4, 5, 6[33].

In equations (33)-(36), the composite prices of intermediate goods and fuels, PT_j and PF_s^C, are defined as CES aggregates of the prices of domestic and imported goods and fuels, according to the CES dual-cost aggregator defined above:

$$PT_j = UC\{PT_j^D,\ PT_j^I;\ \rho_{5j},\ \alpha_{5j}^D,\ \alpha_{5j}^I\}$$

$$PF_s^C = UC\{PF_s^D,\ PF_s^I;\ \rho_{6s},\ \alpha_{6s}^D,\ \alpha_{6s}^I\}$$

Once technical coefficients for intermediate goods, fuels and primary inputs have been determined in each sector -- subject to the given price system -- three crucial matrices can be constructed: the (11 x 11) domestic input-output matrix -- denoted A^D -- the (8 x 8) matrix of intermediate import requirements -- denoted A^I -- and the matrix of primary factor requirements -- denoted A^F (see Figure 4).

The entries of A^D are the domestic input-output coefficients,

$A^D = [x_{1i}^D, fu_{si}^D, x_{7i}^D, x_{8i}^D, fu_{mi}^B]$ with s = 2,..., 6; i = 1,...,11; m = b_1, b_2, b_3;

the entries of A^I are the unit import requirements of intermediate goods,

$A^I = [x_{1i}^I, fu_{si}^I, x_{7i}^I, x_{8i}^I]$ with s = 2,..., 6; i = 1,...,8;

and the entries of A^F are the ratios of primary factors to gross sectoral outputs,

$A^F = [k_i, l_i, \hat{f}_{ii}]$ with $\hat{f}_{ii} = diag[f_{ii}]$, i = 1,...,11,
yielding a (13 x 11) matrix with $f_{ii} = 0$ for i = 5, 7, 8, b_1, b_2, b_3.

Given the (11 x 1) vector of sectoral gross output requirements, $Q = [Q_i]$, total primary factor demands -- denoted K, L, F_1, F_2, F_3, F_4, F_6 -- and the (8 x 1) vector of imports of intermediate goods -- denoted $X^I = [X_i^I]$ -- are determined using the matrices A^F and A^I:

$$\begin{bmatrix} L \\ K \\ F_1 \\ F_2 \\ F_3 \\ F_4 \\ F_6 \end{bmatrix} = A^F \cdot Q \ , \qquad X^I = A^I \cdot \begin{bmatrix} Q_1 \\ \cdot \\ \cdot \\ \cdot \\ Q_8 \end{bmatrix} \tag{37}$$

On the other hand, given the assumption of constant returns to scale in all sectors, the vector of gross outputs is determined by the (11 x 1) vector of final demands $Y = [Y_i]$, using the inverse of the domestic input-output matrix:

$$Q = [I - A^D]^{-1} \, Y \tag{38}$$

C. Final demand

(i) Household consumption

Consumer goods are aggregated into four broad categories: food and beverages, fuel and power, transport and communication and other goods and services (see Table 2). In each region and in each period, consumers spend a fraction of their disposable income on these goods, whereas the rest is saved and takes the form of purchases of capital goods.

Consumer's disposable income (Y^D) is defined as the difference between personal income (Y) and income taxes -- levied at the same rate τ^Y on all sources of income -- net of government transfers (TRG):

$$Y^D = (1 - \tau^Y) \, Y - \nu + TRG$$

where ν is the intercept of the income-tax schedule.

It is assumed that all income generated by economic activity is distributed to consumers. Therefore, personal income is the sum of revenues from primary factors -- which include incomes from labour and (old and new) capital as well as rents from fixed factors -- plus other rents deriving from the differences in domestic and world prices of crude oil and backstop products less depreciation of the existing capital stock[34]. Indexing by j expanding sectors and by n declining sectors, denoting by $(1 - \delta_i)$ depreciation rates by sector and denoting by R_s ($s = 3, b_1, b_2, b_3$) other rents, personal income can be defined as follows:

$$Y = w \cdot L + r^{K^N} \cdot \sum_j K_j + \sum_n r_n^{K^O} \cdot K_n + \sum_f r^f \cdot F_f$$

$$- r^{K^N} \cdot \sum_j (1 - \delta_j) \cdot K_j - \sum_n (1 - \delta_n) \cdot r_n^{K^O} \cdot K_n + \sum_{s=3,b_1,\ldots,b_3} R_s$$

In each region, consumer demand is derived from utility maximisation by a single representative consumer subject to a budget constraint. The structure of household demand -- described in Figure 2 -- can be represented as a four-stage decision tree. First, consumers choose the optimal allocation of disposable income across the four goods and saving. Second, given the per-unit energy content of each good, they choose an optimal consumption-mix of fuels. Third, for each fuel they choose the optimal mix of conventional and backstop products. Fourth, they allocate their consumption of non-energy intermediate goods and conventional fuels among imported and domestic supplies. Since consumer and producer good aggregates do not coincide, the translation of consumer demand into demand for producer goods is ensured by a transition matrix (see Figure 3).

Given the dynamic nature of the model, an important element of consumer decisions is the allocation of resources between consumption and saving. In this respect, decisions can be divided into two steps, subject to convenient separability assumptions. First, given current prices and incomes, the consumer chooses an optimal consumption/saving allocation. Second, given total current consumption, the consumer allocates it optimally across the four goods.

A useful analytical characterisation of this two-step procedure is the so-called Extended Linear Expenditure System (ELES). The ELES combines a Stone-Geary specification of the consumer's instantaneous utility function -- the so-called Linear Expenditure System (LES) -- with an intertemporal utility function, which is additively separable over time (with a constant rate of time preference). The main advantage of the ELES over more conventional formulations is that it accounts for the consumption/saving choice while at the same time allowing for different income elasticities across consumer goods[35].

In the ELES framework, the propensity to consume out of (an appropriate measure of) income is equal to the ratio of the rate of time preference to the rate of return on real and financial assets, under the assumption that the consumer formulates static *point* expectations about future prices, rates of return and labour incomes[36]. Moreover, under the additional assumption that the consumer does not expect any change in future labour incomes, the appropriate intertemporal concept of income coincides with current disposable income. On the other hand, total consumption expenditure is the sum of optimal expenditures on individual categories of goods allocated according to the LES specification.

The household consumption block of GREEN is based on the simplified version of the ELES proposed by Howe (1975). This version is derived from an LES in which saving is treated as an additional "good" with zero minimum consumption requirement -- the so-called "subsistence quantity". Denoting the i-th consumer good by C_i, real saving by σ, the *per capita* subsistence quantity of the i-th consumer good by γ_i, population by POP and defining $C^* = [C_1, \ldots, C_4, \sigma]$, the utility function is defined as,

$$U(C^*) = \sum_{i=1}^{4} \beta_i \ln(C_i - \gamma_i \cdot POP) + \beta_5 \ln(\sigma) \qquad (39)$$

where $\beta_i > 0 \quad (i = 1,\dots, 5), \quad C_i \geq \gamma_i \cdot POP \quad (i = 1,\dots, 4), \quad \sum_i \beta_i = 1.$

Given the above assumptions and denoting nominal saving by S, the consumer's budget constraint can be expressed as,

$$Y^D = \sum_{i=1}^{4} PC_i \cdot C_i + S \qquad (40)$$

Maximisation of (39) subject to (40) and the given price system yields the following demand system in expenditure form[37],

$$PC_i \cdot C_i = PC_i \cdot \gamma_i \cdot POP + \beta_i (Y^D - \sum_{j=1}^{4} PC_j \cdot \gamma_j \cdot POP) \qquad i = 1,\dots, 4 \quad (41)$$

$$S = \beta_5 (Y^D - \sum_{j=1}^{4} PC_j \cdot \gamma_j \cdot POP)$$

In equation (41), the parameter β_i is interpreted as the marginal budget share associated with good i, as in the LES. In addition, β_5 can be interpreted as the marginal propensity to save out of "supernumerary" income, i.e. the income available to the consumer once subsistence quantities of all goods have been purchased[38].

Defining the *marginal propensity to consume* -- $\mu = 1 - \beta_5$ -- and subtracting saving from disposable income, the following expression for the value of aggregate consumption can be derived:

$$\sum_{i=1}^{4} PC_i \cdot C_i = \mu \cdot Y^D + (1 - \mu) \sum_{i=1}^{4} PC_i \cdot \gamma_i \cdot POP$$

where μ can be shown to be the ratio of the rate of time preference to the rate of return on the consumer's real assets.

This formulation of the ELES assumes away any dependence of saving on the opportunity cost of current consumption (i.e. *the rate of return on assets*), by implicitly embodying the latter in the *constant* marginal propensity to consume. As a result, the consumer model is *atemporal* and the price of saving has to be chosen arbitrarily. An important implication of this atemporal specification of consumer behaviour is that no consistent index of intertemporal welfare can be derived[39].

Once the (4 x 1) vector of consumption demands, $C = [C_i]$ (i = 1,..., 4), has been determined, it is translated into a (11 x 1) vector of household demands for intermediate goods, $X_H = [X_{1H}, FU^C_{2H},\dots, FU^C_{6H}, FU^B_{b_1H},\dots,FU^B_{b_3H}, X_{7H}, X_{8H}]$, through a (11 x 4) transition matrix, $TR = [tr_{ij}]$:

$$X_H = TR \cdot C$$

In each column of the transition matrix, the entries tr_{ij} indicate the quantities of (non-energy) intermediate goods and fuels i composing a unit of consumer good j:

$$tr_{ij} = \frac{X_{ijH}}{C_j}, \qquad i = 1, 7, 8$$

$$tr_{ij} = \frac{FU^C_{ijH}}{C_j}, \qquad i = 2,\ldots, 6$$

$$tr_{ij} = \frac{FU^B_{ijH}}{C_j}, \qquad i = b_1,\ldots, b_3$$

with $\sum_j tr_{ij} \cdot C_j = X_{iH}$ for i = 1, 7, 8; $\sum_j tr_{ij} \cdot C_j = FU^C_{iH}$ for i = 2,...,6; and $\sum_j tr_{ij} \cdot C_j = FU^B_{iH}$ for i = b_1, b_2, b_3.

It is assumed that consumers take the transition matrix as a technical datum for all consumer goods except fuel and power (j = 2). In the case of this latter good, consumers choose first an optimal mix of fuels within the given unit energy requirements (e_{jH}), defined as the ratio of total energy used in consumption of good j (E_{jH}) to the consumption of this good:

$$e_{jH} = \frac{\lambda^E_i E_{jH}}{C_j}$$

Second, they choose an optimal mix of conventional and backstop energy sources for each primary fuel.

Consumers are assumed to minimize the cost of total energy expenditure in consuming good j (j = 2), given a nested-CES transformation function defined over the different kinds of fuels and over conventional and backstop primary energy sources:

$$E_{jH} = CES\{FU_{2jH},\ldots, FU_{6jH}; \rho^H_{1j}, \alpha^2_{1jH},\ldots, \alpha^6_{1jH}\} \tag{42}$$

$$FU_{sjH} = CES\{FU^C_{sjH}, FU^B_{b_1jH}, FU^B_{b_2jH}; \rho^s_{2jH}, \alpha^s_{2jH}, \alpha^{b_1}_{2jH}, \alpha^{b_2}_{2jH}\} \quad s = 2, 3, 4 \tag{43}$$

$$FU_{6jH} = CES\{FU^C_{6jH}, FU^B_{b_3jH}; \rho^6_{2jH}, \alpha^6_{2jH}, \alpha^{b_3}_{2jH}\} \tag{44}$$

Given the (composite) prices of conventional and backstop energies, PF^C_s (s = 2,..., 6) and PF^B_m

($m = b_1,\ldots,b_3$), and defining the unit costs of energy c^E_{jH} and fuels c^{FU}_{sjH} in consumption of good j as the duals of equations (42)-(44),

$$c^E_{jH} = UC(c^{FU}_{2jH},\ldots,c^{FU}_{6jH};\ \rho^H_{1j},\ \alpha^2_{1jH},\ldots,\alpha^6_{1jH})$$

$$c^{FU}_{sjH} = UC(PF^C_s,\ PF^B_{b_1},\ PF^B_{b_2};\ \rho^s_{2jH},\ \alpha^s_{2jH},\ \alpha^{b_1}_{2jH},\ \alpha^{b_2}_{2jH}) \qquad s = 2,\ 3,\ 4$$

$$c^{FU}_{6jH} = UC(PF^C_6,\ PF^B_{b_3};\ \rho^6_{2jH},\ \alpha^6_{2jH},\ \alpha^{b_3}_{2jH})$$

the optimal unit requirements of fuels for each unit of energy (a^{fu}_{sjH}) and of conventional and backstop energies for each unit of fuel s ($a^{fu^C}_{sjH}, a^{fu^B}_{sjH}$) used in the consumption of good j can be derived following the same steps as in sub-section III.B.:

$$a^{fu}_{sjH} = (c^E_{jH})^{-\rho^H_{1j}} \left(\frac{c^{FU}_{sjH}}{\alpha^s_{1jH}}\right)^{\rho^H_{1j}}$$

$$a^{fu^C}_{sjH} = (c^{FU}_{sjH})^{-\rho^s_{2jH}} \left(\frac{PF^C_s}{\alpha^s_{2jH}}\right)^{\rho^s_{2jH}}$$

$$a^{fu^B}_{mljH} = (c^{FU}_{ljH})^{-\rho^l_{2jH}} \left(\frac{PF^B_m}{\alpha^m_{2jH}}\right)^{\rho^l_{2jH}}$$

with $s = 2,\ldots,6$; $m = b_1, b_2$ for $l = 2, 3, 4$; and $m = b_3$ for $l = 6$. Finally, the corresponding optimal entries in the transition matrix (i.e. the unit requirement of conventional and backstop energies for consumer good j) can be obtained as

$$tr_{sj} = e_{jH} \cdot a^{fu}_{sjH} \cdot a^{fu^C}_{sjH}$$

$$tr_{mj} = e_{jH} \cdot \sum_{l=2,3,4} (a^{fu}_{ljH} \cdot a^{fu^B}_{mljH}) \qquad m = b_1,\ b_2$$

$$tr_{b_3j} = e_{jH} \cdot a^{fu}_{6jH} \cdot a^{fu^B}_{b_36jH}$$

The final stage of consumer optimisation concerns the choice between domestic supplies and imports, given the assumption of imperfect substitutability among consumer goods. This further step consists in splitting the entries of the transition matrix into domestic and imported components (tr_{ij}^D and tr_{ij}^I, respectively). It is assumed that this choice is made according to a CES aggregator in which substitution elasticities as well as domestic and imported shares for each intermediate good i are the same across consumer goods, i.e. $\rho_{3j}^H = \rho_{3k}^H$, $\alpha_{ijH}^D = \alpha_{ikH}^D$, $\alpha_{ijH}^I = \alpha_{ikH}^I$ for j ≠ k:

$$tr_{ij} = CES(tr_{ij}^D,\ tr_{ij}^I;\ \rho_3^H,\ \alpha_{iH}^D,\ \alpha_{iH}^I)$$

Denoting the composite consumption prices of intermediate goods and conventional fuels by PT_i^H and PF_i^H, respectively, and given prices for after-tax domestic and imported intermediate goods and fuels, expenditure minimisation by consumers yields the following optimal domestic and imported components of the transition matrix:

$$tr_{ij}^D = tr_{ij}\ (PT_i^H)^{-\rho_3^H}\ (\frac{PT_i^D}{\alpha_{iH}^D})^{\rho_3^H} \qquad (44)$$

$$tr_{ij}^I = tr_{ij}\ (PT_i^H)^{-\rho_3^H}\ (\frac{PT_i^I}{\alpha_{iH}^I})^{\rho_3^H} \qquad (45)$$

for i = 1, 7, 8; and,

$$tr_{ij}^D = tr_{ij}\ (PF_i^C)^{-\rho_3^H}\ (\frac{PF_i^D}{\alpha_{iH}^D})^{\rho_3^H} \qquad (46)$$

$$tr_{ij}^I = tr_{ij}\ (PF_i^C)^{-\rho_3^H}\ (\frac{PF_i^I}{\alpha_{iH}^I})^{\rho_3^H} \qquad (47)$$

for i = 2, 4, 5, 6. Note that no equations such as (44)-(47) exist for crude oil and backstop products, since oil is assumed to be perfectly homogeneous across countries and backstop products are not traded on international markets. The domestic and import coefficients for oil are determined as in section III.B; backstop goods satisfy $tr_{ij}^D = tr_{ij}$, $tr_{ij}^I = 0$ ($i = b_1,..., b_3$).

In equations (44)-(47), PT_i^H and PF_i^H are defined as CES aggregates of the prices of domestic and imported goods and conventional fuels, according to the CES dual cost aggregator:

$$PT_i^H = UC(PT_i^D, PT_i^I; \rho_3^H, \alpha_{iH}^D, \alpha_{iH}^I)$$

$$PF_i^H = UC(PF_i^D, PF_i^I; \rho_3^H, \alpha_{iH}^D, \alpha_{iH}^I)$$

Using these definitions and the coefficients of the transition matrix, the composite price of consumption good i (PC_i) can be defined as in equations (1)-(2) of sub-section III.A.

Finally, the transition matrix TR can be partitioned into domestic and foreign sub-matrices $TR^D = [tr_{ij}^D]$, $TR^I = [tr_{ij}^I]$ and the (11 x 1) and (8 x 1) vectors of the domestic and foreign components of household consumption demand for intermediate goods -- denoted $X_H^D = [X_{iH}^D]$, $X_H^I = [X_{iH}^I]$, respectively -- can be derived as follows:

$$X_H^D = TR^D \cdot C$$

$$X_H^I = TR^I \cdot C$$

(ii) Investment and stockbuilding

GREEN does not embody any explicit investment behaviour by firms, either at the sectoral or aggregate level. Therefore, in each period, aggregate investment is derived as a residual identically equal to the sum of personal saving, the depreciation of capital, the government sector net balance and foreign inflows of capital. Aggregate investment is then allocated to individual sectors in order to meet their demands for new capital goods.

It is assumed that aggregate investment (INV) is produced by means of a mixed CES-Leontief technology in which neither labour nor the capital/fixed factor bundle are used as factors of production. The production function for investment has a fixed-coefficients structure for non-energy intermediate inputs (I_i) and the total energy input (E_I), and a nested-CES structure for fuels. In this specification, the mix of fuels (FU_{sI}) and their composition in terms of conventional (FU_{sI}^C) and backstop (FU_{sI}^B) energies is optimally chosen. Denoting the technical coefficients for non-energy intermediate goods and the energy bundle by ι_i and e_I, respectively, this technology can be described as follows,

$$INV = \min\{(\frac{I_1}{\iota_1}, \frac{I_7}{\iota_7}, \frac{I_8}{\iota_8}), \frac{\lambda_i^E E_I}{e_I}\}$$

$$E_I = CES\{FU_{2I},..., FU_{6I}; \rho_{1I}, \alpha_{1I}^2,..., \alpha_{1I}^6\}$$

$$FU_{sI} = CES\{FU_{sI}^C, FU_{b_1I}^B, FU_{b_2I}^B; \rho_{2I}^s, \alpha_{2I}^s, \alpha_{2I}^{b_1}, \alpha_{2I}^{b_2}\} \qquad s = 2, 3, 4$$

$$FU_{6I} = CES\{FU_{6I}^C, FU_{b_3I}^B; \rho_{2I}^6, \alpha_{2I}^6, \alpha_{2I}^{b_3}\}$$

where $\iota_i = \frac{I_i}{INV}$ (i = 1, 7, 8) and $e_I = \frac{E_I}{INV}$.

While ι_i and e_i are parameters that reflect the base-year composition of investment, the technical coefficients associated with the various fuels are determined through a cost-minimisation procedure subject to the CES specification. The resulting optimal technical coefficients for conventional (fu_{sI}^C) and backstop (fu_{sI}^B) energy sources are:

$$fu_{sI}^C = e_I \cdot a_{sI}^{fu} \cdot a_{sI}^{fu^C} \qquad s = 2,..., 6$$

$$fu_{mI}^B = e_i \cdot \sum_{l=2,3,4} (a_{lI}^{fu} \cdot a_{mlI}^{fu^B}) \qquad m = b_1, b_2$$

$$fu_{b_3I}^B = e_i \cdot a_{6I}^{fu} \cdot a_{b_36I}^{fu^B}$$

where,

$$a_{sl}^{fu} = e_l\,(c_l^E)^{-\rho_{1l}}\,(\frac{c_{sl}^{FU}}{\alpha_{1l}^s})^{\rho_{1l}}$$

$$a_{sl}^{fu\,C} = (c_{sl}^{FU})^{-\rho_{2l}^s}\,(\frac{PF_s^C}{\alpha_{2l}^s})^{\rho_{2l}^s}$$

$$a_{mll}^{fu\,B} = (c_{ll}^{FU})^{-\rho_{2l}^l}\,(\frac{PF_m^B}{\alpha_{2l}^m})^{\rho_{2l}^l}$$

(s = 2,..,6; m = b_1, b_2 for l = 2, 3, 4; and m = b_3 for l = 6) and c_l^E, c_{sl}^{FU} are the duals of the above CES transformation functions.

Finally, it is assumed that the demands for intermediate goods and conventional fuels used in the production of the investment good are allocated across domestic supplies and imports according to a CES transformation function, as in equations (31)-(32) above, with elasticity of substitution ρ_3^l and CES distribution parameters α_l^D, α_l^I. Using the resulting optimal technical coefficients for domestic and imported intermediate goods and fuels (denoted ι_i^D, fu_{sl}^D and ι_i^I, fu_{sl}^I, respectively), it is possible to derive investment demands for domestic (I_i^D) and imported goods (I_i^I):

$$I_i^D = \iota_i^D \cdot INV, \qquad I_i^I = \iota_i^I \cdot INV \qquad\qquad i = 1, 7, 8$$

$$I_l^D = fu_{ll}^D \cdot INV, \qquad I_s^I = fu_{sl}^I \cdot INV \qquad\qquad l = 2,\dots, 6, b_1,\dots, b_3;\ s = 2,\dots, 6$$

A similar framework is used to determine the allocation of sectoral demands for aggregate stockbuilding (STB) -- which is an exogenous variable in the model. However, in this case, the fixed-coefficients specification extends to both non-energy intermediate goods and fuels, while a CES specification continues to characterise the choice between conventional and backstop energy sources. Denoting stockbuilding of good i by ST_i, fixed coefficients in stockbuilding by $\xi_i = \frac{ST_i}{STB}$ (i = 1,..., 8) and stockbuilding of conventional and backstop energies by FU_{sST}^C, FU_{sST}^B, the stockbuilding technology is

$$STB = \min\{\frac{ST_1}{\xi_1}, \frac{\lambda_{ST}^E ST_2}{\xi_2},\dots, \frac{\lambda_{ST}^E ST_6}{\xi_6}, \frac{ST_8}{\xi_8}\}$$

$$ST_s = CES(FU^C_{sST}, FU^B_{b_1 ST}, FU^B_{b_2 ST}; \rho^s_{ST}, \alpha^s_{ST}, \alpha^{b_1}_{ST}, \alpha^{b_2}_{ST}) \qquad s = 2, 3, 4$$

$$ST_6 = CES(FU^C_{6ST}, FU^B_{b_3 ST}; \rho^6_{ST}, \alpha^6_{ST}, \alpha^{b_3}_{ST})$$

Cost minimisation subject to this technology yields the following optimal unit inputs of conventional (fu^C_{sST}) and backstop (fu^B_{sST}) energies,

$$fu^C_{sST} = \xi_s \cdot a^{fu^C}_{sST} \qquad s = 2,..., 6$$

$$fu^B_{mST} = \sum_{l=2,3,4} (\xi_l \cdot a^{fu^B}_{mlST}) \qquad m = b_1, b_2$$

$$fu^B_{b_3 ST} = \xi_6 \cdot a^{fu^B}_{b_3 6ST}$$

where,

$$a^{fu^C}_{sST} = (c^{FU}_{sST})^{-\rho^s_{ST}} \left(\frac{PF^C_s}{\alpha^s_{ST}}\right)^{\rho^s_{ST}}$$

$$a^{fu^B}_{mlST} = (c^{FU}_{lST})^{-\rho^l_{ST}} \left(\frac{PF^B_m}{\alpha^m_{ST}}\right)^{\rho^l_{ST}}$$

(s = 2,..,6; m = b_1, b_2 for l = 2, 3, 4; and m = b_3 for l = 6) and the unit costs c^{FU}_{sST} are the duals of the above CES transformation functions.

On the other hand, the allocation of stockbuilding demand across domestic and imported components -- denoted ST^D_i and ST^I_i, respectively -- is determined as in equations (31)-(32), with elasticity of substitution ρ^{ST}_2 and CES distribution parameters α^D_{ST}, α^I_{ST}. Given the resulting optimal technical coefficients ξ^D_i, ξ^I_i, the following stockbuilding demands are obtained:

$$ST^D_i = \xi^D_i \cdot STB, \qquad ST^I_i = \xi^I_i \cdot STB \qquad i = 1, 7, 8$$

$$ST_l^D = fu_{lST}^D \cdot INV, \qquad ST_s^I = fu_{sST}^I \cdot INV \qquad l = 2,\ldots,6, b_1,\ldots,b_3;\ s = 2,\ldots,6$$

These assumptions make it possible to derive the vectors of sectoral demands for imported investment and stockbuilding goods, which are denoted $I^I = [I_i^I]$, $ST^I = [ST_i^I]$.

(iii) Government

The government is assumed to levy excise taxes on carbon emissions and/or energy consumption, value-added taxes on domestic goods (produced or consumed) and imported goods and a flat-rate tax on all sources of income. An additional source of government revenues is the proceeds from sales of emission rights. Therefore, denoting carbon and energy-tax revenues by R^C and R^{EN}, respectively, and revenues from the sale of emission rights by R^E, total government revenues can be expressed as:

$$REV = R^C + R^{EN} + \sum_{i=1}^{8} (\tau_i^D \cdot P_i \cdot Q_i + \tau_i^I \cdot P_i^{WT} \cdot X_i^I) + (\nu + \tau^Y \cdot Y) + R^E$$

Crucial components of government revenues are the carbon and energy taxes, T^C and T^{TJ}. The former is expressed as a fixed amount of US$ per ton of CO_2 emissions, the latter is expressed as a fixed amount of US$ per Terajoule. While their determination will be discussed below, it is useful at this stage to determine how revenues from these taxes are generated and how the taxes can be translated into *ad valorem* fuel-specific tax rates.

The steps needed to convert a given carbon tax into fuel-specific carbon tax levels and fuel-specific *ad valorem* tax rates are illustrated in Table 3 with a numerical example based on U.S. data. The first step is to convert total demand for fossil-fuel s, FU_s ($s = 2,\ldots,5$), into a corresponding amount of CO_2 emissions. This involves translating real fuel consumption FU_s into Terajoules, using fuel-specific technical conversion factors ϕ_s, and converting Terajoules into CO_2 emissions, using fuel-specific emission coefficients ε_s[40]. Given the overall carbon tax T^C, it is then possible to derive government revenues from this tax by summing over the demands for primary fossil fuels and imports of refined oil products[41]:

$$\begin{aligned}
R^C &= T^C \cdot \left[\sum_{s=2}^{4} \epsilon_s \cdot \phi_s \cdot \left(\sum_{i=1}^{8} FU_{si}^C + \sum_{i=H,I,ST,G} FU_{si}^C\right)\right] \\
&+ T^C \cdot \left[\epsilon_{b_1} \cdot \phi_{b_1} \cdot \left(\sum_{i=1}^{8} FU_{b_1 i}^B + \sum_{i=H,I,ST,G} FU_{b_1 i}^B\right) + \epsilon_5 \cdot \phi_5 \cdot \left(\sum_{i=1}^{8} FU_5 i^I + \sum_{i=H,I,ST,G} FU_{5i}^I\right)\right] \\
&= T^C \cdot \left(\sum_{s=2}^{4} \epsilon_s \cdot \phi_s \cdot FU_s^C + \epsilon_{b_1} \cdot \phi_{b_1} \cdot FU_{b_1}^B + \epsilon_5 \cdot \phi_5 \cdot FU_5^I\right) = T^C \cdot \left(\sum_{s=2}^{4} \epsilon_s \cdot FU_s^{C,TJ} + \epsilon_{b_1} \cdot FU_{b_1}^{B,TJ} + \epsilon_5 \cdot FU_5^{I,TJ}\right)
\end{aligned}$$

where $FU_s^{C,TJ}$, $FU_{b_1}^{B,TJ}$ are total demands for conventional fuel s and the "dirty" backstop b_1 and $FU_5^{I,TJ}$ is import demand for refined oil products, all expressed in Terajoules.

In order to compute the fuel-specific *ad valorem* tax rates implied by the carbon tax, T^C is first converted into fuel-specific excise taxes per Terajoule (T_s^{TJ}) of each kind of carbon-based fuel s (s = 2,..,5 ,b_1),

$$T_s^{TJ} = T^{C} \cdot \epsilon_s$$

This makes it possible to derive government revenues by kind of fuel (R_s^C):

$$R_s^C = T_s^{TJ} \cdot FU_s^{i,TJ}$$

with i = C for s = 2, 3, 4; i = B for s = b_1; and i = I for s = 5. Finally, denoting total exports of fuel s by EX_s, its *ad valorem* tax rate is computed as the ratio of government fuel-specific revenues to the total value of domestic absorption of the fuel[42]:

$$\tau_s^{FU} = \frac{R_s^C}{PF_s^D \cdot FU_s^D + PF_s^I \cdot FU_s^I - PF_s^D \cdot EX_s}$$

The energy tax affects the energy content of all sources of energy, including the carbon-free sources such as nuclear and hydroelectric energies. Since these energy sectors are not distinguished in GREEN, the energy content of the conventional carbon-free energy sectors is assumed to depend on the carbon-free fixed factor F_6. Denoting the energy content (in Terajoules) of the carbon-free fixed factor by F_6^{TJ}, government revenues from energy taxation can be derived as above by summing over primary demands for all kinds of energy and imports of refined oil products, given the energy tax T^{TJ} [43]:

$$\begin{aligned} R^C = {} & T^{TJ} \cdot \left[\sum_{s=2}^{4} \Phi_s \cdot \left(\sum_{i=1}^{8} FU_{si}^C + \sum_{i=H,I,ST,G} FU_{si}^C \right) \right] \\ & + T^{TJ} \cdot \left[\sum_{s=b_1,..,b_3} \Phi_s \cdot \left(\sum_{i=1}^{8} FU_{si}^B + \sum_{i=H,I,ST,G} FU_{si}^B \right) + \Phi_5 \cdot \left(\sum_{i=1}^{8} FU_5 i^I + \sum_{i=H,I,ST,G} FU_{5i}^I \right) + F_6^{TJ} \right] \\ = {} & T^{TJ} \cdot \left(\sum_{s=2}^{4} \cdot FU_s^{C,TJ} + \sum_{s=b_1,..,b_3} FU_s^{B,TJ} + FU_5^{I,TJ} + F_6^{TJ} \right) \end{aligned}$$

The fuel-specific *ad valorem* tax rates implied by the energy tax can be computed as above.

Total revenues are allocated among transfer and non-transfer expenditures. Both types of expenditures -- denoted TRG and G, respectively -- are exogenous in real terms. However, the allocation of G among purchases of intermediate goods (XG) and demands for old and new capital (K_G^O, K_G^N) and labour (L_G) is determined by utility maximisation subject to a budget constraint for non-transfer expenditures, under the assumption that the government behaves as an aggregate "consumer" of goods and primary factors[44].

Denoting the unit cost of government non-transfer expenditures by c^G, the composite price of government purchases of XG by PG and the (fixed) government deficit by DEF, the allocation of non-transfer expenditures results from the maximisation of the following CES utility function:

$$U_G(XG, K_G, L_G) = CES(XG, K_G, L_G; \rho_G, \alpha_G^1, ..., \alpha_G^3)$$

subject to:

$$REV - TRG + DEF = PG \cdot XG + r^{K^N} \cdot K_G^N + r_G^{K^O} \cdot K_G^O + w \cdot L_G - (1 - \delta_G)\,(r_G^{K^O} \cdot K_G^O + r^{K^N} \cdot K_G^N)$$

where $(1 - \delta_G)$ is the depreciation rate associated with government capital and $r_G^{K^O} \neq r^{K^N}$ if and only if the government sector is declining over time.

The implied optimal government expenditures are

$$XG = G \cdot (c^G)^{-\rho_G} \left(\frac{PG}{\alpha_G^1}\right)^{\rho_G}$$

$$K_G = G \cdot (c^G)^{-\rho_G} \left(\frac{r^{K^N}}{\alpha_G^2}\right)^{\rho_G} = K_G^O + K_G^N$$

$$L_G = G \cdot (c^G)^{-\rho_G} \left(\frac{w}{\alpha_G^3}\right)^{\rho_G}$$

where c^G is the dual of the CES aggregator:

$$c^G = UC(PG, r^{K^N}, r^{K^O}, w; \rho_G, \alpha_G^1, ..., \alpha_G^3)$$

and PG is a weighted average of the after-tax prices of intermediate goods:

$$PG = \sum_{i=1,7,8} (\psi_i^D \cdot PT_i^D + \psi_i^I \cdot PT_i^I) + \sum_{i=2}^{6} (\psi_i^D \cdot PF_i^D + \psi_i^I \cdot PF_i^I) + \sum_{i=b_1,..,b_3} \psi_i^D \cdot PF_i^D$$

Finally, government purchases of intermediate goods XG are allocated across sectors and among domestic and imported commodities in proportions ψ_i^D and ψ_i^I, such that for i = 1,...,8,

$$X_{iG}^D = \psi_i^D \cdot XG$$

s (P_{is}) to the world import price of the same commodity (P_i^{WT}), according to the region-specific trade elasticities ρ_{ir}^{WT}:

$$M_{irs} = M_{ir} \cdot (P_i^{WT})^{-\rho_{ir}^{WT}} \, (\frac{P_{is}}{\alpha_{ir}^{sWT}})^{\rho_{ir}^{WT}}$$

where the world import price of commodity i (P_i^{WT}) is defined as a CES aggregate of the export prices of trading partners:

$$P_i^{WT} = UC\{P_{is}, \, s \neq r; \rho_{ir}^{WT}, \, \alpha_{ir}^{1WT}, ..., \, \alpha_{ir}^{6WT}\}$$

Oil producers are competitive price-takers in all regions. Net imports of crude oil (i = 3) by region r are determined as the difference between total production and total demand by the region, at the given real world price of oil P^{CO}:

$$M_{ir} = Q_{ir} - FU_{ir}$$

For each country r, total exports of good i -- denoted EX_{ir} -- can then be determined as the sum of imports of good i from country r by all other regions s ($s \neq r$):

$$EX_{ir} = \sum_{s \neq r} M_{isr}$$

Finally, the current account of any region r can be determined as follows:

$$CA_r = \sum_{i=1}^{8} P_i^{WT} \cdot (EX_{ir} - M_{ir})$$

(v) Trade in emission rights

The model can be solved under three regimes concerning CO_2 emissions. In reference runs, no constraints on emissions are imposed and there is no carbon tax. In counterfactual simulations, two possibilities are explored. In the base case, emission constraints are imposed at the regional level and region-specific carbon taxes are computed. In an alternative case, an initial allocation of emission rights is assumed and a single emission constraint is imposed at the world level. In this case, a single world carbon tax is computed under the assumption that regions are allowed to trade emission rights.

The carbon tax can be interpreted as the shadow price of CO_2 emissions. The determination of this price is part of the equilibrium solution of the model, which is discussed below. However, when it is possible to trade in emission rights, the world price of the latter is identical to the single world level of the carbon tax.

It is useful to discuss here the implications of trade in permits for financial flows across and within regions. As already mentioned in sub-section III.C.(iii), it is assumed that, in each region, the proceeds from the sale of emission rights accrue to the government.

$$X_{iG}^{I} = \psi_i^{I} \cdot XG$$

Coefficients ψ_i^D and ψ_i^I are determined in the same way as the technical coefficients ι_i^D, ι_i^I and fu_{sI}^D, fu_{sI}^I described in the previous sub-section. A fixed-coefficients structure is assumed for non-energy intermediate goods and the energy bundle, while substitution is allowed among fuels and among conventional and backstop energies, according to a two-stage nested-CES specification, with first-stage elasticity of substitution ρ_1^G and CES distribution parameters α_{1G}^s (s = 2,..., 6) and second-stage elasticity ρ_{2G}^s and distribution parameters α_{2G}^s (s = 2, 3, 4, b_1, b_2, b_3). Finally, the choice between domestic and imported goods is determined by means of a CES transformation function, with elasticity of substitution ρ_3^G and CES distribution parameters α_G^D, α_G^I.

The government budget is not necessarily balanced in each period. However, the implications of government imbalances for the accumulation (or decumulation) of government liabilities and the associated net interest flows are ignored.

(iv) Foreign trade

Each region has import demands for all traded goods. The only non-traded goods in GREEN are the backstop products. For each producer good i (1,..., 8), total imports by region r (r = 1,..., 12) -- denoted M_{ir} -- are the sum of imports of good i for use in production (X_i^I), household and government consumption (X_{iH}^I and X_{iG}^I, respectively) or for investment (I_i^I) and stockbuilding (ST_i^I) purposes:

$$M_{ir} = X_i^I + X_{iH}^I + X_{iG}^I + I_i^I + ST_i^I$$

With the sole exception of crude oil, total imports are allocated among trading partners under the assumption that each good is differentiated by country of origin. Given the imperfect substitutability of good i (i ≠ 3) across regions, each country is assumed to minimise expenditure on total imports M_{ir}, subject to a CES import function defined over imports M_{irs} of region r from all other regions s (s ≠ r):

$$\min_{M_{irs}} \quad \sum_{s \neq r} P_{is} \cdot M_{irs}$$

$$\textit{subject to} \qquad M_{ir} = CES\{M_{irs},\ s \neq r; \rho_{ir}^{WT},\ \alpha_{ir}^{1WT}, \ldots, \alpha_{ir}^{6WT}\}$$

Given the world price system, this procedure yields optimal import demands from trading partner s that are inversely related to the ratio of the price of commodity i in country

Denoting the world carbon tax by T^C, the constraint on emission levels imposed in region r in the base case by $\overline{CE}_r$ and by CE_r the level of emissions generated in region r in the alternative case, government revenues (expenditures) from the sale (purchase) of emission rights in region r (R_r^E) are determined as follows:

$$R_r^E = T^C \cdot (\overline{CE}_r - CE_r)$$

In addition, sales and purchases of emission rights must be balanced at the world level:

$$\sum_r T^C \cdot (\overline{CE}_r - CE_r) = 0$$

D. Supply of primary factors and mobility of capital

In GREEN, primary factors include labour, old and new capital and fixed factors. While labour and new capital are predetermined at the beginning of each period, the supply of primary factors is assumed to be sensitive to contemporaneous own-price movements. Therefore, the determination of these supplies is an integral part of the static equilibrium solution of the model.

(i) Price sensitivity of fixed factors

Among the fixed factors, land, coal and the carbon-free resource are assumed to depend on their contemporaneous rentals. In addition, supplies of natural gas and crude oil are also assumed to depend on their prices, but only when production is below potential. Own-price sensitivity of factor supplies (F_f^S) is modelled according to the following simple constant-elasticity specification:

$$F_f^S = \Phi_f \cdot \left(\frac{r^f}{RE}\right)^{\eta_f} \qquad f = 1, 2, 3, 4, 6$$

where Φ_f and η_f are factor-specific constants and elasticities, respectively.

(ii) Mobility of old capital across sectors

The aggregate supply of old capital is predetermined, being equal in each period to the depreciated stock of capital inherited from the past. However, since individual sectors are allowed to disinvest over and above their sector-specific depreciation rates, sectoral supplies of old capital are sensitive to changes in the relative rentals of old and new capital goods. Moreover, the mobility of capital between sectors is assumed to be restricted by sector-specific disinvestment elasticities. Therefore, each sector faces in principle an upward-sloping supply curve for old capital.

Denoting the sector-specific depreciation rates and disinvestment elasticities by $(1 - \delta_i)$ and κ_i, respectively, and the relative rental of old to new capital by RR_i, the supply of old capital goods by sector i is determined according to the following disinvestment function (Δ_i):

$$\Delta_i = f(RR_i;\ \delta_i, \kappa_i) = \begin{cases} 0 & \text{if} \quad RR_i = 1 \\ \delta_i \cdot K_i^O (1 - RR_i^{\kappa_i}) & \text{if} \quad RR_i < 1 \end{cases}$$

where,

$$RR_i = \begin{cases} 1 & \text{if} \quad K_i \geq \delta_i \cdot K_i^O \\ \dfrac{r_i^{K^O}}{r^{K^N}} < 1 & \text{if} \quad K_i < \delta_i \cdot K_i^O \end{cases}$$

Consequently, the total of old capital goods supplied on second-hand markets (Δ) is the sum of disinvestments originating from all sectors:

$$\Delta = \sum_i \Delta_i$$

E. Closure

The reconciliation of all sectoral financial balances in an AGE model is known as the "closure rule"; and the way this is specified has a critical bearing on simulation results. The standard closure in GREEN defines total gross investment residually, as the sum of personal saving, depreciation, the government balance, stockbuilding and net foreign capital inflows in each region r[45]:

$$I_r = S_r + r_r^{K^N} \cdot \sum_j (1 - \delta_{jr}) \cdot K_{jr} + \sum_n (1 - \delta_{nr}) \cdot r_{nr}^{K^O} \cdot K_{nr} +$$
$$+ (REV_r - GTR_r - G_r) - CA_r$$

F. Equilibrium

In each period, a temporary equilibrium is determined subject to the given (static) price expectations, to the predetermined factor supplies and to the exogenous real world prices of backstop products. In each region, equilibrium is defined as a price vector $P = (r^{K^N}, r_i^{K^O}, w, r^f; f = 1, 2, 3, 4, 6)$ such that the following market-clearing conditions are satisfied:

-- in each declining sector, demand for old capital goods (K_i^O) equals the depreciated capital stock inherited from the previous period minus disinvestment:

$$K_i^O = \delta_i \cdot K_i - \Delta_i \tag{48}$$

-- aggregate demand for new capital (from private and government sectors) equals supply of new capital vintages (I) plus aggregate supply of old capital goods originating from declining sectors:

$$\sum_i K_i^N + K_G^N = I + \Delta \tag{49}$$

-- aggregate demand for fixed factor f (f = 1, 2, 3, 4, 6) equals aggregate supply:

$$F_f = F_f^S \tag{50}$$

-- aggregate demand for labour by private and government sectors equals aggregate supply (L^S):

$$L + L_G = L^S \tag{51}$$

-- in each sector i (i = 1,..., 8, b_1,..., b_3), the following zero-profit condition holds:

$$P_i \cdot Q_i = (\sum_{j=1,7,8} (PT_j^D \cdot a_{ji}^D + PT_j^I \cdot a_{ji}^I) + \sum_{s=2}^{6} (PF_s^D \cdot fu_{si}^D + PF_s^I \cdot fu_{si}^I)) \cdot Q_i$$
$$+ r^{K^N} \cdot K_i^N + r_i^{K^O} \cdot K_i^O + w \cdot L_i + r^i \cdot F_i + R_i \tag{52}$$

where $K_i^N = 0$ in declining sectors, $r^{K^N} = r_i^{K^O}$ in expanding sectors, $F_i = 0$ for i = 5, 7, 8, b_1,..., b_3, $a_{ji}^D = a_{ji}^I = fu_{si}^D = fu_{si}^I = 0$ for i = b_1,..., b_3 and $R_i = 0$ for s = 1, 2, 4,..., 8.

Equation (48) determines the rental rates of old capital in declining sectors, equation (49) determines the rental rate of new (and old) capital in expanding sectors, equation (50) determines the rental rates of fixed factors, equation (51) determines the real wage rate and equation (52) determines producer prices[46]. A world temporary equilibrium is obtained when equilibrium price vectors P are found for all regions.

In simulations in which CO_2 emissions are restricted at the regional level, additional equilibrium prices are required which equate total emissions in each region to the given constraints on emission levels. The resulting equilibrium price in any region r is the carbon tax (T_r^C) or the energy tax (T_r^{TJ}). These taxes can be interpreted as the shadow prices associated with the emission constraint. Denoting the upper bound on emissions (expressed in tons of CO_2) in region r by $\overline{CE_r}$ and recalling that CO2 emissions originate from the Terajoule consumption of carbon-based conventional and backstop fuels (FU_{sr}^{TJ}), these taxes are determined in each region by the following material balance constraint[47]:

$$\sum_{s=2}^{4} \epsilon_s \cdot FU_{sr}^{C,TJ} + \epsilon_{b_1} \cdot FU_{b_1 r}^{B,TJ} + \epsilon_5 \cdot FU_5 r^{I,TJ} \leq \bar{CE}_r \tag{53}$$

When emissions are constrained at the world level and trade in emission rights is allowed, a single constraint such as (53) determines the world tax level as the shadow price of world CO_2 emissions.

Regional and world equilibrium imply that, in each region r and for each sector i, production is equal to intermediate and final uses of good i:

$$Q_{ir} = \sum_j X_{ijr} + Y_{ir}$$

where final demand for good i by country r (Y_{ir}) is defined as the sum of domestic household and government consumption, investment, stockbuilding and exports for that good:

$$Y_{ir} = X_{irH}^D + X_{irG}^D + I_{ir}^I + ST_{ir}^D + EX_{ir}$$

Finally, a world "budget constraint" must hold, whereby the total value of world imports is equal to the total value of world exports:

$$\sum_{r=1}^{12} CA_r = 0$$

G. Dynamics

The dynamics of GREEN are defined by simple equations which describe how the stocks of capital and fossil-fuel resources evolve over time.

(i) Capital accumulation

The aggregate capital stock is determined in each period t by an accumulation function equating the beginning-of-period stock (K_t) to the sum of the depreciated capital stock inherited from the previous period and the previous-period gross investment. This reflects the assumption that there is a lag in embodying new capital vintages in the capital stock. Denoting the aggregate depreciation rate in period t by ($1 - \delta_t$), this accumulation function can be expressed as follows:

$$K_t = \delta_{t-1} \cdot K_{t-1} + I_{t-1} \tag{54}$$

Sectoral capital stocks evolve in a similar way, but embody the additional assumption that the depreciated capital stock can be scrapped at a rate which exceeds the (constant) sector-specific depreciation rates ($1 - \delta_i$). This second-hand capital is then supplied to other sectors according to the disinvestment functions Δ_i described in sub-section III.D.(ii). The decision to disinvest is assumed to be taken in the current period, by comparing the rental rates of new and old vintages. Since second-hand capital is assumed to be homogeneous in demand with new capital vintages, sectors cannot both invest and disinvest at the same time.

As a result, some sectors decline while others expand in each period. Given these assumptions, the sectoral accumulation functions can be expressed as follows:

$$K_{it} = \delta_i \cdot K_{it-1} + I_{it-1} - \Delta_{it} \tag{55}$$

Sectoral and aggregate capital accumulation functions are reconciled by defining $\delta_t = \sum_i \delta_i \cdot \frac{K_{it}}{K_t}$ and summing equation (55) over sectors:

$$\begin{aligned} \sum_i K_{it} &= \sum_i \delta_i \cdot K_{it-1} + \sum_i I_{it-1} - \sum_i \Delta_{it} = \\ &\delta_{t-1} \cdot K_{t-1} + I_{t-1} = K_t \end{aligned} \tag{56}$$

Equation (56) states that, in each period, second-hand capital goods provided by declining sectors are identically equal *ex post* to the excess of sectoral investments over the new vintage of capital embodied in the current aggregate capital stock:

$$\sum_i \Delta_{it} = I_{t-1} - \sum_i I_{it-1}$$

(ii) <u>Short- and long-run elasticities</u>

With putty/semi-putty technology, substitutability between capital and the other factors of production is lower in the inherited capital stock than in capital originating from current period investment. Given this specification, the overall interfactor and interenergy elasticities of substitution differ in the short- and in the long-run. Over time the short-run elasticities converge to the long-run elasticities characterising new capital formation. Figure 5 shows several convergence paths for interfuel elasticities associated to an elasticity of 2 for new capital vintages and several values of old vintage elasticities.

The gap between short- and long-run elasticities and the speed of the convergence process depend in a crucial way on the dynamics of the capital stock. It can be shown that, in any period, the short-run elasticity of substitution between two factors is a linear combination of the elasticities on old and new capital, weighted by the share of new capital in the total capital stock. The larger are net replacement rates -- i.e. the combination of depreciation and new capital formation -- the smaller the gap between short- and long-run elasticities and the faster the convergence of the former to the latter. Therefore, in GREEN net replacement rates have important implications for the dynamic response of the economy to changes in relative prices such as those caused by carbon taxation.

(iii) <u>Resource depletion sub-model</u>

The resource depletion sub-model is implemented only for crude oil and natural gas. Coal is not assumed to be resource-constrained, although its extraction costs are increasing. A resource depletion path for both oil and gas is traced out by means of a standard model with proven and yet-to-find reserves. Some allowance is also made for price sensitivity of resource supply. Thus, the resource depletion path depends in any given period on the past evolution of prices.

(a) **The depletion mechanism**

The depletion model is based on the assumption that the resource base, i.e. the sum of proven and yet-to-find reserves -- can be estimated with a given probability[48]. Given this estimate, the potential supply path is determined by two technological parameters: (i) the rate of discovery of new reserves -- hereafter called the "conversion rate"[49]; and (ii) the rate at which resources are extracted from proven reserves -- hereafter called the "extraction rate". Generally, these coefficients are not constant over time. For instance, the extraction rate can vary widely in the short-term when a new discovery increases the stock of proven reserves. However, the expectation is that they will tend towards a stable level as geological uncertainty is reduced. The extraction rate is assumed to be a constant parameter given by the base-year ratio of production to proven reserves. On the other hand, the conversion rate is derived from the calibration procedure described in Section VI below. Actual supply of oil and gas is bounded above by the potential supply profile, with the slack between actual and potential being determined by the supply functions for oil and gas described in III.D.(i) above.

Denoting, in each period t, the extraction rate by r_i, the conversion rate by d_i, proven reserves by $RES_{i,t}$, yet-to-find reserves by $YTFR_{i,t}$ and newly discovered reserves by $NRES_{i,t}$, the following equations describe potential supply ($Q_{i,t}$) and newly discovered reserves of fossil fuel i (i = 3, 4) in each region:

$$Q_{i,t} = r_i \cdot RES_{i,t} \tag{57}$$

$$NRES_{i,t} = d_i \cdot YTFR_{i,t} \tag{58}$$

The equation of motion for the level of proven reserves at the beginning of any period t is:

$$RES_{i,t} = RES_{i,t-1} + NRES_{i,t-1} - Q_{i,t-1} \tag{59}$$

Substituting equations (57)-(58) into (59), this equation can be rewritten as

$$RES_{i,t} = (1 - r_i) \cdot RES_{i,t-1} + d_i \cdot YTFR_{i,t-1}$$

Finally, given the initial conditions $RES_{i,0}$ and $YTFR_{i,0}$ and defining the parameter $\Pi_{i,0} = \dfrac{RES_{i,0}}{YTFR_{i,0}}$, the equation can be iterated forward n periods to obtain:

$$\frac{RES_{i,n}}{RES_{i,0}} = (1 - r_i)^n \cdot + d_i \cdot L(d_i, r_i; n) \cdot \frac{1}{\Pi_{i,0}} \qquad \textbf{(60)}$$

where $L(d_i, r_i; n) = \sum_{k=1}^{n} (1 - r_i)^{n-k} \cdot (1 - d_i)^{k-1} = \dfrac{(1 - r_i)^n - (1 - d_i)^n}{(d_i - r_i)}$.

Equation (60) is used in the calibration procedure for parameters d_i as well as in the determination of price elasticities. Since, by assumption, coefficients r_i and d_i are strictly positive and smaller than one, equation (60) satisfies the long-run depletion property, i.e. $RES \to 0$ as $n \to \infty$. For a given set of initial conditions, however, the time profiles of the depletion paths may present striking differences in the short and medium-term depending upon the interaction between the "extraction" equation (57) and the "conversion" equation (58). Figure 5 shows the pattern of a typical depletion path. Potential output first increases with the stock of proven reserves before declining and converging more or less quickly to zero.

Given the resource base and the depletion parameters (r_i and d_i), the depletion path can also be affected by the decision of producers to supply oil and gas below potential at the going market prices. In this case, the slack between actual and potential output adds to future reserves and increases future potential output levels, modifying the time profile of potential supply.

(b) **Price sensitivity of resource supply**

The assumption that the depletion parameters and the resource base are exclusively determined by technical and/or geological factors is certainly restrictive. In the real world, market forces will tend to create a linkage between the investment needed to find new reserves or to improve the resource exploitation technology on the one hand and profit conditions on the other. Therefore, in principle, investment and production decisions should depend on market structure and future demand expectations. In the current version of GREEN, expectations are myopic and markets are assumed to be perfectly competitive. Therefore, this linkage was proxied by the very simple assumption that the level or the conversion rate of yet-to-find reserves of crude oil and natural gas is sensitive to the prices of oil and gas.

Denoting the price elasticities of the conversion rate and of the yet-to-find reserves for each fuel type by ω_i and υ_i, respectively, the associated constant terms by Ω_i and Υ_i, and the real price of fossil fuel i by $\tilde{P}_i$, the following specifications were assumed:

$$d_i(\tilde{P}_i) = \Omega_i \cdot (\tilde{P}_i)^{\omega_i} \qquad \textbf{(61)}$$

$$YTFR_i(\tilde{P}_i) = \Upsilon_i \cdot (\tilde{P}_i)^{\upsilon_i} \qquad \textbf{(62)}$$

Equations (61) and (62) are mutually exclusive since the calibration procedure for the resource depletion sub-model only has one degree of freedom (see Section VI). Hence, price sensitivity can be introduced either through the conversion rates d_i *or* the yet-to-find reserves $YTFR_i$. However, the impact of price sensitivity will be somewhat different according to the chosen alternative. Figure 6 illustrates the main differences between the two mechanisms. When the d-coefficient is price sensitive, the production path becomes more concave in the short and medium-run but converges faster to the reference level. When the level of YTFR reserves is price-sensitive, an oil price increase leads to higher reserves, inducing an upward shift in the production path relative to the reference case.

H. Welfare measures

In GREEN, the welfare losses/gains of emission abatement policies are expressed in terms of Hicksian "equivalent variation" (EV), defined to be the amount of income that would have to be taken away from the consumer at pre-policy consumer prices (PC^b) to make him as well off as he would be at post-policy consumer prices (PC^s). In other words, EV is the change in real income necessary to ensure that the optimal choices of consumers at prices PC^b ensure the same level of utility obtained at prices PC^s. Denoting disposable income by Y^D, the indirect utility function by $V(PC, Y^D)$ and the expenditure function by $E(PC, V)$, the equivalent variation is usually defined as follows (Varian, 1978, p.210):

$$V(PC^b, Y^D - EV) = V(PC^s, Y^D)$$

or

$$EV = E(PC^s, V^s) - E(PC^b, V^s)$$

This definition applies to static welfare comparisons in which disposable income is assumed to be constant before and after the policy change. In GREEN simulations this will not be the case, since at each point in time pre- and post-policy endowments will be different due to changes in the pattern of capital accumulation and resource depletion. Therefore, an alternative definition of equivalent variation is used, as in Ballard *et al.* (1985). This is simply defined as the additional income required to obtain post-policy utility levels at pre-policy prices:

$$EV = E(PC^b, V^s) - E(PC^b, V^b) \qquad (1)$$

In this framework, the change in utility levels includes changes in both prices and endowments, but the equivalent variation in income is computed at a common set of prices. In GREEN simulations, these prices are benchmark-year prices expressed in 1985 US$[50].

At each point in time, EV_t can be computed using definition (1) and the indirect utility function and the expenditure function associated with the ELES specification of preferences[51]. Using the notation introduced in section III.C.(i) and defining $k = \sum_{i=1}^{5} \beta_i \cdot \ln(\beta_i)$, $a(PC_t) = \sum_{i=1}^{4} PC_{i,t} \cdot \gamma_i$ and $b(PC_t) = \prod_{i=1}^{5} PC_{i,t}^{\beta_i}$, the following two expressions can be computed for all periods t:

$$V(PC_t, Y_t^D) = k + \ln\left[\frac{Y_t^D - a(PC_t)}{b(PC_t)}\right] \tag{2}$$

$$E(PC_0, V_t) = a(PC_0) + e^{V_t - k} \cdot b(PC_0) \tag{3}$$

where the price of savings $PC_{5,t}$ is defined as an average of the four consumer prices, weighted by their respective budget shares, and the benchmark-year is indexed by 0. Equation (2) is the value of the ELES indirect utility obtained in period t at the current set of prices. Equation (3) is the real income equivalent of utility V_t, evaluated at the benchmark-year prices. From equation (3), the equivalent variation in each period t is computed as follows:

$$EV_t = E(PC_0, V_t^s) - E(PC_0, V_t^b) = b(PC_0) \cdot e^{-k} \cdot (e^{V_t^s} - e^{V_t^b}) \tag{4}$$

Equation (4) is the appropriate measure for comparing pre-policy welfare in period t with post-policy welfare *in the same period*. However, it is inadequate for performing intertemporal welfare comparisons for two reasons. First, comparisons over time need to be done with a summary measure, which expresses the present value of the cumulated welfare changes. Second, this measure should exclude changes in utility due to saving. Since the utility of saving is just the utility of the future consumption stream associated with it, including in the summary measure the welfare originating from saving would involve an element of double counting over the simulation period[52].

Given the separability of consumption and saving in the ELES specification, it is possible to derive the indirect utility of consumption in period t ($V_{c,t}$) and its real income equivalent as in equations (2) and (3). Defining $k_c = \sum_{i=1}^{4} \beta_i \cdot \ln(\beta_i)$ and $b_c(PC_t) = \prod_{i=1}^{4} PC_{i,t}^{\beta_i}$, the following expressions can be obtained,

$$V_c(PC_t, Y_t^D) = k_c + \ln\left[\frac{Y_t^D - a(PC_t)}{b_c(PC_t)}\right]$$

$$E(PC_0, V_{c,t}) = a(PC_0) + \left[e^{V_{c,t} - k_c} \cdot b_c(PC_0)\right]^{\frac{1}{1-\beta_5}}$$

from which the equivalent variation excluding saving (E_t^c) can be computed in each period t as in (4).

Based on the time series of equivalent variations E_t^c, a summary measure of the intertemporal change in welfare caused by the policy was constructed. In each region, the cumulated sum of welfare changes was normalised by total income earned during the simulation period. In addition, it was assumed that households would assign a smaller weight to welfare changes distant in the future[53]. Denoting the (exogenous) time-preference rate by ζ, the real income equivalent by $\bar{Y}_t^D$ and the final simulation period by T, the summary measure $\tilde{EV}$ can be expressed as follows,

$$\tilde{EV} = \left(\frac{1}{\sum_{t=1}^{T} \frac{\bar{Y}_t^D}{(1+\zeta)^t}} \right) \cdot \left(\sum_{t=1}^{T} \frac{EV_t^c}{(1 + \zeta)^t} \right)$$

I. Solution algorithm

Static equilibria of GREEN are obtained by an iterative solution method which uses a *tâtonnement* procedure based on the Gauss-Siedel algorithm[54]. The sequence of static equilibria is period-related using the capital accumulation and resource depletion functions described in the previous sub-section.

IV. DATA

A. General overview

The single-country data structure of GREEN is described in Figure 4. Country/region data sets are linked through foreign trade. Model simulations are based on a benchmark-year data set collected from various sources. There are four basic data requirements:

-- National input-output (I-O) tables provide data for intermediate and final demands and for the structure of value-added (see Annex I for a list of sources concerning national I-O tables). I-O tables are usually supplemented by data from other sources -- including OECD *National Accounts* (OECD, 1990), UN *National Account Statistics* (United Nations, 1990) as well as IEA energy statistics and energy balances (International Energy Agency, 1987, 1989, 1990).

-- Transition matrices convert the consumer-good classification of sectors into a producer-good classification. These matrices are based on Eurostat *National Accounts* (Eurostat, 1986).

-- Bilateral foreign trade matrices provide the link between the country data sets. These are based on OECD *Foreign Trade Statistics* (OECD, 1987) for bilateral trade concerning the OECD area and on the *CHELEM* data base compiled by the French research institute CEPII (CEPII, 1988) for intra-area trade flows in the non-OECD regions. The result is a fully disaggregated (200 x 200) world trade matrix on a country basis for each GREEN sector.

-- Population projections are needed in the calibration of the ELES demand system. These projections are drawn from the World Bank data file by Bulatao *et al.* (1990).

The choice of the base-year is important because some of the simulation results may be sensitive to the initial level of energy prices. For most countries, 1985 was chosen; this is the year for which the latest I-O tables were available for most OECD countries. When I-O data for 1985 did not exist, the most recent available I-O tables were used instead.

Data collection was designed to provide the maximum flexibility in the construction of regional groupings and to make it possible to upgrade data sets as new information becomes available. Therefore, data were collected on a country basis and data sets for regional areas were created through country aggregation. Table 4 shows the current regional groupings of GREEN. The energy-exporting LDCs region groups countries whose net exports of energy account for a significant share of their domestic energy production[55]. The former Soviet Union, the CEECs, China, India, the DAEs and Brazil were treated as separate regions in view of their potential importance as sources of CO_2 emissions over the simulation period[56].

Sectoral disaggregation was dictated by the need to stress the relative importance of fossil and non-fossil energy production. Within fossil energy production, energy sources associated with different CO_2 emission factors were distinguished. The use of fossil and non-fossil energy sources as inputs into the production of finished goods and services was captured in a simplified way by distinguishing agriculture and three other manufacturing sectors: refined oil products, energy-intensive industries and other industries and services. Table 5 reports these sectoral definitions in terms of industrial (ISIC) and trade (SITC) classifications. Consistency between sectoral outputs and I-O figures is ensured by an iterative bi-proportional adjustment process for material balances[57].

For most of the LDCs, no I-O tables are available. In these cases, the necessary data bases were collected through a "minimum information procedure" that makes use of consistent published data. In addition to the sources listed above, this procedure uses UN *Industrial Statistics* (United Nations, 1989), *Commodity Statistics* (United Nations, 1989) and *International Trade Statistics* (United Nations, 1989a, 1989b) and statistics by the *Food and Agriculture Organisation* (FAO, 1990). These sources usually provide the elementary figures concerning primary factors and production (value-added and its components, imports and outputs), final demand (household and government consumption, investment, stock changes and exports) and energy balances for coal, oil, natural gas and electricity. Where data are unavailable -- often the case at the level of intermediate demands -- estimations were made using coefficients from I-O tables for countries at a similar level of development. An illustration of this minimum information procedure is provided in Annex II for the case of Nigeria.

The data for the RoW region necessitated a special treatment, given the lack of I-O tables for the vast majority of the countries in the region. Based on complete I-O tables for Chile and Morocco, I-O tables for four other countries -- Syria, Israel, Argentina and Zimbabwe -- were constructed using the minimum information procedure. These tables were aggregated in order to get average input-output coefficients for this group of countries. The resulting average I-O table served as a basis for the creation of a table for the residual countries in RoW, in which the input-output flows were inflated to correspond to the GDP structure of this region.

B. Issues in collecting intermediate and final demand data

The construction of the intermediate and final demand data sets involves several problems. Some are common to all countries, while others are specific to non-OECD countries. Among the first, the most noticeable issue concerns the disaggregation of crude oil and natural gas. These sectors are usually grouped together under the same ISIC code in most industrial statistics. Therefore, separate values for intermediate demands for crude oil and natural gas were estimated using unit domestic (or world) prices and production volumes provided by UN or IEA energy statistics. An example of this approximate disaggregation is provided in Table 6 for the United States and Nigeria. The resulting figures are then adjusted to the corresponding output values given by National Accounts or I-O tables. Another issue concerns the splitting of total-use matrices into domestic and imported components, for which there is no recent information available. In this case, data were extrapolated assuming identical import shares across all intermediate and final demands. Finally, in the absence of any other information, the rents earned by the fixed factors in the four energy sectors were assumed to be equal to the operating surpluses in each sector.

Among the problems specific to non-OECD regions, the most important are: (i) the allocation of energy outputs among industry, the service sector and household demands; (ii) the identification of the components of value-added in agriculture; and (iii) the treatment of the so-called "unallocated industry" uses of energy. As to the first, the allocation was done on the basis of volumes provided by the IEA balance sheets, under the assumption that the unit market price paid by energy consumers is the same irrespective of whether energy is used by an intermediate industrial sector or by households[58]. A crude solution to the second problem was to use data from the I-O table of a country for which disaggregation of agricultural value-added was available. As to the last problem, it was assumed for simplicity that all unallocated industry uses of energy reflect household demand for fuel and power[59].

V. PARAMETERISATION

There are a very large number of behavioural parameters in GREEN. Model simulations require that all these parameters be numerically specified. It is common practice in AGE modelling to fix a certain number of "key" parameters on the basis of empirical evidence or the modeller's priors, while other parameters are adjusted in order to reproduce the benchmark-year data set under the assumption that the economy is in a steady-state equilibrium in that particular period. This section identifies the key parameters of GREEN, provides their current numerical values and discusses the empirical evidence supporting these choices.

In each regional model, the key exogenous parameters are the following:

(a) the elasticities of substitution among inputs at the various stages of the production process for old and new capital, i.e. the elasticity of substitution between labour and the capital/energy/fixed factor bundle in each sector (ρ_{1i}^{O}, ρ_{1i}^{N}), the elasticity of substitution between energy and the capital/fixed factor bundle in each sector (ρ_{2i}^{O}, ρ_{2i}^{N}), the inter-energy elasticity of substitution in each sector (ρ_{3i}^{O}, ρ_{3i}^{N}) and the elasticities of substitution between conventional and backstop energy sources in each sector (ρ_{4i}^{sO}, ρ_{4i}^{sN});

(b) the inter-energy elasticities of substitution in the production of the investment good (ρ_{1I}), in consumer demand for each good (ρ_{1j}^{H}) and in government demand for intermediate goods (ρ_{1}^{G});

(c) the elasticities of substitution between conventional and backstop energy sources in the production of the investment good (ρ_{2I}^{s}) and inventories (ρ_{2ST}^{s}), in consumer demand for each good (ρ_{2jH}^{s}) and in government demand for intermediate goods (ρ_{2G}^{s});

(d) the elasticities of substitution between domestic and imported intermediate goods (ρ_{5i}) and fuels (ρ_{6i}) in each production sector, in household consumption (ρ_{3}^{H}), in the production of the investment good (ρ_{3}^{I}), in the demand for stockbuilding (ρ_{2}^{ST}) and in government demand for intermediate goods (ρ_{3}^{G});

(e) the elasticities of substitution between government inputs (ρ_{G});

(f) the elasticities of substitution between imports of good i in country r with respect to exports of good i by other countries (ρ_{ir}^{WT});

(g) the income elasticities of household consumption demand for different goods ($\beta_i \cdot \frac{Y}{\sum_{i=1}^{4} PC_i \cdot C_i}$; $i = 1,\ldots, 4$);

(h) the own-price supply elasticities of fixed factors (η_f);

(i) the extraction rates (r_s) and the ratios of proven to yet-to-find reserves (Π_s) of the resource-base sub-model;

(j) the disinvestment elasticities in each sector (κ_i);

(k) the depreciation rates in each sector ($1 - \delta_i$); and

(l) the CO_2-emission coefficients of each fossil fuel (ϵ_s).

Given the large number of these parameters, the choice of the numerical values to be imposed in baseline simulations relied on a number of sources. A first source was previous Secretariat experience with the parameterisation of the WALRAS model. This concerned particularly parameters of consumer demand and international trade. Second, some parameter values were derived from benchmark-year observed data. This was the case, for instance, for depreciation rates, extraction rates and the ratios of proven to yet-to-find reserves. Third, a specific literature search was undertaken for certain key parameters.

Given the focus of GREEN on the production and use of various energy sources, the literature search concentrated on the values of inter-factor and inter-energy elasticities of substitution in production. The survey covered two strands of literature: (i) econometric estimates; and (ii) other models used to address the CO_2 issue.

A. Econometric estimates

In GREEN the various nests of the production structure are represented by CES technologies, in which substitutability is expressed by a single parameter. However, most econometric estimates of inter-factor and inter-energy elasticities of substitution are based on translog specifications, in which substitutability can be measured in several ways. The literature search focused on the so-called Allen elasticities, which are widely used in empirical analyses because they are symmetric and unit-free. Allen elasticities are *compensated* (i.e. real output constant), share-weighted cross-elasticities of demand[60]. Some studies only reported cross-elasticities, which are neither symmetric nor unit free because they depend on the size of one of the input shares. In these cases Allen elasticities have been derived from the cross-elasticity estimates[61].

GREEN runs over a 65-year time horizon using a mixture of 5- and 20-year steps. Thus, simulations are concerned with both medium- and long-term developments. This is reflected in the putty/semi-putty specification of technology, which allows for significant adjustment costs in the short-run and convergence to long-run outcomes over time. Parameterisation of the putty/semi-putty production functions requires choosing values for elasticities of substitution on old and new capital. The parameterisation strategy was to anchor production behaviour to elasticities on new capital, which are the elasticities prevailing in the long-run, and choose elasticities on old capital such that the implied medium-term elasticities are in the mid-range of the available empirical estimates. Therefore, the survey provides evidence on both upper-bound (long-run) elasticity estimates based on cross-section data and shorter-run estimates based on time-series data.

(i) Inter-factor elasticities of substitution

Tables 7 to 11 summarise estimates of capital-labour, energy-labour and energy-capital elasticities of substitution from a variety of time-series (TS), cross-section (CS) and cross-country (CC) studies. Countries are grouped in three regions: North America, Europe and Pacific.

The estimates reported in Table 7 indicate that capital (K) and labour (L) inputs are generally substitutable independently of the sample period, of the type of data, of sectoral detail [aggregate (Agg.) or manufacturing (Man.)] and of model specification (CES, translog, generalised-Leontief, logit). Most estimated elasticities lie within a range of 0.5 to 1.5. Estimates in North American countries are frequently at or above unity, while in European and Pacific countries elasticities average at 0.5-0.7.

With the exception of INTERLINK, these estimates usually concern labour-capital substitution rather than the substitution between labour and the capital/energy (E) bundle, as required in GREEN. However, the estimates of labour-energy elasticities reported in Table 8 indicate that these inputs are often substitutable to the same extent as capital and labour[62]. Therefore, the assumption of identical capital-labour and energy-labour elasticities -- implicit in GREEN's nested-CES framework-- does not seem overly restrictive, and the elasticities reported in Table 7 are likely to provide a good guide for the parameterisation of the model.

The technical relationship between capital and energy in production has been widely debated in the last two decades. But there is little agreement on the sign of the relationship, let alone its magnitude. Empirical estimates suggesting complementarity between the two factors are at least as frequent as findings suggesting substitutability. The sign and magnitude of the estimated elasticities depend on a number of factors, such as the dimension of the production space [e.g. the inclusion of intermediate inputs (M), inventories (I) or fixed factors (F) and the degree of disaggregation of the energy input], the specification of the models (e.g. static or dynamic), the definition of the capital aggregate [e.g. equipment (K_e) vs. structures (K_s), working (K_w) vs. fixed capital) and the nature of technical change (e.g. neutral or biased).

Table 9 [from Carrère & Devezeaux (1988)] nicely summarises the variety of results stemming from the literature of the 1970s and early 1980s. It suggests that the most important influence on the sign of the estimated elasticities is the nature of the data. Studies using pooled cross-section or cross-country data usually find that capital and energy are substitutes, while time-series studies find complementarity between the two inputs. A widely held opinion is that the former yield long-run elasticities and the latter short-run ones [Griffin (1981)]. However, this is not a unanimous view and much of the recent debate leaves open the possibility of capital-energy complementarity, even in the long-run[63]. Attempts at estimating dynamic production models, which distinguish between short- and long-run substitution possibilities, are no help in resolving this issue: some such studies provide estimates of long-run complementarity[64]. At the same time, it is generally agreed that capital-energy elasticities have not been stable over time, especially after the two major oil shocks.

Table 10 presents additional information on the capital-energy issue. The studies surveyed are either based on more recent data or control for some of the factors listed above. For example, Pindyck (1979) and Turnovsky *et al.* (1982) disaggregate energy into four components -- electricity (El), oil and other petroleum products (P), coal (C) and natural gas (G) -- while Hogan (1989), Berndt & Hesse (1986) and Hesse & Tarka (1986) disaggregate into electric and non-electric (NEl) energy inputs; Carrère & Devezeaux (1988) compare estimates of an identical model over time-series and cross-country data; Field & Grebenstein (1980) distinguish between working capital (Kw) and fixed capital (Kf); Delorme & Lester (1986) distinguish between equipment (Ke) and structures (Ks); and Hogan (1989) and Berndt & Hesse (1986) estimate dynamic production models.

Overall, if negative elasticities are neglected as "short-run" estimates, tables 9 and 10 suggest long-run capital-energy elasticities ranging from 0.4 to 1.6, with no clear pattern emerging across regional groupings. In addition, there is some evidence that capital substitutes with non-electric energy more easily than with electricity. However, these conclusions should be taken with caution in view of the lack of robustness mentioned above[65].

Given the uncertainty surrounding the capital-energy debate and the wide range of estimates presented in Tables 9 and 10, the values assumed for the elasticity between the two kinds of capital and energy in GREEN ensure that energy and capital are complementary in the short- to medium-term and substitutable in the long-run[66]. On the other hand, this uncertainty strongly supports the imposed nesting hierarchy of the model. A different hierarchy, based on a capital-labour bundle, would impose restrictions (i.e. a common substitution elasticity between energy and inputs in the bundle) that have little empirical content[67].

(ii) **Inter-energy elasticities of substitution**

In spite of their crucial role in determining the outcomes of carbon taxation, econometric estimates of inter-energy elasticities of substitution are scarce and not very reliable. In many cases, estimates are based on very specific industrial sectors (such as food processing) and are not very useful for GREEN. In other cases, results are reported on a state-by-state or plant-by-plant basis, and it is difficult to infer their aggregate counterparts. In addition, estimates of interfuel elasticities are highly sensitive to model specification and choice of sample period. For instance, identical data sets can yield elasticities with different signs when estimates are based on translog or logit production functions [Considine (1990)]. Finally, substitutability among energy inputs has been clearly affected by the two oil shocks [Hesse & Tarka (1986), Ilmakunnas & Torma (1989), Hall (1986)], so that only studies including recent observations are empirically relevant.

Table 11 presents some evidence on interfuel substitution possibilities for North America, the Pacific region and Europe. These numbers suggest that substitutability between electric and non-electric energy is sizeable, ranging from .9 to 1.5 in European countries and to two-digit numbers in the United States and Japan. At a more disaggregate level, substitution possibilities between different kinds of fuel also seem substantial in both the United States and Japan, with the possible exceptions of petrol and electricity and, especially, natural gas and coal. Lack of substitutability between coal and natural gas is confirmed by other studies for France and Germany [Estrada & Fugleberg (1989)] and the United States [Hudson & Jorgenson (1974)][68]. Finally, both Considine (1988) and Estrada & Fugleberg (1989) estimated that natural gas and electricity are the most substitutable among energy inputs.

The economic interpretation of these estimates is not always straightforward. The econometric analysis of substitution possibilities among different kinds of energy inputs is usually based on the assumption that energy and capital are weakly separable in production. In this context, firms are assumed to first choose a cost-minimising energy-mix and subsequently choose the optimal capital-energy bundle. Strictly speaking, this only makes sense in situations where dual-fire or multi-energy technologies are available. Otherwise, substitution possibilities depend on the installation of new capital and, therefore, separability breaks down. Since firms having multiple power-generating technologies generally represent a small fraction of the data on which most econometric studies are based, estimation results should be considered with caution[69].

In an attempt to control for this kind of aggregation bias, Sullivan & Siemon (1981) present estimates for elasticities of substitution between petrol, coal, natural gas and electricity on the basis of a U.S. data set comprising 459 steam electric plants capable of burning coal, oil and gas over the 1969-75 period. By including only plants that already have installed multi-energy technologies, they can interpret their results as *upper-bound* estimates for interfuel substitution possibilities. Their estimates suggest long-run inter-energy elasticities ranging from 2 to 3 for 60 per cent of the plants in the sample, while for 85 per cent of the plants the elasticities range from zero to 3. These results suggest that plausible elasticity values for GREEN simulations should approach 2 in the long-run and lie between 0.5 and unity in the medium-term[70].

As with the other key parameters of the model, a literature review was undertaken of econometric estimates of Autonomous Energy Efficiency Improvements (AEEI). Unfortunately, econometric attempts to pin down plausible values of AEEI have been generally unsuccessful to date. For the United States, results range from no evidence to even negative values for autonomous time trends of this type[71]. In contrast to this, descriptive analyses, based on energy end-use data, suggest that AEEI is positive and may even be expected to increase over time.

B. Parameterisation of other models

A review of the parameter values imposed in other models which address the CO_2 issue yielded a limited amount of information, due to the heterogeneity of model structure, geographical coverage and time horizons. In addition, with a few exceptions, notably Whalley and Wigle (1991) and Edmonds *et al.* (1987), authors do not report having undertaken extensive literature searches backing their choice of values. Finally, although model results appear to be crucially dependent on the elasticities chosen, few authors report results of sensitivity analyses[72].

The review of models covered inter-factor and inter-energy elasticities in production as well as energy supply elasticities, AEEI and inter-energy substitution elasticities in final demand. Table 12 provides a summary of the main features of the surveyed models. Their parameterisation is summarised in Table 13.

Surprisingly, most models addressing the CO_2 issue have nesting hierarchies based on a capital-labour bundle, in spite of the fact that -- as noted above -- this choice finds little empirical support in the econometric literature. Imposed elasticities of substitution between the capital-labour bundle and energy range from 0.25 (Bergman, 1988) to 0.4 (Manne and Richels, 1990) or 0.5 (Whalley and Wigle, 1991). The review of the models also provided very little information on the value of the inter-energy elasticity of substitution in production. For instance, Whalley and Wigle (1991) arbitrarily set this elasticity to unity, citing the lack of compelling econometric evidence. On the other hand, inter-fuel elasticities in final demand are generally assumed to be larger than the corresponding production elasticities, reflecting easier substitution possibilities for goods such as heating. For instance, Whalley and Wigle (1989) use a value of 4 for this elasticity, while Edmonds and Barns (1990) set this elasticity to 3.

Very little backing was also found for energy supply elasticities and AEEI, reflecting the lack of unambiguous econometric estimates of these parameters. As to supply elasticities, Edmonds and Barns (1990) use a long-run value of 1.0 for oil and coal, while Whalley and Wigle use a supply elasticity of 0.5 for carbon-based energy resources[73]. For AEEI, most modelers have assumed values based on economic reasoning. Thus, Manne and Richels (1990) assume, in early simulation periods, values of 0.25 per cent for the USSR, 0.5 per cent for the OECD and 1 per cent for China, arguing that the lower the level of industrialisation in a region the higher is the scope for technical progress in the use of energy. On the other hand, Mintzer (1987) assumes different AEEI values for different kinds of fuels, with the lowest for nuclear energy and the highest for natural gas.

C. Parameterisation of GREEN

Tables 14-18 report the values imposed on the key parameters (a)-(k) of GREEN. CO_2-emission coefficients (l) are reported in Table 3. Although the choice of parameter values was guided by the literature search and the other sources of information described above, a number of simplifying assumptions were made. First, identical values for the CES elasticities of substitution were imposed in *all* regions, in production, international trade and in the government sector (Table 14). This is not very realistic, but the literature review provided little guidance on country-specific values for these parameters. International trade elasticities are smaller than those imposed in the WALRAS model due to the *medium-term* nature of GREEN simulations. Substitution among government inputs is the same as in the WALRAS model. Second, inter-energy elasticities of substitution were assumed to be the same for producers, consumers, the government sector and in the "production" of the typical investment good. Third, elasticities of substitution between conventional and backstop energies were assumed to be equal in all sectors. Fourth, in the absence of any empirical evidence, disinvestment elasticities were assumed to be identical across both sectors and regions, while depreciation rates were assumed to be identical across regions (Table 18)[74].

Table 15 reports income elasticities of consumer demand. Consistent with empirical evidence, these were assumed to be higher for all goods in less developed regions. Table 16 presents supply elasticities of fixed factors. Since empirical evidence on these parameters is virtually non-existent, these values largely reflect Secretariat priors[75]. In general, upward elasticities were assumed to be higher in regions where fixed factors are more abundant. Upward and downward elasticities for fossil fuels are defined relative to *potential* supply of these factors, assumed to be almost infinite for coal and finite for oil and natural gas in each period. The low upward elasticity of the carbon-free resource reflects the important costs associated with the extension of existing non-fossil energy supply (e.g. nuclear power). Finally, Table 17 reports the parameters of the resource-base sub-model, which are assumed to be equal to their base-year observed values[76].

As with all AGE models, the critical issue is not the magnitude of the parameters *per se*, it is the sensitivity of simulation results to the particular choice of parameters (a)-(l). While certain parameters -- such as CO_2-emission factors, depreciation rates and extraction rates -- are not very controversial, others are surrounded by a large degree of uncertainty. It is essential to know which of the latter can affect in important ways the simulation results. The results of some limited sensitivity analysis with alternative values of the inter-energy elasticity of substitution, AEEI and the foreign trade elasticities are reported in Burniaux, Martin, Nicoletti and Oliveira Martins (1991). They show that CO_2-emission paths, carbon tax levels and welfare effects depend crucially on inter-energy elasticities of substitution, AEEI and on supply elasticities of the fixed factors -- particularly of the carbon-free resource.

VI. CALIBRATION

Given the specification of the model and numerical values for its key behavioural parameters, GREEN has been calibrated using the benchmark-year data set described in Section IV. In static AGE models, the calibration procedure involves adjusting a certain number of parameters in order to obtain a solution of the general equilibrium system that reproduces the observed data in the base-year. In a dynamic model such as GREEN, calibration also requires that any other exogenous constraint on the transition path from the base-year to the end-year equilibria be satisfied. Therefore, dynamic calibration results depend not only on the benchmark data set but also on the values of exogenous variables along the transition path.

In GREEN, the exogenous variables are: (i) the real world prices of backstop products ($\bar{P}^B$); (ii) the production targets for crude oil and natural gas in each region and in specific periods; (iii) real output and population growth in each region; and (iv) Harrod-neutral energy-augmenting technical progress in each sector i and region r (λ^E_{ir}) -- the so-called "autonomous energy efficiency improvement" (AEEI). Given these exogenous variables, a sequence of temporary equilibria is computed from 1985 to 2050, under two crucial assumptions: (i) the economy was in equilibrium in 1985; and (ii) the growth path from 1985 to 2050 is balanced, i.e. along the path the capital-labour ratio remains constant in efficiency units. Other assumptions relate to the closure of the model. These concern in each region (i) government real expenditures, which are assumed to grow at the same rate as aggregate output; (ii) the government budget, which is assumed to be fixed in real terms at its benchmark-year value; and (iii) the current account, which is assumed to be fixed at its benchmark-year value in terms of the *numéraire* of the model.

These assumptions make it possible to compute values for the following "static" calibration parameters:

(a) the CES distribution parameters associated with the choices of firms (α^{jO}_{si}, α^{jN}_{si}, α^{D}_{si}, α^{I}_{si}), consumers (α^{j}_{siH}, α^{D}_{sH}, α^{I}_{sH}), government (α^{j}_{G}, α^{j}_{sG}, α^{D}_{G}, α^{I}_{G}) and with the Armington specification of international trade (α_{ir}^{jWT}), the production of the investment good (α_{sI}^{j}, α_{I}^{D}, α_{I}^{I}) and stockbuilding (α_{ST}^{j}, α_{ST}^{D}, α_{ST}^{I})[77];

(b) the subsistence quantities of the consumer goods (γ_i) and the aggregate marginal propensity to consume (μ);

(c) the constant intercept of the income-tax schedule (ν) and the *ad valorem* tax rates on domestic and imported *non-energy* intermediate goods (τ_i^D, τ_i^I);

(d) the constant terms in the fixed-factor supply functions (Φ_f);

as well as for the following "dynamic" calibration parameters:

(e) the price elasticities of the depletion rate or the level of yet-to-find reserves (ω_f and υ_f, respectively) for crude oil and natural gas and their associated constant terms (Ω_f and Υ_f, respectively) as well as the conversion rates themselves (d_f).

(f) the rates of Harrod-neutral technical progress affecting labour and the capital/fixed factor bundle in each sector (λ_i^L and λ_i, respectively).

The calibration of the resource depletion sub-model requires some discussion, since the procedure involves several steps. The procedure is based on equation (60) of Section III. Each regional sub-model is calibrated in order to reproduce some plausible production targets for crude oil and natural gas in a reference oil price scenario, $\overline{P}_{ref}^{CO}$. This ensures that the production paths for fossil fuels are consistent with medium-term projections supplied by energy experts or by simulation models that concentrate only on the energy sector. In the current version of GREEN, these projections are drawn from several sources, including International Energy Agency (IEA) forecasts for the year 2005.

Given the level of potential production for fuel i projected in period t in the reference price scenario ($Q_{i,t}^{ref}$), the level of reserves implied by this production target ($RES_{i,t}^{ref}$) is given by equation (57) of Section III. Therefore, in principle, it is possible to derive the reference value of the conversion rate d_i^{ref} by solving equation (60) with respect to d_i[78]. Denoting by $RES_{i,0}$ base-year reserves of fuel i, the equation can be rearranged to yield:

$$d_i = \frac{(RES_{i,t}^{ref}/RES_{i,0}) - (1-r_i)^t}{L(d_i;r_i,t)} \cdot \Pi_{i,0} \tag{63}$$

The conversion rate can be derived as the fixed point of equation (63) in the range [0,1]. Given the high degree of the polynomial in d_i, the solution must be found by numerical methods and the equation can have multiple real or complex roots. Fortunately, in most of the cases the equation yielded a unique real solution in the admissible range[79].

Once the depletion path is calibrated to a reference price scenario, the second step consists in deriving the elasticities of d_i and $YTFR_i$ to the oil price. To this end, two price scenarios were provided by the IEA: (i) a low-price scenario $\overline{P}^{CO}_{low}$, in which the real world price of crude oil is fixed at its 1990 level ($19 per barrel) throughout the period; and (ii) a high-price scenario $\overline{P}^{CO}_{high}$, in which the oil price rises to $32 per barrel by 2000 and then remains constant until 2020. In each region, production targets corresponding to the low- and high-price scenarios ($Q^{low}_{i,t}$ and $Q^{high}_{i,t}$, respectively) are provided[80]. Using the same procedure described above, equation (53) can be used to find values for the rate of conversion in the low- and high-price scenarios (d^{low}_i and d^{high}_i, respectively). Downward price elasticities can then be calculated numerically as follows:

$$\omega^d_i = \frac{Log\, d^{low}_i - Log\, d^{ref}_i}{Log\,\overline{P}^{CO}_{low} - Log\,\overline{P}^{CO}_{ref}} \qquad (64)$$

Similarly, upward elasticities can be calculated using d^{high}_i and $\overline{P}^{CO}_{high}$ in the above equation. Alternatively, the elasticities of $YTFR_i$ to oil prices can be derived by fixing coefficients d_i at their values in the reference price scenario and solving equation (63) with respect to $YTFR_i$. Assuming that the initial estimate $YTFR_{i,0}$ corresponds to the reference price scenario, the values of the yet-to-find reserves implied by the production targets corresponding to the low- and high-price scenarios can be used to derive upward and downward oil-price elasticities of $YTFR_i$ (υ_i)[81].

Table 19 reports the values of the exogenous variables. Growth rates of real GDP by region reflect the assumptions of the Energy Modeling Forum (EMF12) exercise. AEEI is assumed to be equal to 1 per cent in all periods and in all regions. This extreme simplifying assumption reflects the large range of uncertainty surrounding this key exogenous variable. It is, however, very close to the AEEI values assumed in the latest IPCC scenario. Therefore, figures in Table 19 must be taken as benchmark values reflecting a state of ignorance, although their choice does follow the conventional wisdom in energy forecasting that the energy/output ratio is expected to decline by 1 per cent a year.

Exogenous variables can have the same crucial influence on the simulation results as some of the key parameters described in the previous Section. In particular, the AEEI plays a key role in any analysis of the CO_2 issue, since *ceteris paribus* the higher is its value the lower is the growth of emissions[82]. Similarly, an important role can be played by GDP and population growth rates, which affect the growth of energy demand.

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2. In GREEN, capital is a "produced" good. However, there is no explicit capital-producing sector since the capital good is a bundle of intermediate goods and services only.

3. Fossil and non-fossil fixed factors correspond to available resources of coal, natural gas, crude oil and the carbon-free energy source, which includes hydroelectric and nuclear power. These are *primary* factors, which earn the rents associated with their scarcity. It is assumed, for simplicity, that these rents are identical to the operating surpluses of the corresponding sectors.

4. In GREEN, labour and capital are not tradeable and their supply is limited and uneven across regions. Therefore the price of backstop products would tend to differ internationally. Since a unique exogeneous world price for each backstop product is imposed, the rents associated to the scarcity of these two primary factors are redistributed in each region to domestic consumers.

5. In practice, it is assumed in the model that all countries/regions supply oil at potential except the energy-exporting LDCs.

6. Production technology has a nested CES structure, which implies separability among subsets of different input bundles.

7. Capital is assumed to be perfectly mobile after 2010, when the step length of simulations increases from five to twenty years.

8. A similar approach to the treatment of adjustment costs in an AGE model was used by Fullerton (1983).

9. Alternatively, the oil price can be assumed to be exogeneous over the simulation period.

10. In making this choice, consumers face the same range of conventional and backstop energy products as firms.

11. This *atemporal* specification of consumer behaviour makes it impossible in the current version of the model to compute changes in intertemporal welfare implied by policies aimed at curbing the level of CO_2 emissions. Welfare comparisons can only be performed using static welfare indicators such as changes in household real income -- the so-called "Hicksian equivalent variation". These can be cumulated over time using an *ad hoc* rate of time preference.

12. The demand model derives from the Extended Linear Expenditure System (ELES), first proposed by Lluch (1973). The version of the ELES embodied in GREEN is atemporal [Howe (1975)]. In this formulation, the marginal propensity to save out of supernumerary income is constant and independent of the rate of reproduction of capital.

13. These issues are discussed in Whalley and Wigle (1991).

14. Since no separate carbon-free electric sector is distinguished in GREEN, the tax is applied at the level of the fixed factor in the electricity sector.

15. It is also possible in principle to implement *inter-regional* agreements. In this case, trade in permits only occurs between the regions participating in the agreement and a single carbon tax is computed for these regions.

16. Natural gas and coal are assumed to be heterogeneous goods due to transportation costs. These costs are typically much higher for natural gas and coal than for crude oil.

17. The real world price of oil is computed with respect to a weighted average of real exchange rates in the four OECD regions. On the other hand, in each country/region, the real exchange rate is defined as the ratio of a weighted average of domestic primary factor prices to the *numéraire* of the model, which is the price of labour in the United States.

18. These assumptions imply that imbalances in the government budget and in international trade as ratios to national GDPs converge to zero in the long-run, due to GDP growth.

19. Static expectations are typically inconsistent with actual economic outcomes over time. Therefore, future events -- such as pre-announced carbon taxes or depletion of exhaustible resources -- do not have any influence on agents' decisions and market outcomes, until they actually occur. The leading alternative expectational hypothesis is perfect foresight. However, in practice, no software currently exists which is capable of solving a large multi-sector, multi-region dynamic AGE model such as GREEN under the hypothesis of perfect foresight. This technical issue is discussed in Shoven and Pereira (1988).

20. As in most other dynamic AGE models, convergence to a balanced growth path is not guaranteed, but can be imposed through a suitable calibration of the parameters of the model. The resulting path is not necessarily unique, since there may be several ways to calibrate the model in order to ensure convergence.

21. The number of rental values for old capital goods is equal to the number of contracting sectors.

22. The model assumes a constant capital/labour ratio (in efficiency units) over the simulation period.

23. The following notational conventions are adopted in this section. Conventional production sectors are indexed i = 1,...,8 and backstop production sectors are indexed $m = b_1, b_2, b_3$, in the same order as in Table 1. Consumer goods are indexed i = 1,...,4, in the same order as in Table 2. Matrices and vectors are indicated by square brackets containing their generic element, e.g. if A is a (n x p) matrix, it will be denoted $A = [a_{ij}]$. Endogenous variables and exogenous variables or parameters are separated by a semicolon as arguments of functions, e.g. if y depends on k endogenous variables $x_1,...,x_k$ and s parameters and/or exogenous variables $z_1,...,z_s$, the corresponding function is denoted $y = f(x_1,...,x_k; z_1,...z_s)$.

24. In practice, given capital inputs K_i, K_j and their rental rates r_i, r_j in two sectors i and j ($i \neq j$), their observed base-year ratio in value terms is assumed to be equal to the ratio of their adjusted magnitudes K_i^* and K_j^*, whose values are computed at the fictitious rentals $r_i^* = r_j^* = 1$. This yields the following relationship between factor efficiencies and observed factor prices:

$$\frac{(K_i^*/K_i)}{(K_j^*/K_j)} = \frac{r_i}{r_j}$$

25. As will be explained below, the carbon tax can be interpreted as the "shadow price" of CO_2 emissions. The carbon tax and the energy tax can be combined in an energy *cum* carbon tax. In this case a weighted average of the two taxes -- with exogenous weights -- is determined in equilibrium.

26. The real world price of crude oil is defined as the price of oil deflated by a weighted average of real exchange rates in the OECD area. The real world prices of the backstop products are defined as the prices of backstops deflated by a weighted average of world real exchange rates.

27. Explicit account of tariffs, taxes and subsidies on energy inputs makes it possible to simulate changes in the fiscal structure aimed at removing existing distortions in relative energy prices.

28. In practice, there are no fuel-specific taxes on the carbon-free sources of energy in the model. In addition, τ^{FU} on imported and domestic fuels is not identical, since the tax on imported fuels is adjusted in order to neutralise the indirect effects of the carbon tax on domestic intermediate costs. The tax rate on domestic fuels is not applied on own-consumption of fossil fuel i in fossil-fuel sector i.

29. The real exchange rate, RE, is defined in any region as the ratio of a weighted average of primary factor prices to the *numéraire*.

30. For the expression of the dual-cost of a CES production function, see Varian (1978).

31. Note that technical progress is associated with only one of the inputs at each stage of the production process. In addition, it is defined with respect to a balanced-growth path. Therefore, it is neutral in the sense of Harrod.

32. Backstop products are also homogeneous, but no incentives to trade exist for these goods, since they are assumed to be available in unlimited quantities at the same price in all countries.

33. Given the homogeneity of oil across countries of origin, the input-output coefficients for oil are determined assuming that countries cannot import and export oil at the same time. Denoting total imports and exports of oil by M_3 and EX_3, in any sector the input of domestic and imported oil per unit of output is, respectively:

$$fu_3^D = \frac{Q_3 - EX_3}{Q_3 - (EX_3 - M_3)}$$

$$fu_3^I = \frac{M_3}{Q_3 - (EX_3 - M_3)}$$

with $EX_3 = 0$ if $EX_3 - M_3 < 0$ and $M_3 = 0$ if $EX_3 - M_3 > 0$.

34. In the case of crude oil, rents above the normal remuneration of the fixed factor are generated by the assumption that non-OPEC countries always produce oil at potential. Therefore, domestic marginal production costs and the world price are not necessarily equal. In the case of backstop products, whose world price is exogenous, rents derive from international differences in the cost of labour and capital, which are assumed to be immobile across countries.

35. The ELES was first proposed by Lluch (1973). Both Cobb-Douglas and CES demand systems impose unit income elasticities across goods. Other demand models, such as the translog or AIDS, are more flexible than the ELES but are difficult to implement in AGE models.

36. Point expectations are expectations held with certainty. A single rate of return on real and financial assets can be defined only subject to the assumption of perfect capital markets.

37. See Howe (1975).

38. Since subsistence quantities are defined in *per capita* terms, the saving rate is constant as long as income grows at the same rate as population and prices are given

39. In GREEN, the model is calibrated on a constant marginal propensity to consume. The price of saving is defined as a weighted average of the prices of consumer goods. An alternative way to proceed would be to let the rate of return on assets be variable over time and equal to a weighted average of the rentals on real assets. Consumer choice would then be truly intertemporal, with the model being calibrated on a constant rate of time preference and the marginal propensity to consume depending on the rate of return on assets.

40. See Annex III for a table of energy conversion factors.

41. In each region, imports of refined oil products are part of the total demand for primary fossil fuels.

42. Domestic absorption is the appropriate variable, given the assumption that the carbon tax is imposed on fossil-fuel consumption only. Note that the definition of after-tax fuel prices of Section III.A. implies that the *ad valorem* fuel-specific tax rate will be lower the higher are the value-added tax rates applied to intermediate goods before the imposition of the carbon tax.

43. The energy content of the carbon-free fixed factor is assumed to be proportional to the energy content of the production of the electricity sector, with a proportionality factor given by the share of the fixed factor in total energy inputs of the electricity sector adjusted by a calibration parameter Λ:

$$F_6^{TJ} = \left(\frac{F_6}{F_6 + \sum_{j=2,\ldots,5} FU_{j6}} + \Lambda \right) \cdot \phi_6 \cdot Q_6$$

The parameter Λ is calibrated in the benchmark year using the observed share of nuclear, hydroelectric and other carbon-free energy sources in total energy production of the electricity sector. The quantities F_6 and FU_{j6} are adjusted dynamically in order to take into account the differential rates of technical progress attached to fossil-fuels and the capital/fixed factor bundle.

44. It is assumed that the government does not "consume" any fixed factor.

45. Depreciation must be added since personal saving is computed from disposable income as defined in sub-section III.C.(i), which is net of depreciation of capital.

46. For backstop products, whose prices are exogenous, equation (52) determines output.

47. When simulations concern a carbon *cum* energy tax, the constraint (53) determines an average tax, which is decomposed into carbon and energy taxes using fixed exogenous weights.

48. However, the economic meaning of a *fixed* stock of a non-renewable resource may be questioned (see Adelman, 1990).

49. This coefficient is also called the "resource depletion factor" in the literature, e.g. Manne and Richels (1990).

50. These prices are normalised to unity both in the baseline and alternative scenarios.

51. The expressions for the indirect utility and expenditure functions for ELES preferences can be found, for example, in Theil (1980).

52. The only admissible utility of saving in an intertemporal measure of welfare is that deriving from last period's saving.

53. Normalising by total income implies that growth in income and population assign progressively larger weights on welfare losses distant in the future. This effect is partly compensated by discounting of the future by the households. A discount rate of 1.5 percent was chosen, following Auerbach and Kotlikoff (1987).

54. See Burniaux *et al.* (1990) for a discussion of the comparative advantages of this algorithm in solving large non-linear models and for a detailed discussion of static equilibrium determination.

55. The criterion used assigned a country to this region whenever its net exports of at least one of the primary energy resources were positive over a sufficiently long period of time. The classification in Table 4 is based on data for the 1983-86 period from *Energy Statistics Yearbook*, 1986, United Nations (Table 2, p. 30).

56. I-O tables for the former Soviet Union and China are based on domestic price structures that can be expected to involve large distortions, especially in energy sectors.

57. This adjustment process is operated by a RAS subroutine.

58. An additional problem was created by an apparent anomaly in the I-O table for the former Soviet Union, which reported abnormally high own-consumption of crude oil in the crude oil sector, probably due to Soviet accounting conventions. Since this induced convergence problems, it was decided to adjust the I-O table in order to reallocate this item to other sectors.

59. As a result, total fuel and power use exceeds the corresponding figure from the National Accounts. The excess was reallocated automatically to the "other industries and services" sector by the RAS sub-routine.

60. The closest analog to a CES elasticity in a translog framework is the so-called Morishima elasticity. However, the Morishima elasticity is not symmetric. For a discussion of the various elasticity measures and their comparative advantages, see Blackorby and Russell (1989).

61. Given the production technology $Y = f(X_1,...,X_n)$, with factor prices $W_1,...,W_n$ and factor shares $S_i = X_iW_i/Y$, (unweighted) cross elasticities are defined as:

$$\eta_{ij} = \frac{\partial \ln X_i}{\partial \ln W_j} = S_j \cdot \sigma_{ij}$$

where σ_{ij} is the Allen elasticity of the input share i to the price of input j. Therefore, Allen elasticities can be inferred from cross elasticities, even if the input shares are unknown using the following relationship:

$$\sigma_{ij} = \eta_{ij}(1 + \sum_{i \neq j} \frac{\eta_{ji}}{\eta_{ij}}) \qquad \forall\ i \neq j$$

62. In some cases, complementarity can result from the inclusion of non-production workers in the data [see Turnovsky *et al.* (1982)]. The results of Hesse and Tarka (1986) suggest that substitutability may depend on the definition of the energy aggregate and that it may have declined in more recent years.

63. See, for instance, the discussion on energy prices and productivity growth by Berndt & Wood (1987).

64. See, for instance, Norsworthy & Harper (1981) and Berndt, Morrison & Watkins (1981). Hogan (1989) suggests that these results are due to weaknesses in model specification.

65. A distinctive feature of this literature is that t-statistics associated with elasticities are seldom reported. When they are, lack of significance seems pervasive.

66. In the Spring 1991 version of GREEN, capital and energy were assumed to be complementary throughout the simulation period.

67. The possibility of short-run complementarity and long-run substitutability between capital and energy is a property of the nesting hierarchy of GREEN in conjunction with the putty/semi-putty technology. Given the CES elasticities between labour and the capital/energy/fixed factor bundle (ρ_1) and between energy and the capital/fixed factor bundle (ρ_2), the Allen partial elasticiy of substitution between capital and energy is (Sato, 1967):

$$\sigma_{KE} = \rho_1 + \frac{(\rho_2 - \rho_1)}{S_{KE}}$$

where S_{KE} is the share of the capital/energy bundle in total output. For reasonable values of this share and appropriate values of the elasticities of substitution at each of the nesting levels, both complementarity and substitutability between capital and energy can be obtained. This flexibility is lost with alternative nesting hierarchies, such as for instance in the Global 2100 model of Manne and Richels (1990).

68. Unfortunately, these authors report only cross elasticities between natural gas and other energy inputs, making it impossible to derive Allen elasticities comparable to those in Table 11.

69. For instance, estimates of negative elasticities probably reflect the lack of dual- or multiple-fire capabilities, rather than complementarity between energy inputs.

70. Furthermore, given the assumed CES technology, it might be desirable to incorporate additional nesting levels in the production structure of GREEN, in order to account for the possible lower substitutability between subsets of the energy inputs -- such as gas and coal.

71. See Brown and Philips (1989), Hogan (1988) and Jorgenson and Wilcoxen (1989) for the first type of results, and Hogan and Jorgenson (1990) for negative estimates of the AEEI over the 1958-79 period.

72. Whalley and Wigle (1991), Manne and Richels (1990) and Bergman (1988) are the only authors who report the results of sensitivity analyses.

73. Estimates of supply elasticities usually concern the OPEC countries and focus on the strategic supply response over relatively short periods of time [Kouris (1981), Pindyck (1979)]. Therefore, they provide little guidance for parameter values for use in long-run models.

74. Depreciation rates were kept constant at base-year levels computed from OECD *National Accounts Statistics*.

75. On the lack of empirical estimates of energy supply elasticities, see also Whalley and Wigle (1991).

76. Data for the computation of these parameters was drawn from Masters, Root and Attanasi (1990).

77. No base-year values were available for the distribution parameters of the CES nest corresponding to the choice between conventional and backstop energy sources, since these will exploited only in the future. Therefore, an arbitrary value of 0.3 was imposed in the calibration procedure.

78. In the Energy-Exporting LDCs a conversion rate of 0.1 was imposed in order to match a reasonable production profile. Furthermore, the extraction rate was adjusted downwards in order to account for the fact that oil production in this region was below potential supply in the base year.

79. In a few cases, the equation admitted two solutions; in these cases the implausible values, e.g. too high or too low values of d_i, were dropped. In other cases, it was necessary to modify one calibration parameter in order to find a unique solution. The adjustment was mainly made via the parameter r_i, but an alternative solution would be to modify the initial estimate of $YTFR_i$.

80. No low and high-price scenarios were available for the CEECs, the DAEs, Brazil, India and RoW. Upward and downward elasticites of 0.1 were imposed in these regions.

81. In the current version of the model yet-to-find reserves are assumed to be at the upper bound of their uncertainty range and the resource sub-model is calibrated on the conversion rate d.

82. For instance Manne and Richels (1990) argue, on the basis of sensitivity analyses of their model, that a reduction of the AEEI from 1 to 0 per cent per annum would double energy demand by the year 2050.

References

ADELMAN, M.A. (1990), "Mineral depletion, with special reference to petroleum", *Review of Economics and Statistics* (February), pp. 1-10.

AUERBACH, A.J., AND L.J. KOTLIKOFF (1987), *Dynamic Fiscal Policy*, Cambridge University Press, Cambridge.

BALLARD, C.L., D. FULLERTON, J.B. SHOVEN AND J. WHALLEY (1985), *A General Equilibrium Model for Tax Policy Evaluation*, The University of Chicago Press, Chicago and London.

BELTRAMO, M.A. (1989), "Modelling fuel-switching between natural gas and fuel oil in US manufacturing", *Energy Economics* (January), pp. 70-78.

BERGMAN, L. (1988), "Energy policy modelling: a survey of general equilibrium approaches", *Journal of Policy Modelling*, Vol. 10, No. 3.

BERNDT, E.R. and D.M. HESSE (1986), "Measuring and assessing capacity utilization in the manufacturing sectors of nine OECD countries", *European Economic Review*, 30, pp. 961-989.

BERNDT, E.R., C.J. MORRISON and G. CAMPBELL WATKINS (1981), "Dynamic models of energy demand: an assessment and comparison", in *Modeling and Measuring Natural Resource Substitution*, E.R. Berndt and B.C. Field (eds), the MIT Press, Cambridge, Massachusetts, pp. 259-289.

BERNDT, E.R. and D.O. WOOD (1987), "Energy price shocks and productivity growth: a survey", *Energy Markets and Regulation: Essays in Honor of M.A. Adelman et al.*, The MIT Press, pp. 305-342.

BLACKORBY, C. and R.R. RUSSELL (1989), "Will the real elasticity of substitution please stand up? (A comparison of the Allen/Uzawa and Morishima elasticities)", *American Economic Review*, Vol. 79, No. 4, pp. 882-888.

BLITZER, C., R.S. ECKAUS, S. LAHIRI and A. MEERAUS (1990), "A general equilibrium analysis of the effects of carbon emission restrictions on economic growth in a developing country", mimeo (January).

BROWN, S.P.A. and K.R. PHILIPS (1989), "An econometric analysis of U.S. oil demand", Federal Reserve Bank of Dallas (January).

BULATAO, R.A., E. BOS, P.W.S. STEPHENS AND M.T. VU (1990), *World Bank Population Projections 1989-90 Edition*, Johns Hopkins University Press.

BURNIAUX, J.M., F. DELORME, I. LIENERT and J.P. MARTIN (1989-1990), "WALRAS -- A multi-sector, multi-country applied general equilibrium model for quantifying the economy-wide effects of agricultural policies", *OECD Economic Studies*, No. 13 (Winter), pp. 69-102.

BURNIAUX, J.M., J.P. MARTIN, G. NICOLETTI and J. OLIVEIRA MARTINS (1991), "The costs of policies to reduce global emissions of CO_2: initial simulation results with GREEN", *OECD Department of Economics and Statistics, Working Papers*, No. 103, (June).

CARRÈRE, M.A. and J.-G. DEVEZEAUX DE LAVERGNE (1988), "Les effets des prix énergétiques sur les comportements d'investissement à long terme : une comparaison des sept grands pays de l'OCDE", *Recherches Économiques de Louvain* 54 (3), pp. 337-364.

Central Statistics Office (1988), *Census of Industrial Production 1985*, Dublin.

CHELEM, Banque de données du CEPII (1988), Document de travail no 88-14, Centre d'Etudes Prospectives et d'Informations Internationales, Paris, (décembre).

CHUNG, J.W. (1987), "On the estimation of factor substitution in the translog model", *Review of Economics and Statistics*, Vol. LXIX, No. 3 (August), pp. 409-417.

CONSIDINE, T.J. (1989), "Separability, functional form and regulatory policy in models of interfuel substitution", *Energy Economics*, Vol. 11, No. 2.

CONSIDINE, T.J. (1990), "Estimating the demand for energy and natural resource inputs: trade-offs in global properties", *Applied Economics*, 21, 7, pp. 931-945.

DELORME, F. and J. LESTER (1986), "The structure of production in ten Canadian industries", *Working Paper No. 86-1*, Department of Finance, Canada.

EDMONDS, J.A., J.M. REILLY, R.H. GARDNER and A.L. BRENERT (1987), "Uncertainty analysis of the IEA/ORAU CO_2 emissions model", *The Energy Journal*, Vol. 8, No. 3.

EDMONDS, J.A., and BARNS (1990), "Estimating the marginal cost of reducing global fossil fuel CO_2 emissions", mimeo, Pacific Northwest Laboratory, Washington, D.C.

ESTRADA, J. and O. FUGLEBERG (1989), "Price elasticities of natural gas demand in France and West Germany", *The Energy Journal*, Vol. 10, No. 3 (July).

FAO (1990), *Yearbook 1988*, Vol. 42 & 67, Rome.

FIELD, B.C. and C. GREBENSTEIN (1980), "Capital-energy substitution in U.S. manufacturing", *Review of Economics and Statistics*, Vol. LXII, No. 2 (May), pp. 207-212.

FULLERTON, D. (1983), "Transition losses of partially mobile industry-specific capital", *Quarterly Journal of Economics* (February), pp. 107-125.

FUSS, M.A. (1977), "The demand for energy in Canadian manufacturing", *Journal of Econometrics*, 5, pp. 89-116.

GRIFFIN, J.M. (1977), "Inter-fuel substitution possibilities: a translog application to intercountry data", *International Economic Review*, Vol. 18, No. 3 (October), pp. 755-770.

GRIFFIN, J.M. (1981), "The energy-capital complementarity controversy: a progress report on reconciliation attempts", in *Modeling and Measuring Natural Resource Substitution*, E.R. Berndt and B.C. Field (eds.), The MIT Press, Cambridge, Massachusetts, pp. 70-80.

HALL, V.B. (1986), "Industrial sector fuel price elasticities following the first and second major oil price shocks", *Economic Letters*, 20, pp. 79-82.

HESSE, D.M. and H. TARKKA (1986), "The demand for capital, labor and energy in European manufacturing industry before and after the oil price shocks", *Scandinavian Journal of Economics*, Vol. 88, No. 3, pp. 529-546.

HOGAN, W.M. (1989), "A dynamic putty-semi-putty model of aggregate energy demand", *Energy Economics* (January), pp. 53-69.

HOGAN, W.M. and D.W. JORGENSON (1990), "Productivity trends and the cost of reducing CO_2 emissions", Harvard University (January).

HOWE, H. (1975), "Development of the extended linear expenditure system from simple saving assumptions", *European Economic Review*, Vol. 6, pp. 305-310.

ILMAKUNNAS, P. and H. TÖRMÄ (1989), "Structural change in factor substitution in Finnish manufacturing", *Scandinavian Journal of Economics*, Vol. 91, No. 4, pp. 705-721.

International Energy Agency (1987), *OECD Energy Statistics 1970-1985*, Paris.

International Energy Agency (1989), *World Energy Statistics and Balances 1971-1987*, Paris.

International Monetary Fund (1989), *International Financial Statistics Yearbook 1989*.

JARRETT, P. and R. TORRES (1987), "A revised supply block for the major seven countries in INTERLINK", *OECD Department of Economics and Statistics Working Papers*, No. 41 (April).

JORGENSON, D.W. and P.J. WILCOXEN (1989), "Environmental regulation and U.S. economic growth", Harvard Institute of Economic Research (July).

LLUCH, C. (1973), "The extended linear expenditure system", *European Economic Review*, Vol. 4, pp. 21-32.

MANNE, A.S. and R.G. RICHELS (1990*a*), "CO_2 emission limits, an economic cost analysis for the USA", *The Energy Journal* (January).

MANNE, A.S. and R.G. RICHELS (1990b), "Global CO_2 emission reductions, the impact or rising energy costs", mimeo (February).

MANNE, A.S. and R.G. RICHELS (1990*c*), "Global 2100: model formulation", Stanford University (November), mimeo.

MASTERS, C.D., D.H. ROOT and E.D. ATTANASI (1990), "World oil and gas production -- future production realities", *Annual Review of Energy*, Vol. 15, pp. 23-51.

MINTZER, I.M. (1987), "A matter of degrees: the potential for controlling the greenhouse effect", World Resources Institute, Research Report 5 (April).

NORDHAUS, W.D. (1979), "The efficient use of energy resources", Cowles Foundation Monograph 26, Yale University Press.

NORDHAUS, W.D. and G.W. YOHE (1983), "Future paths of energy and carbon dioxide emissions" in *Changing Climate: Report on the Carbon Dioxide Assessment Committee*, Washington, National Academy Press, pp. 87-185.

NORSWORTHY, J.R. and M.I. HARPER (1981), "Dynamic models of enerrgy substitution in U.S. manufacturing", in *Modeling and Measuring Natural Resource Substitution*, E.R. Berndt and B.C. Field (eds), the MIT Press, Cambridge, Massachusetts, pp. 177-208.

OECD (1987), *Foreign Trade by Commodities 1985*, C Series, Vol. 1 & 2, Paris.

OECD (1990), *National Accounts, Detailed Tables 1976-1988*, Paris.

PEREIRA, A. and SHOVEN, J. (1988), "Survey of dynamic general equilibrium models for tax policy evaluation", *Journal of Policy Modelling*, 10, pp. 401-436.

PINDYCK, R.S. (1979), "Interfuel substitution and the industrial demand for energy: an international comparison", *The Review of Economics and Statistics*, pp. 169-179.

SATO, K. (1967), "A two-level constant-elasticity-of-substitution production function", *The Review of Economic Studies*, 34, pp.201-218.

SULLIVAN, B. and D. SIEMON (1981), "Interfuel substitution -- upper bound estimates", *The Energy Journal*, Vol. 2, No. 2 (April), pp. 107-118.

THEIL, H. (1980), *The System-Wide Approach to Microeconomics*, The University of Chicago Press, Chicago.

TORRES, R., P. JARRETT and W. SUYKER (1989), "Modelling business sector supply for the smaller OECD countries", *OECD Economics and Statistics Department Working Papers*, No. 71 (October).

TURNOVSKY, M., M. FOLIE and A. ULPH (1982), "Factor substitutability in Australian manufacturing with emphasis on energy inputs", *The Economic Record* (March), pp. 61-72.

United Nations (1989), *Industrial Statistics Yearbook 1987*, Vol. 1, New York.

United Nations (1989), *International Trade Statistics Yearbook 1987*, Vol. 1 & 2, New York.

United Nations (1989), *Statistical Yearbook for Asia and the Pacific 1989*, Bangkok.

United Nations (1990), *National Accounts Statistics 1987*, New York.

United Nations (1990), *Energy Statistics Yearbook 1988*, New York.

UNCTAD (1989), *Commodity Yearbook 1989*, New York.

UNCTAD (1990), *Handbook of International Trade and Development Statistics 1989*, New York.

VARIAN, H.R. (1978), *Microeconomic Analysis*, Norton, New York.

WHALLEY, J. and R. WIGLE (1989), "Cutting CO_2 emissions: the effect of alternative policy approaches", paper presented to NBER conference on Applied General Equilibrium Modelling, San Diego (September).

WHALLEY, J. and R. WIGLE (1991), "The international incidence of carbon taxes", in R. Dornbusch and J.M. Poterba (eds.), *Global Warming: Economic Policy Responses*, Cambridge, Massachussetts, MIT Press

ANNEX I:

- Sources for countries with available Input-Output tables :

Australia : Australian Bureau of Statistics. 1983-84 Australian National Accounts. Input-Output Tables. Canberra, 1989.

Canada : Statistics Canada. Canada Year Book 1985. Ottawa, 1988.

Denmark : Danmarks Statistik. Input-output tabeller og analyser, 1985. Copenhagen 1989.

Finland : Central Statistical Office of Finland. National Accounts. Panos-Tuotos (Input-Output Tables) 1985. Helsinki, 1988.

France : INSEE. "Tableau des Entrées-Sorties 1985." Paris, 1989.

Germany : Statistisches Bundesamt. Volkswirtschaftliche Gesamtrechnungen. Reihe 2: Input-Output-Tabellen 1984. Wiesbaden, 1988.

Japan : Research and Statistics Department, Ministry of International Trade and Industry. 1985 Input-Output Tables. Tokyo, 1987.

Netherlands : C.B.S. Nationale Rekeningen. Input-Output Table for the Dutch Economy 1985. The Hague, 1987.

Norway : "WMAT Selgerverdi 1985." Supplied to the Secretariat by the national authorities.

Spain : Instituto Nacional de Estadística. Contabilidad Nacional de España. Cuentas Nacionales y Tabla Input-Output. Madrid, 1990.

U. K. : "The Use Matrix - Commodity Analysis of Purchases by Industry from Domestic Production in 1984."

U.S.A. : U.S. Department of Commerce / Bureau of Economic Analysis. "Survey of Current Business." Washington D.C. January 1990.

China, P.R. : National Centre for Development Studies. Research School of Pacific Studies. The Australian National University. "Modelling the Post-Reform Chinese Economy." Will Martin. Canberra, 1990.

U.S.S.R. : "L'Economie Soviétique en Libre-Echange, les Conditions Initiales du redéploiement économique." Gérard Duchêne et Claudia Senik-Leygonie. Contribution au colloque international "Les relations entre la Communauté européenne et l'Europe de l'Est." Université Bordeaux-1. 4-6 October 1990.

India : Central Statistics Organisation, Department of Statistics, Indian Ministry of Planning. Input-Output Transactions Table 1983-1984. New Delhi, 1990.

Bulgaria and Czechoslovakia: World Bank data.

Hungary : National Planning Office. Input-Output Matrix 1989.

Poland : Commission of the European Communities - European Economy: Competitiveness and industrial restructuring in Czechoslovakia, Hungary and Poland by G. Hughes and P. Hare. 1991.

Romania : National Commission for Statistics. Statistical Yearbook of Romania 1990: Balanta legaturilor dintre ramuri, 1989

Yugoslavia : Savezni zavod za statistiku. Statistical Yearbook of Yugoslavia 1990: Proizvodnja I Raspodela Po Delatnostima, 1988. Beograd, 1990.

USSR and Eastern Europe : Vienna Institute for Comparative Economic Studies. COMECON data 1989. Vienna, 1990.

Brazil : Fundação instituto brasileiro de geografia e estatistica. Matriz de insumo-produto Brasil - 1980. Rio de Janeiro, 1989.

Korea, R. of : 1986 input-output tables (65 sectors).

Taiwan : Statistical Yearbook of the Republic of China, 1986: 1984 input-output table.

Chile : Matriz de Insumo Producto para la Economia Chilena 1986.

Morocco : Matrice de Comptabilité sociale, Maroc 1985.

Annex II

The "Minimum Information Procedure": The Case of Nigeria (1983)

Nigeria has been chosen to illustrate the case of a country for which data sources are very sparse. No National Accounts for Nigeria are available after 1983; therefore, the "minimum information procedure" has been used to estimate a 1983 I-O table. In addition, data from the UN Industrial Statistics are missing. A short description of the method used to produce a Nigerian data set is as follows:

-- **Agriculture**: primary factors are estimated from National Accounts figures and corresponding information from the data base for Libya and Cameroon.

-- **Crude oil and natural gas**: estimates based on world prices (see Table 6) yield a $13.2 billion value of crude oil output and a $0.5 billion value of natural gas output. The corresponding estimate of the total value of crude oil and natural gas based on the National Accounts is $16.2 billion. Given export values obtained from trade statistics, these figures would imply an upward domestic/world price bias of 18 per cent. In the absence of any better information, it was decided to assume an upward bias between domestic and world prices of 10 per cent only, which implies that our estimate of the total output value for crude oil and natural gas is 13.5 per cent lower than the corresponding estimate based on National Accounts.

-- **Refined oil**: the output value is obtained by i) assuming that all the crude oil which is not directly exported is used by refineries (therefore, there is no other intermediate or final use of crude oil); and ii) estimating the value of refined oil output by applying a fixed technical coefficient (drawn from the U.S. I-O table) to this intermediate use of crude oil.

-- **Electricity**: value added comes from National Accounts and the output value is estimated by applying the U.S. production structure to energy inputs estimated from the IEA data.

-- **Energy-intensive industries**: value added and output data are usually provided by the UN Industrial Statistics. Since, in the case of Nigeria, these data are missing, they are estimated by applying the same energy input coefficient of countries where this information is available to the energy input figures estimated from the IEA balance sheets.

-- **Household consumption**: values of household consumption demands for the four consumer goods are obtained combining National Accounts data and the consumption shares reported for 1980 in "World Comparisons of Purchasing Power and Real Product for 1980", United Nations, Eurostat, 1987.

-- **Energy uses**: they are derived from the structure of uses estimated in note [16] of the following table on the basis of the IEA Abbreviated Energy Balances.

In countries for which UN Industrial Statistics are available, these data can be used to obtain better estimates of the output values of the refined oil, electricity and energy-intensive sectors. Blank areas in the following table are filled up on the basis of the I-O table of another country (for instance, Indonesia) for which complete data are available, using the RAS biproportional adjustment method.

IO TABLE FOR NIGERIA: 1983 (millions US $) exch.rate (Naira/1$) = 0.7234

TABLE 3.1 : TOTAL INTERMEDIATE DEMAND

	AGRICUL	COAL MIN.	CRUDE OIL	NATUR. GAS	REFINED OIL	ELECTRIC.	ENER.INT.	IND.&SERV.	TOTAL
AGRIC.									
COAL	0 [16]a	0 [16]a		0		0 [16]a	0 [16]a		
CR.OIL	0	0		0	3423	0	0	0	3423
NAT.GAS	0	0		54 [16]	0	488 [16]e	0		
REFINED O	179 [16]b			0	0 [16]b	54 [16b]	941 [16]b		
ELECTRL	38 [16]d			0	2 [16]d	0 [16]d	261 [16]d		
ENER.INT.									
IND.&SERV.									
TOTAL	5922	0	277	48	4852	672	3954	23663	39388
								test on consistency :	39388

PRIMARY FACTORS :

	AGRICUL	COAL MIN.	CRUDE OIL	NATUR. GAS	REFINED OIL	ELECTRIC.	ENER.INT.	IND.&SERV.	TOTAL
LABOR	4725		218	8					19381
CAPITAL	5371		146	6					45276 [9]
FIX.FACT.	6721		12820	479					
TAX-SUB.	0		39	2					2597 [9]
TOTAL	16817 [1]	0	13223 [1]	494 [1]	1049 [4]a	637 [1]	855 [1]a	34178	67254 [2]
OUTPUT	22739 [8]	0	13500.34 [8]	541.9547 [8]	5901 [4]a	1309 [1]	4809 [4]	57841	106642 [8]
IMPORT	799 [5]a	3 [5]b	0	0	71 [5]c	0	1268 [5]d	8746	10887 [2]
TOTAL	23539	3	13500	542	5971	1309	6078	66587	117529

implied domestic price distortion
0.1

1309.111 estimate of electricity,gas... distribution output based on energy input

16231 for reference NA figure
0.707164 dom.price distortion without correction

(continued)

[1] National Accounts Statistics : detailed tables, Volume II, 1975-1987, OECD, Paris 1989 and National Accounts Statistics : main aggregates and detailed tables, 1986, United Nations, Table 4.1
a = energy intensive industries group based on National Accounts (Table 4.1) and Industrial Statistics (see [4]). It includes :
ISIC 341 : paper and product
ISIC 351+352 : chemical products
ISIC 371 + 372 : iron and steel, non-ferrous metals

[2] National Accounts Statistics : main aggregates and detailed tables, 1986, United Nations, Table 1.1

[3] Handbook of international trade and development statistics, 1988, United Nations, Table 4.2 (based on distribution of imports for 1982)

[4] Industrial Statistics Yearbook, 1987, United Nations.
a = ISIC 353+354 and National Account Statistics

[5] International Trade Statistic Yearbook, 1987, United Nations :
a = SITC 00 + 034 + 036 + (041 to 045) + 054 + 057 + 07 + 2 - (25+27+28)
b = SITC 3 - SITC 33
c = petroleum products (SITC 332)
d = SITC 5 + (SITC 67+68) + (SITC 251+641) [approx. for 1983]

[6] done by splitting the aggregated value added "crude petroleum and natural gas" on the basis of estimated values of output using world prices :
a = for crude oil :

- world price	216.0451	$/t	Unctad world average export price fob	217.431295	'Unctad commodity yearbook
- output	61048	1000t	IEA Energy Statistics	214.659	'= 1986 energy statistics
- value	13189.12	mill.$			

b = for natural gas

	INDUSTRY	- price	186.13	$/toe	ELECTRICITY - price	186.13	$/toe	HOUSEHOLDS - price	186.13	$/toe
		- output	2647	000 toe	- output	0	000 toe	- output	0	000 toe
		- value	493	mill.$	- value	0	mill.$	- value	0	mill.$
	TOTAL nat.gas		493							
dom.dem.	2647	TOTAL	13681.81							
tot.requ.	2647									

Source : price = unit value of 1 exported toe (Trade statistics, UN; IEA World Energy Statistics and Balances)

[7] Unctad Commodity Yearbook, 1989, United Nations.
a = Table 3.11.3
b = Table 3.11.2

[8] Based on the X/VA ratio for Cameroon

[9] National Accounts Statistics : main aggregates and detailed tables, 1986, United Nations, Table 1.3

(continued)

TABLE 3.2 :TOTAL FINAL DEMAND

	food	fuel & power	transport & communic.	rest of hous. consumption	TOTAL HOUS. CONSUMP.	GOVERNM. CONSUMP.	INVESTM.	STOCK CHANGES	EXPORTS	TOTAL FIN. DEMAND	TOTAL AVAILAB.
AGRIC.								0	361 [15]a		23539
COAL	0	0 [16]a	0	0	0			0	0		3
CR.OIL	0	0	0	0	0	0	0	0	10077 [7]b		13500
NAT.GAS	0	0	0	0	0			0	0		542
REFINED O	0	695 [16]b		0				-174 [16]b	0		5971
ELECTRI.	0	397 [16]d	0	0	397			340 [16]d	0		1309
ENER.INT.									10 [15]b		6078
IND.& SER									344		66587
TOTAL	28821	938	1743	15282	46783	7687	12338	541	10792	78141	117529
									test on consistency :	78141	

PRIMARY FACTORS :

	food	fuel & power	transport & communic.	rest of hous. consumption	TOTAL HOUS. CONSUMP.	GOVERNM. CONSUMP.	INVESTM.	STOCK CHANGES	EXPORTS	TOTAL FIN. DEMAND	TOTAL AVAILAB.
LABOR	0	0	0	0	0	0	0	0	0	0	19381
CAPITAL	0	0	0	0	0	0	0	0	0	0	45276
FIX.FACT.	0	0	0	0	0	0	0	0	0	0	-
TAX-SUB.	0	0	0	0	0	0	0	0	0	0	2597
TOTAL	28821 [11]a	938 [11]a	1743 [11]	15282	46783 [2]	7687 [2]	12338 [2]	541	10792 [2]	78141	67254 [2]
							Non adjusted:	541 [2]		test on consistency :	67254.22

STATISTICAL DISCREPANCIES :

without adjustment :	-1.5E-11
with adjustment:	1.46E-11

[11] National Accounts Statistics : main aggregates and detailed tables, 1986, United Nations, Table 2.5
a = purchasing power comparisons, 1980, Eurostat, UN.

[12]

[13] National Accounts Statistics : main aggregates and detailed tables, 1986, United Nations, extrapolation based on Table 2.9

[14] extrapolated from Industrial Statistics Yearbook, 1987, United Nations, column 12.

[15] International Trade Statistic Yearbook, 1987, United Nations :
a = SITC 00 + 034 + 036 + (041 to 045) + 054 + 057 + 07 + 2 - (25+27+28)
b = SITC 5 + (SITC 67+68) + (SITC 251+641) [approx. for 1983]

(continued)

[16] World energy statistics and balances: 1971-87, OECD, 1989.

a = coal balance

total domestic demand	35.2	
of which :		
- agriculture :	0	0.00%
- own use :	0	0.00%
- electricity :	1.8	5.11%
- hous.fuel and power		
(residential + unallocated ind.)	4.9	13.92%
- stock var. and wastes :	3.7	10.51%
- energy intens.industries :	2.6	7.39%

b = oil balance (processed products)

					dom.prices (see Energy prices and taxes, IEA, OECD, 1989)
total domestic demand	11259.2				
of which :					
- agriculture :	336.8	2.99%	industry uses	9845.6	1
- own use :	0	0.00%			
- electricity :	102.5	0.91%	electricty uses	102.5	1
- hous.fuel and power					
(residential + unallocated ind.)	1311.1	11.64%	household uses	1311.1	1
- stock var. and wastes :	-327.8	-2.91%			
- energy intens.industries :	1774.6	15.76%	AVERAGE PRICE		1

c = natural gas balance

total domestic demand	2647	0.138867	estimated share of gas distribution in total output of electricity, gas, water distribution sector (source : Industrial Statistic		
					dom.prices (see Energy prices and taxes, IEA, OECD, 1989)
of which :					
- agriculture :	0	0.00%	industry uses	2647	1
- own use :	261.8	9.89%			
- "greenhou." manuf.	27	1.02%	electricty uses	0	1
- electricity :	0	0.00%			
- hous.fuel and power			household uses	0	1
(residential + unallocated ind.)	0	0.00%			
- stock var. and wastes :	0	0.00%	AVERAGE PRICE		1
- energy intens.industries :	36.7	1.39%			

d = electricity balance

total domestic demand	766	0.861133	estimated share of gas distribution in total output of electricity, gas, water distribution sector (source : Industrial Statistic		
					dom.prices (see Energy prices and taxes, IEA, OECD, 1989)
of which :					
- agriculture :	25.8	3.37%	industry uses	496.3	1
- own use :	0	0.00%			
- "greenhou." manuf.	0	0.00%	electricty uses	0	1
- hous.fuel and power					
(residential + unallocated ind.)	269.7	35.21%	household uses	269.7	1
- stock var. and wastes :	231.1	30.17%			
- energy intens.industries :	175.6	22.92%	AVERAGE PRICE		1

e = assuming that natural gas output is not used by other sectors than gas distribution (as part of electricity)

ENERGY CONVERSION TABLE

To convert horizontal row into vertical column multiply by

Units	Joule	Calorie	Btu	Kwh	TCE	TOE	Barrel	B.cm
Joule	1.00	4.187	1055.1	3.600E+06	2.931E+10	4.187E+10	5.736E+09	3.726E+16
Calorie	0.239	1.00	252.01	8.598E+05	7.000E+09	1.000E+10	1.370E+09	8.899E+15
Btu	9.48E-04	3.97E-03	1.00	3412.0	2.778E+07	3.968E+07	5.437E+06	3.531E+13
Kwh	2.78E-07	1.163E-06	2.93E-04	1.00	8141.4	11630.6	1593.4	1.035E+10
TCE (a)	3.412E-11	1.429E-10	3.600E-08	1.228E-04	1.00	1.43	0.196	1.271E+06
TOE (b)	2.388E-11	1.000E-10	2.520E-08	8.598E-05	0.70	1.00	0.137	8.899E+05
Barrel (c)	1.743E-10	7.299E-10	1.839E-07	6.276E-04	5.11	7.30	1.00	6.496E+06
B.cm (d)	2.684E-17	1.124E-16	2.832E-14	9.662E-11	7.866E-07	1.124E-06	1.540E-07	1.00

(a) One ton of coal equivalent assumed to equal 7 million kilo calories.
(b) One ton of oil equivalent assumed to equal 10 million kilo calories.
(c) 7.3 barrels assumed to equal 1 ton of oil equivalent.
(d) Billion cubic metres of natural gas.

	Primary Emission Factor	Range (% +/-)
Natural Gas	0.64	0.1
Oil	0.84	3.0
Coal	1.09	3.0
Other Solid Fuels	0.89	>10

Exa	1.0E+18
Peta	1.0E+15
Tera	1.0E+12
Giga	1.0E+09
Mega	1.0E+06
Kilo	1.0E+03

TABLE 1

Sectors of production in GREEN :

1. AGRICULTURE
2. COAL MINING (conventional)
3. CRUDE OIL (conventional)
4. NATURAL GAS (conventional)
5. REFINED OIL PRODUCTS
6. ELECTRICITY, GAS AND WATER DISTRIBUTION (conventional)
7. ENERGY-INTENSIVE INDUSTRIES
8. OTHER INDUSTRIES AND SERVICES

b1. CARBON-BASED BACKSTOP FUEL

b2. CARBON-FREE BACKSTOP FUEL

b3. BACKSTOP ELECTRIC OPTION

TABLE 2

Breakdown of household consumption in GREEN :

1. FOOD AND BEVERAGES
2. FUEL AND POWER
3. TRANSPORT AND COMMUNICATION
4. OTHER GOODS AND SERVICES

TABLE 3: Converting a carbon tax of 250 $ per ton of carbon in the United States into fuel-specific taxes.

	emission coefficients (a) [1]	fuel-specific carbon tax (b) [2]=[1]*250$	domestic demand (c) [3]	value of domestic demand (d) [4]	estimated unit fuel price in US $/Terajoule [5]=[4]/[3]	fuel-specific ad valorem tax rate ([2]*[3])/[4]
coal	23.8	5950	18.994	23535	1239	4.802
crude oil	19.2	4800	25.927 (e)	124446	4800	1.000
gas	13.7	3425	19.856	57369	2889	1.185

(a) Tons of carbon per Terajoule (source : *Environmental Data Report*, Table 1.1. UNEP 1989).

ˋ) US dollars per Terajoule.

housands of Terajoule.

ˋions 1985 US dollars (as estimated on the basis of the 1985 input-output table.)

(e) 619.372 thousand metric tons of oil are equivalent to 25.927 thousand TJ, given that 1 toe = 41.86 10**9 J and 1 TJ = 10**12 Joules.

Table 4

Regional and country coverage of GREEN :

Separate Regions	Other OECD	Central and Eastern Europe	Dynamic Asian Economies (a)	Energy-Exporting LDCs			Rest of the World
				OPEC	non-OPEC		
United States	Austria	Bulgaria	Hong Kong				Remaining countries representing 5,3 % of World GDP and 5,4 % of World CO2 emissions. Major countries are: Argentina, Pakistan, Israel, Syria, Chile, Morocco
	Finland	Czechoslovakia	South Korea				
Japan	Norway	Hungary	Philippines	Algeria	Angola	COAL	
	Sweden	Poland	Singapore	Ecuador	Benin		
EC	Australia	Romania	Taiwan	Gabon	Brunei	South Africa	
	New Zealand	Yugoslavia	Thailand	Indonesia	Cameroon		
China	Canada			Iran	Colombia	GAS	
	Turkey			Iraq	Congo		
Former USSR				Kuwait	Malaysia	Bolivia	
				Libya	Mexico		
India				Nigeria	Oman		
				Qatar	Peru		
Brazil				Saudi Arabia	Trinidad & T.		
				Utd. Arab Em.	Tunisia		
				Venezuela	Egypt		

(a) Differs from the standard definition of DAEs by including Philippines and excluding Malaysia. The latter country is included in the Energy-exporting LDCs.

Table 5. Sectoral definitions in GREEN.

Sectors :	ISIC	SITC
1) Agriculture	11 - 13	00 + 034 + 036 (041 to 045) + 054 + 057 + 07 (2 - 25 - 266 - 27 - 28
2) Coal mining	210	322 + 323
3) Crude oil	220	333
4) Natural gas	220	341
5) Refined oil	353 + 354	334 + 335
6) Electricity, gas, water (1)	4	35
7) Energy intensive industries(2)	341 + 351 + 352 + 371 + 372	(25 + 64) + 5 + 67 + 68
8) Other ind. and services	230+290+rest of 3+ 5 to 9	1+2+4+(6 to 9)-(64+67+68)

(1) Includes hydro-electricity, electricity produced by nuclear power and by other carbon-free energy sources.

(2) Includes paper and pulp products (ISIC 341), chemicals (ISIC 351 and 352), iron and steel (ISIC 371), and non-ferrous metals (ISIC 372).

Table 6: Estimation of intermediate demands for crude oil and natural gas in the United States and Nigeria

United States

Crude oil:

domestic price	24.09$/barrel or 176,34$/t (1)
output	442,507 million t (2)
value	78031.2 million $

Natural gas:

Uses	domestic prices (3)	quantities (4)	values (million $)
Industry	152,18.$10^2$$/tcal.	2527033.7 tcal.	38456
Electricity	136,15.$10^2$$/tcal.	748128.9 tcal.	10186
Households	235,79.$10^2$$/tcal.	1088279.3 tcal.	25661
Exports			711
			TOTAL = 75014

Nigeria

Crude oil:

world price	216.0451 $/t (5)
output	61048 1000t (6)
value	13189.12 million $

Natural gas:

Uses	world price	quantities	values (million $)
Industry	186.13 $/toe	2647 000 toe	493
Electricity	186.13 $/toe	0 000 toe	0
Households	186.13 $/toe	0 000 toe	0
Exports			0
			TOTAL = 493

1. US *Industrial Outlook*, 1989, Table 5, p.10-4
2. UN *Energy Statistics Yearbook*, 1986
3. IEA (1989), *Energy prices and taxes*
4. IEA (1987), *Energy Statistics 1970-1985*, Volume II. Quantities are adjusted in order to account for the import penetration ratio (0,054).
5. UNCTAD world average export price fob 217.431295
6. IEA Energy Statistics 214.659

TABLE 7a. Survey of interfactor and interenergy elasticities of substitution
Econometric estimates: capital-labour substitutability (a)
North America

Author	INTER LINK(b) (1987)	Carrere & Devezeaux (1988)		Chung (1987)	Pindyck (1979)	Berndt & Hesse (1986)(c)	Delorme & Lester (1986)	
Country							(d)	(e)
USA	0.74	1.55	0.45	1.23	1.41	0.45		
CAN	0.64	1.21	0.47		1.43	0.48	-0.74	1.12
							3.15	1.03
Model	[KE]L CES	KLE Translog	KLE Translog	KLEM Translog	KL[PCGEI]M Translog	KLEINEI Translog	KsKeLEMI Translog	
Data	Agg.TS 60-83	Agg.TS 60-84	Agg.CC-TS 60-84	Man.TS 47-71	Agg.CC-TS 59-73	Agg.TS 60-82	Man.CS-TS 61-80	
Comment							Man. durables Man.non-durables	

Notes: (a) Allen elasticities;
(b) Jarrett & Torres (1987);
(c) Allen elasticities computed from output elasticities;
(d) Elasticity between structures and labour;
(e) Elasticity between equipment and labour.

TABLE 7b. Survey of interfactor and interenergy elasticities of substitution
Econometric estimates: capital-labour substitutability (a)
Pacific

Author	INTER LINK(b) (1987)	Macro models (c)	Carrere & Devezeaux (1988)		Turnovsky et al. (1982)	Pindyck (1979)
Country						
JAP	0.32		0.78	0.54		0.7
ASL	0.42	0.5			2	
NZD	0.44	0.69				
Model	[KE]L CES	KL CES	KLE Translog	KLE Translog	KL[PCGEI]M Translog	KL[PCGEI]M Translog
Data	Agg.TS 60-83	Agg.TS (a)	Agg.TS 60-84	Agg.CC-TS 60-84	Man.TS 46-75	Agg.CC-TS 59-73
Comment					Biased technical progress	

Notes: (a) Allen elasticities;
(b) Sources are Jarrett & Torres (1987) for Japan and Torres et al. (1989) for Australia and New Zealand;
(c) National macro-econometric model estimates [as reported in Jarrett & Torres(1987)].

TABLE 7c. Survey of interfactor and interenergy elasticities of substitution
Econometric estimates: capital-labour substitutability (a)
Europe

Author	INTER LINK(b) (1987)	Macro models (c)	Carrere & Devezeaux (1988)		Ilmakunnas & Torma (1989)	Pindyck (1979)	Berndt & Hesse (1986)(d)	Hesse & Tarka (1986)
Country								
GER	0.73		0.33	0.51		0.71	0.74	0.8
FRA	0.72		0.83	0.4		0.72	0.23	0.83
UKM	0.77		2.57	0.21		0.64	0.5	0.77
ITA	0.64		0.4	0.52		0.7	0.66	0.79
OST	0.38							
BEL	0.47	0.81						0.75
DEN	0.44	0.69						
FIN	0.62	1			0.36		0.92	0.83
GRE	0.63	0.5						
IRE	0.4	0.32						
NET	0.43	0.38				0.7		0.84
NOR	0.38					0.71	0.37	0.81
SPA	0.64							
SWE	0.41					0.69	0.37	0.78
SWI	0.63							
Model	[KE]L CES	KL CES	KLE Translog	KLE Translog	KLEINEIM Gen.Leont.	KL[PCGEI]M Translog	KLEINEI Translog	KLEINEIM Translog
Data	Agg.TS 60-83	Agg.TS (a)	Agg.TS 60-84	Agg.CC-TS 60-84	Man.CS-TS 60-81	Agg.CC-TS 59-73	Agg.TS 60-82	Agg.CC-TS 73-80
Comment					Post-1974 estimates			Biased tech. change

Notes : (a) Allen elasticities;
(b) Sources are Jarrett & Torres (1987) for the major four and Torres et al. (1989) for the smaller countries;
(c) National macro-econometric model estimates [as reported in Jarrett & Torres (1987)];
(d) Allen elasticities estimated from output elasticities.

TABLE 8a. Survey of interfactor and interenergy elasticities of substitution
Econometric estimates: labour-energy substitutability (a)
North America

Author	Carrere & Devezeaux (1988)		Chung (1987)	Pindyck (1979)	Delorme & Lester (1986)
Country					
USA	0.24	0.99	1.9	0.05	0.66
CAN	-0.92	0.99		0.42	0.62
Model	KLE Translog	KLE Translog	KLEM Translog	KL[PCGEI]M Translog	KsKeLEMI Translog
Data	Agg.TS 60-84	Agg.CC-TS 60-84	Man.TS 47-71	Agg.CC-TS 59-73	Man.CS-TS 61-80
Comment					Manuf. durables Manuf. non-durables

Notes: (a) Allen elasticities.

TABLE 8b. Survey of interfactor and interenergy elasticities of substitution
Econometric estimates: labour-energy substitutability (a)
Pacific

Author	Carrere & Devezeaux (1988)		Turnovsky et al. (1982)	Pindyck (1979)
Country				
JAP	0.54	0.98		1.15
ASL			-2.7	
Model	KLE Translog	KLE Translog	KL[PCGEI]M Translog	KL[PCGEI]M Translog
Data	Agg.TS 60-84	Agg.CC-TS 60-84	Man.TS 46-75	Agg.CC-TS 59-73
Comment			Biased technical progress	

Notes: (a) Allen elasticities.

TABLE 8c. Survey of interfactor and interenergy elasticities of substitution
Econometric estimates: labour-energy substitutability (a)
Europe

Author	Carrere & Devezeaux (1988)		Ilmakunnas & Torma (1989)		Pindyck (1979)	Hesse & Tarka (1986)	
Elasticity	σ_{LE}		σ_{LEI}	σ_{LNEI}	σ_{LE}	σ_{LEI}	σ_{LNEI}
Country							
GER	0.54	0.99			1.23	0.3	-0.14
FRA	0.74	0.99			1.17	0.04	-0.12
UKM	-0.79	0.99			1.1	0.26	0.36
ITA	1.15	0.98			1.11	0.26	0.14
BEL						0.5	0.23
FIN			0.55	0.0		0.26	-0.02
NET					1.11	0.17	-0.07
NOR					1.14	0.2	-0.18
SWE					1.1	0.13	-0.05
Model	KLE Translog	KLE Translog	KLEINEIM Gen.Leont.		KL[PCGEI]M Translog	KLEINEIM Translog	
Data	Agg.TS 60-84	Agg.CC-TS 60-84	Man.CS-TS 60-81		Agg.CC-TS 59-73	Agg.CC-TS 73-80	
Comment			Post-1974 estimates			Biased tech. change	

Notes : (a) Allen elasticities.

Table 9. **Capital-energy elasticities in manufacturing in the major seven OECD countries**

Author	Country	Factors	Data	Production function	Capital-energy elasticity
Berndt and Wood (1975)	U.S.	KLEM	TS (47-71)	Translog	-3.22 (1965)
Hudson and Jorgenson (1974)	U.S.	(KE) (LM)	TS (47-71)	Trg-Cobb-D	-0.31 (1971)
Hudson and Jorgenson (1977)	U.S.	KLEM	TS (47-71)	Translog	-1.39
Griffin and Gregory (1976)	U.S.	KLE	CS-TS	Translog	+1.07 (1965)
Ozatalay *et al.* (1979)	U.S.	KLEM	CS-TS	Translog	+1.22
Artus-Peyroux (1981)	U.S.	KLE	TS (63-78)	Translog	-0.78 (1978)
Khaled (1978)	U.S.	KLEM	TS (47-71)	GBC (1)	-1.96 (1959)
Matsui (1979)	Japan	KLE	TS (60-75)	Translog	-2.11
Ozatalay *et al.* (1979)	Japan	KLEM	CS-TS	Translog	1.88
Fuss (1977)	Canada	KLEM	CS-TS	Translog	-0.02
Berndt and Wood (1979)	Canada	(KE) (LM)	CS-TS	Trg-Cobb-D	-0.015
Magnus (1979)	Canada	KLEM	CS-TS	Translog	-2.21 (3)
Fuss *et al.* (1979)	Canada	KLEM	CS-TS	Translog	0.42 (1962-1971)
Denny-Pinto (1975)	Canada	KLEM	TS	GL (2)	-11.9 (1965)
Griffin-Gregory (1976)	West Germany	KLE	CS-TS	Translog	1.03 (1965)
Ozatalay *et al.* (1979)	West Germany	KLEM	CS-TS	Translog	1.15
Artus-Peyroux (1981)	West Germany	KLE	TS (63-75)	Translog	-0.08 (1978)
Griffin-Gregory (1976)	France	KLE	CS-TS	Translog	1.05 (1965)
Artus-Peyroux (1981)	France	KLE	TS (63-78)	Translog	-0.95 (1978)
Devezeaux (1986)	France	KLEM	TS (60-82)	Translog	-5.70 (1970)
Devezeaux (1986)	France	KLE	TS (60-82)	Translog	-1.55 (1970)
Griffin-Gregory (1976)	Italy	KLEM	CS-TS	Translog	1.03 (1965)
Griffin-Gregory (1976)	U.K.	KLEM	CS-TS	Translog	1.04 (1965)
Artus-Peyroux (1981)	U.K.	KLE	TS	Translog	0.13
Hunt (1984)	U.K.	KLE	TS	Translog	-1.64 (3)

1. Generalised Box Cox.
2. Generalised Leontief.
3. Average value.

Source: Carrère and Devezeaux (1988).

TABLE 10a. Survey of interfactor and interenergy elasticities of substitution
Econometric estimates: capital-energy substitutability (a)
North America

Elasticity	σ_{KE}								σ_{EK}		σ_{NEK}	
Author	INTER LINK(b) (1987)	Pindyck (1979)	Carrere & Devezeaux (1988)		Field & Grebenstein (1980)		Delorme & Lester (1986)		Hogan (1989)	Berndt & Hesse (1986)	Hogan (1989)	Berndt & Hesse (1986)
Country					(c)	(d)	(e)	(f)	(g)(h)	(g)	(g)(h)	(g)
USA	0.4	1.77	0	0.67	-3.5	2.1			0.73	0.77	0.43	1.83
CAN	0.4	1.48	2.47	0.72			4.7	1.53		0.58		0.85
							-2	3.4				
Model	[KE]L CES	KL[PCGEI]M Translog	KLE Translog		KfKwLE Translog		KsKeLEMI Translog		[KL]EINEIT Dynamic Translog	KLEINEI Restricted Translog	[KL]EINEIT Dynamic Translog	KLEINEI Restricted Translog
Data	Agg.TS 60-83	Agg.CC-TS 59-73	Agg.TS 60-84	Agg.CC-TS 60-84	Man.CS 71		Man.CS-TS 60-81		Agg.TS 60-84	Agg.TS 60-82	Agg.TS 60-84	Agg.TS 60-82
Comment							Durables / Non Durables		Long-run elasticity between KL bundle and EI		Long-run elasticity between KL bundle and NEI	

Notes: (a) Allen elasticities;
(b) Jarrett & Torres (1987);
(c) Elasticity between fixed capital and energy;
(d) Elasticity between working capital and energy;
(e) Elasticity between structures and energy;
(f) Elasticity between equipment and energy;
(g) Allen elasticities estimated from cross-price or output elasticities;
(h) NEI does not include transport oils (T)

TABLE 10b. Survey of interfactor and interenergy elasticities of substitution
Econometric estimates: capital-energy substitutability (a)
Pacific

	σ_{KE}					σ_{EIX}	σ_{NEIX}
Author	INTER LINK(b) (1987)	Turnovsky et al. (1982)	Pindyck (1979)	Carrere & Devezeaux (1988)		Hogan (1989)	Hogan (1989)
Country						(c)	(c)(d)
JAP	0.95		0.74	0.21	0.78	0.66	0.82
ASL		2.26					
Model	[KE]L CES	KL[PCGEI]M Translog	KL[PCGEI]M Translog	KLE Translog		[KL]EINEIT Dynamic Translog	[KL]EINEIT Dynamic Translog
Data	Agg.TS 60-83	Man.TS 46-75	Agg.CC-TS 59-73	Agg.TS 60-84	Agg.CC-TS 60-84	Agg.TS 60-84	Agg.TS 60-84
Comment		Biased technical progress				Long-run elasticity between KL bundle and EI	Long-run elasticity between KL bundle and NEI

Notes: (a) Allen elasticities;
(b) Sources are Jarrett & Torres (1987) for Japan and Torres et al. (1989 for Australia;
(c) Allen elasticities estimated from cross-price elasticities;
(d) NEI does not include transport oils (T).

TABLE 10c. Survey of interfactor and interenergy elasticities of substitution
Econometric estimates: capital-energy substitutability (a)
Europe

Elasticity	σ_{KE}				σ_{EIX}		σ_{NEIX}	
Author	INTER LINK(b) (1987)	Pindyck (1979)	Carrere & Devezeaux (1988)		Berndt & Hesse (1986)(c)	Hesse & Tarka (1986)	Berndt & Hesse (1986)(c)	Hesse & Tarka (1986)
Country								
GER	0.4	0.66	-0.69	0.73	0.94	0.5	-1.57	0.48
FRA	0.58	0.56	-1.66	0.57	0.14	0.48	0.88	1.61
UKM	0.67	0.36	6.58	0.56	-0.81	0.35	0.17	0.64
ITA	0.77	0.67	-1.28	0.71	0.39	0.43	0.67	0.58
BEL						0.5		0.51
FIN					-2.24	0.66	7.43	0.7
NET		0.59				0.69		0.74
NOR		0.59			1.21	0.46	1.56	0.49
SWE		0.63			0.69	0.18	3.63	0.5
Model	[KE]L CES	KL[PCGEI]M Translog	KLE Translog		KLEINEI Restricted Translog	[KLEINEI]M Translog	KLEINEI Restricted Translog	[KLEINEI]M Translog
Data	Agg.TS 60-83	Agg.CC-TS 59-73	Agg.TS 60-84	Agg.CC-TS 60-84	Agg.TS 60-82	Agg.TS-CC 73-80	Agg.TS 60-82	Agg.TS-CC 73-80
Comment						Biased tech. change		Biased tech. change

Notes: (a) Allen elasticities;
(b) Jarrett & Torres (1987);
(c) Allen elasticities estimated from output elasticities.

TABLE 11a. Survey of interfactor and interenergy elasticities of substitution
Econometric estimates: interenergy elasticities (a)
North America

Author	Hogan (1989) (b)			Griffin (1977)			Considine (1988) (b)					
Elasticity	σ_{EINEI}	σ_{EIT}	σ_{NEIT}	σ_{PG}	σ_{PC}	σ_{GC}	σ_{OC}	σ_{GP}	σ_{GEI}	σ_{PEI}	σ_{PC}	σ_{CEI}
Country												
USA	11.69	1.5	1.04	0.6	0.5	0.2	-3.62	0.59	2.02	-0.1	0.65	1.1
CAN				0.7	0.5	0.1						
Model	[KL]EINEIT Dyn. Translog			KL[PCG] Translog			GPCEI Translog					
Data	Agg.TS 60-84			Electricity sector CC-TS 55-69			Agg.TS 70-85					
Comment	Long-run elasticity			Neutral tech.change								

Notes: (a) Allen elasticities;
(b) Allen elasticities estimated from cross-price elasticities.

TABLE 11b. Survey of interfactor and interenergy elasticities of substitution
Econometric estimates: interenergy elasticities (a)
Pacific

Author	Hogan (1989) (b)			Turnovsky, Folie & Ulph (1982)						Griffin (1977)		
Elasticity	σ_{EINEI}	σ_{EIT}	σ_{NEIT}	σ_{OC}	σ_{GP}	σ_{GEI}	σ_{PEI}	σ_{PC}	σ_{CEI}	σ_{GP}	σ_{CP}	σ_{OC}
Country												
JAP	33.47	-1.89	18.68							3.67	0.6	0.2
AUS				-1.55	4.5	3.18	-0.78	3.03	.81			
Model	[KL]EINEIT Dyn. Translog			KL[PCGEI]M-Translog						KL[PGC] Translog		
Data	Agg.TS 60-84			Man. TS 46-75						Electricity sector CC-TS 70-85		
Comment	Long-run elasticity			Biased tech. change						Neutral tech.change		

Notes: (a) Allen elasticities;
(b) Allen elasticities estimated from cross-price elasticities.

TABLE 11c. Survey of interfactor and interenergy elasticities of substitution
Econometric estimates: interenergy elasticities (a)
Europe

Author	Ilmakunnas & Torma (1989)	Hesse & Tarka (1986)	Griffin (1977)		
Elasticity	σ_{EINEI}	σ_{EINEI}	σ_{PG}	σ_{PC}	σ_{CG}
Country					
GER		1.38	0.8	0.3	0.1
FRA		1.45	0.5	0.5	0.2
UKM		1.24	2.2	0.4	-0.03
ITA		1.31	1.3	1.1	-0.04
OST			0.5	0.6	0.2
BEL		1.2	0.5	0.6	0.2
DEN			-	0.6	-
FIN	0.91	1.27	0.7	0.7	0.1
GRE			-	1.1	-
IRE			-	1.4	-
NET		1.28	1.9	0.5	-0.03
NOR		1.44	-	5.5	-
POR			1.7	1.0	-0.07
SPA			2.9	0.5	-0.05
SWE		1.51	8.2	3.1	-0.8
Model	KLEINEIM Gen.Leont.	KLEINEIM Translog	KL[PCG] Translog		
Data	Man.CS-TS 60-81	Agg.CC-TS 73-80	Electricity sector CC-TS 55-69		
Comment	Post-1974 estimates	Biased tech.change	Neutral tech.change		

Notes: (a) Allen elasticities.

Table 12

Summary of main features of models used to address the greenhouse gas issue

Article	Model structure	Country/region	Time horizon	Comments
Whalley & Wigle (1991)	Comparative-static AGE. Nested CES, 5 products in each region, 3 traded commodities (carbon-based energy products, energy-intensive goods, other goods)	6 regions: EC, North America, Japan, Other OECD, Oil exporters, RoW	1990-2030 (Benchmark 1982)	-- Nested CES [KLF][ELNEL] -- 3 primary factors -- 2 energy inputs
Edmonds and Barns (1990)	Partial equilibrium model. Detailed dynamic energy sub-model with <u>ad hoc</u> link to rest of the economy Supply functions for various fuels and energy sources.	9 regions: US, Canada & Europe Pacific, Eastern Europe & USSR China, Middle East, Africa, Latin America South East Asia	1975-2075	
Manne & Richels (1990)	"Global 2100" dynamic optimising model. Detailed energy model, based on activity analysis, linked to a simple macro-framework. The individual regions are unlinked.	5 regions: US, Other OECD, Eastern Europe, China, RoW	1990-2100	-- Nested CES [KL][ELNEL] -- 2 primary factors -- 8 non-electric fuels -- 6 electricity technologies

Table 12 (cont.)

Article	Model structure	Country coverage	Time horizon	Comments
Mintzer (1987)	Global model, energy sub-model based on Edmonds & Reilly (1985)	3 regions: OECD, East block Developing countries	1985-2075	-- Same parameterisation as in Edmonds and Barns (1990)
Blitzer, Eckaus, Lahiri & Meeraus (1990)	Dynamic optimising AGE model. 10 sectors.	Egypt	25 years from 1987 benchmark	-- Production functions taken from engineering specification -- 4 energy inputs
Nordhaus (1979)	Global linear programming model. Detailed energy demand system. Exogenous supply for fossil and nuclear fuels.	US, RoW	1980-2100	
Nordhaus & Yohe (1983)	Extension of Nordhaus (1977)			
Bergman (1988)	Static AGE model	Sweden	2000 1979 benchmark	-- Nested CES [KL][EI] -- 2 primary factors -- 2 energy inputs

Table 13

Values of elasticities/parameters used in different models

Energy supply elasticities

Whalley and Wigle (1991)	Carbon based	0.5
	(sensitivity analysis	0.1 to 1.5)
Edmonds and Barns (1990)	Oil	1.0
	Coal	1.0

Inter-factor and inter-energy elasticities

i) Elasticity of substitution between KL bundle and E

Whalley and Wigle (1991)		0.5
Manne and Richels (1990)	OECD	0.4
	elsewhere	0.3
Bergman (1988)	Sweden	0.25
	(sensitivity analysis	0.1 to 0.5)

ii) Inter-energy elasticity of substitution

Whalley and Wigle (1991)	1.0

iii) Inter-fuel elasticity of substitution in final demand

Whalley and Wigle (1991)	4.0
Edmonds and Barns (1990)	3.0

Autonomous energy efficiency improvement
(average annual increase in %)

Manne and Richels (1990)		1990	2050
	OECD	0.5	0.5
	China	1.0	0.5
	E. Europe	0.25	0.5
	RoW	0.0	0.5

Mintzer (1987)	Coal and nuclear	0.2
	(sensitivity analysis	0.2 to 1.5)
	Oil, gas, unconventional oil	0.3

Table 14. CES Elasticities of substitution (all regions)

Sector: / Elasticity (1):	1		2	3	4	5	6		7		8		Back-stops	Government
Labour/KEF(ρ_{1i})	-0.12	-1.0	0.0	0.0	0.0	0.0	0.0		-0.12	-1.0	-0.12	-1.0	0	..
E/KF(ρ_{2i})	0.0	-0.8	0.0	0.0	0.0	0.0	0.0	-0.8	0.0	-0.8	0.0	-0.8	0	..
Inter-energy (ρ_{3i}) (2)	-0.25	-2.0	0.0	0.0	0.0	0.0	-0.25	-2.0	-0.25	-2.0	-0.25	-2.0	0	..
Conventional versus back-stop (ρ^{s}_{4i}) (3)	-10		..	..	..	-10	-10		-10		-10		..	..
Domestic/imported (ρ_{4i}, ρ_{5i}) (4)	-3.0		-4.0	∞	-4.0	-4.0	-4.0		-2.0		-2.0		0	..
Government inputs (ρ_G)														-0.75
World trade (ρ^{WT}_{ir})	-4.0		-5.0	∞	-5.0	-3.0	-0.5		-3.0		-3.0		..	..

1. The first figure refers to the elasticity with respect to old capital, the second to the elasticity with respect to new capital.

2. An elasticity range of -0.25/-2.0 is also assumed for government (ρ^{G}_{2}) demand and in the production of the typical investment good (ρ_I). The inter-energy elasticity in consumer demand (ρ^{H}_{ij}) is -1.2.

3. An elasticity of 10 between conventional and back-stop energies is also assumed for consumer (ρ^{s}_{2jH}) and government (ρ^{s}_{2G}) demand and in the production of the investment good (ρ^{s}_{2I}) and inventories (ρ^{s}_{sT}).

4. The same elasticities have been assumed for consumers (ρ^{C}_{2}), the government (ρ^{G}_{3}), and for investment (ρ^{I}_{2}) and stockbuilding (ρ^{ST}_{2}).

Table 15: **ELES Income elasticities** ($\beta_i \cdot Y/\Sigma_i^4 PC_i C_i$)

Region : Elasticity of demand for:	USA	Japan	EC	Other OECD	Energy Exporting LDCs	Former USSR	China	India	CEECs	DAEs	Brazil	RoW
Food and beverages	0.5	0.5	0.5	0.5	0.6	0.6	0.7	0.7	0.6	0.6	0.6	0.6
Fuel and power	0.5	0.5	0.5	0.5	0.6	0.6	0.8	0.8	0.6	0.6	0.6	0.6
Transport and communications	0.8	0.8	0.8	0.8	0.9	0.9	1.2	1.2	0.9	0.9	0.9	0.9
Other goods and services	1.1	1.1	1.1	1.1	1.2	1.2	1.5	1.5	1.2	1.2	1.2	1.2

Table 16: Own-price elasticities of fixed factors (^{7}f)

Factor (1):	Land		Coal		Oil		Natural gas		Carbon free	
United States	2.0	0.5	4.0	∞	∞	∞	0.0	3.0	0.2	∞
Japan	1.0	0.5	4.0	∞	∞	∞	0.0	3.0	0.2	∞
EC	1.0	0.5	4.0	∞	∞	∞	0.0	3.0	0.2	∞
Other OECD	1.0	0.5	4.0	∞	∞	∞	0.0	3.0	0.2	∞
CEECs	3.0	0.5	5.0	∞	∞	∞	0.0	4.0	0.2	∞
Energy Exporting LDCs	3.0	0.5	5.0	∞	0.0	3/1 (2)	∞	∞	0.2	∞
Former Soviet Union	3.0	0.5	4.0	∞	∞	∞	0.0	4.0	0.2	∞
India	3.0	0.5	5.0	∞	∞	∞	0.0	4.0	0.2	∞
China	3.0	0.5	5.0	∞	∞	∞	0.0	4.0	0.2	∞
DAEs	3.0	0.5	5.0	∞	∞	∞	0.0	4.0	0.2	∞
Brazil	3.0	0.5	5.0	∞	∞	∞	0.0	4.0	0.2	∞
RoW	3.0	0.5	5.0	∞	∞	∞	0.0	4.0	0.2	∞

1. The first figure is the upward supply elasticity, the second figure is the downward supply elasticity.

2. Elasticities phase in between 1990 and 2050.

Table 17: **Parameters of the resource-base sub-model**

Region : Resource:	USA	Japan	EC	Other OECD	Energy Exporting LDCs	CEECs	Former USSR	India	China	DAEs	Brazil	RoW
Crude oil:												
Extraction rate (r) (1)	0.063	0.042	0.063	0.054	0.013	0.067	0.057	0.053	0.046	0.05	0.077	0.06
Ratio of proven to yet-to-find reserves (2)	0.693	1.0	1.14	0.208	1.66	0.5	0.442	0.643	0.237	0.067	0.28	0.28
Natural gas:												
Extraction rate (r) (1)	0.055	0.017	0.027	0.027	..	0.027	0.019	0.017	0.017	0.017	0.055	0.055
Ratio of proven to yet-to-find reserves (2)	0.478	0.4	1.13	1.13	..	1.0	0.916	0.115	0.115	0.053	0.038	0.038

1. The reported observed base-year rates, have been adjusted in some cases in order to find a solution for the calibration equation of the conversion rate (d) (see text).

2. Following EMF12 guidelines, these ratios correspond to the upper bound in the uncertainty range of Masters, Root and Attanasi (1990).

Table 18: Other Parameters (all sectors)

Parameter:	Disinvestment elasticity (2)		Depreciation rate
United States	0.7	∞	0.027
Japan	0.7	∞	0.029
EC	0.7	∞	0.017
Other OECD	0.7	∞	0.022
CEECs	0.7	∞	0.015
Energy Exporting LDCs (1)	0.7	∞	0.023
Former Soviet Union	0.7	∞	0.032
India	0.7	∞	0.018
China	0.7	∞	0.013
DAEs	0.7	∞	0.015
Brazil	0.7	∞	0.014
RoW	0.7	∞	0.016

1. A larger disinvestment elasticity was imposed in the coal mining sector in order to prevent convergence problems due to the tendency of the coal price to drop to zero in Energy-exporting LDCs when a carbon tax is introduced.

2. The first figure refers to the 1990-2030 period, the second to the 2030-2050 period.

Table 19. **Exogenous variables in GREEN**

	1985-1990	1990-2000	2000-2010	2010-2030	2030-2050
AEEI	1	1	1	1	1
United States					
Population (1) (2)	..	0.79	0.43	..	0.04
GDP (1)	2.6	2.6	2.1	1.7	1.4
Production targets (3):					
Crude oil	..	..	0.68 (4)	..	..
Natural gas	..	..	1.3 (5)	..	..
EC					
Population (1) (2)	..	0.12	-0.09	..	-0.27
GDP (1)	2.3	2.2	1.6	1.4	1.1
Production targets (3):					
Crude oil	..	..	0.84 (4)	..	..
Natural gas	..	..	1.21 (5)	..	..
CEECs					
Population (1) (2)	..	0.41	0.27	..	0.13
GDP (1)	2.7	2.7	2.1	1.8	1.4
Production targets (3):					
Crude oil	..	..	0.85 (4)	..	..
Natural gas	..	..	2.05 (5)	..	..
Energy-exporting LDCs (6)					
Population (1) (2)	..	2.41	1.81	..	1.08
GDP (1)	3.6	3.6	3.2	2.5	2.2
Former Soviet Union					
Population (1) (2)	..	0.63	0.42	..	0.24
GDP (1)	2.5	2.6	2.1	1.7	1.4
Production targets (3):					
Crude oil	..	..	..	1.0 (5)	..
Natural gas	..	..	..	1.71 (7)	..
China					
Population (1) (2)	..	1.34	0.75	..	0.32
GDP (1)	4.5	4.6	4.0	3.0	2.7
Production targets (3):					
Crude oil	..	..	1.46 (4)	..	..
Natural gas	..	..	7.83 (7)		
Japan					
Population (1) (2)	..	0.38	-0.06	..	-0.25
GDP (1)	3.8	3.7	2.5	2.1	1.9
Production targets (3):					
Crude oil	..	..	1.0 (4)	..	..
Natural gas	..	..	..	..	..

Table 19. *Continued*

	1985-1990	1990-2000	2000-2010	2010-2030	2030-2050
Other OECD					
Population (1) (2)	..	1.27	0.72	..	0.33
GDP (1)	2.2	2.2	1.6	1.4	1.1
Production targets (3):					
Crude oil	..	..	0.94 (4)	..	..
Natural gas	..	..	..	..	..
India					
Population (1) (2)	..	1.87	1.24	..	0.71
GDP (1)	4.7	4.6	4.1	3.0	2.7
Production targets (3):					
Crude oil	..	..	1.43 (4)	..	..
Natural gas	..	..	..	..	..
DAEs					
Population (1) (2)	..	1.47	0.92	..	0.46
GDP (1)	4.4	4.4	3.8	2.9	2.6
Production targets (3):					
Crude oil	..	..	1.0 (4)	..	..
Natural gas	..	..	..	..	..
Brazil					
Population (1) (2)	..	1.82	1.1	..	0.6
GDP (1)	4.4	4.4	3.9	2.9	2.6
Production targets (3):					
Crude oil	..	..	2.0 (4)	..	..
Natural gas	..	..	..	..	..
RoW					
Population (1) (2)	..	2.63	2.19	..	1.37
GDP (1)	3.6	3.5	3.0	2.3	1.9
Production targets (3):					
Crude oil	..	..	..	..	..
Natural gas	..	..	..	..	..

1. Percentage growth rates.

2. Periods for population growth rates are 1985-2000, 2000-2020 and 2020-2050. Source: Bulatuo *et al.* (1990)

3. Index (1985 = 1.00 reference price scenario).

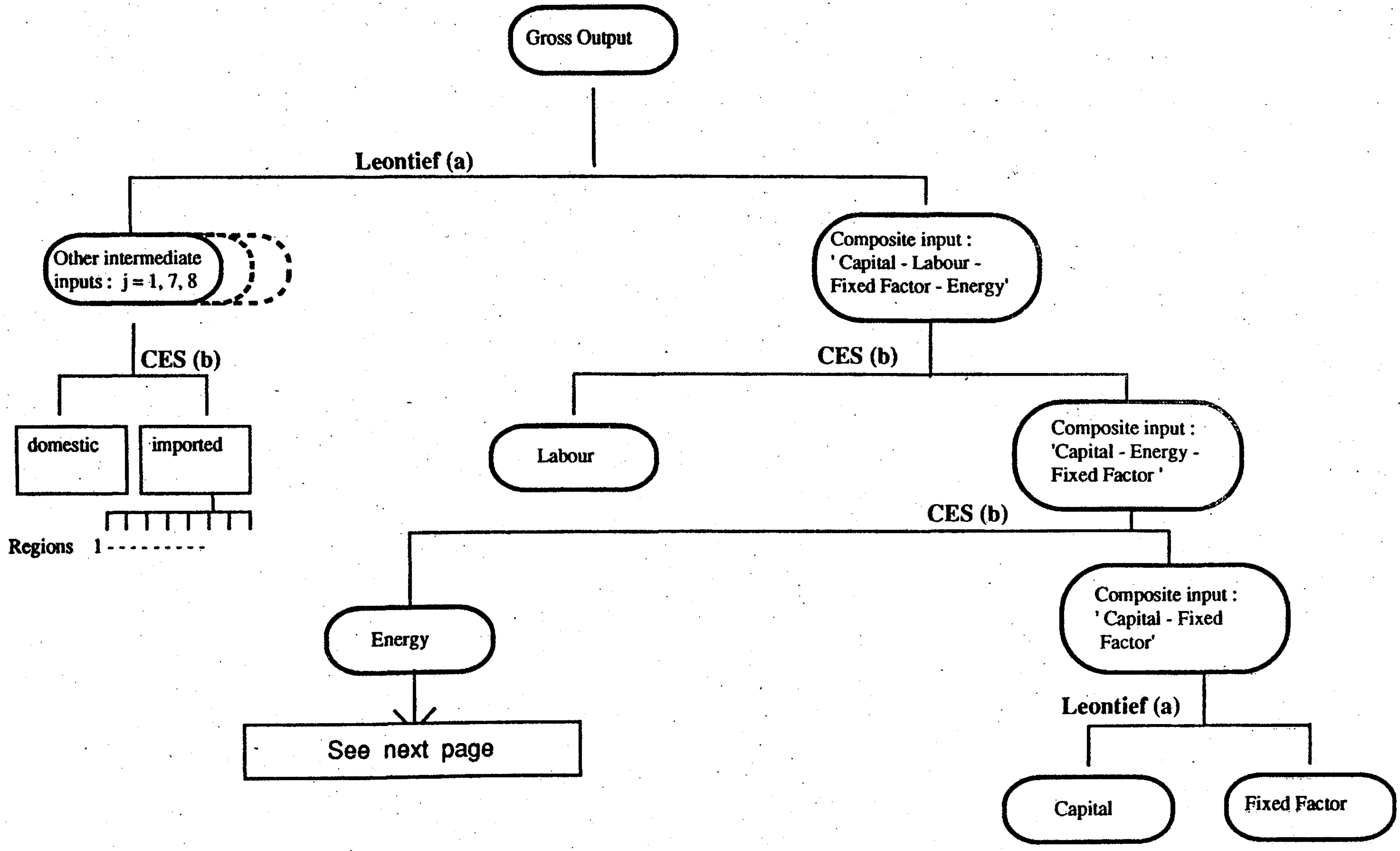
4. IEA production targets in 2005.

5. Secretariat estimates.

6. In the Energy-exporting LDCs a conversion rate of 0.1 was imposed in order to match a reasonable production profile. Potential supply of gas is assumed to be infinite.

7. Calibrated on the production profile of Edmunds and Reilly (1990).

Figure 1a : Structure of production in GREEN



a. Leontief : fixed coefficients

b. CES : constant elasticity-of-substitution

Figure 1b: Energy and backstop technologies in GREEN

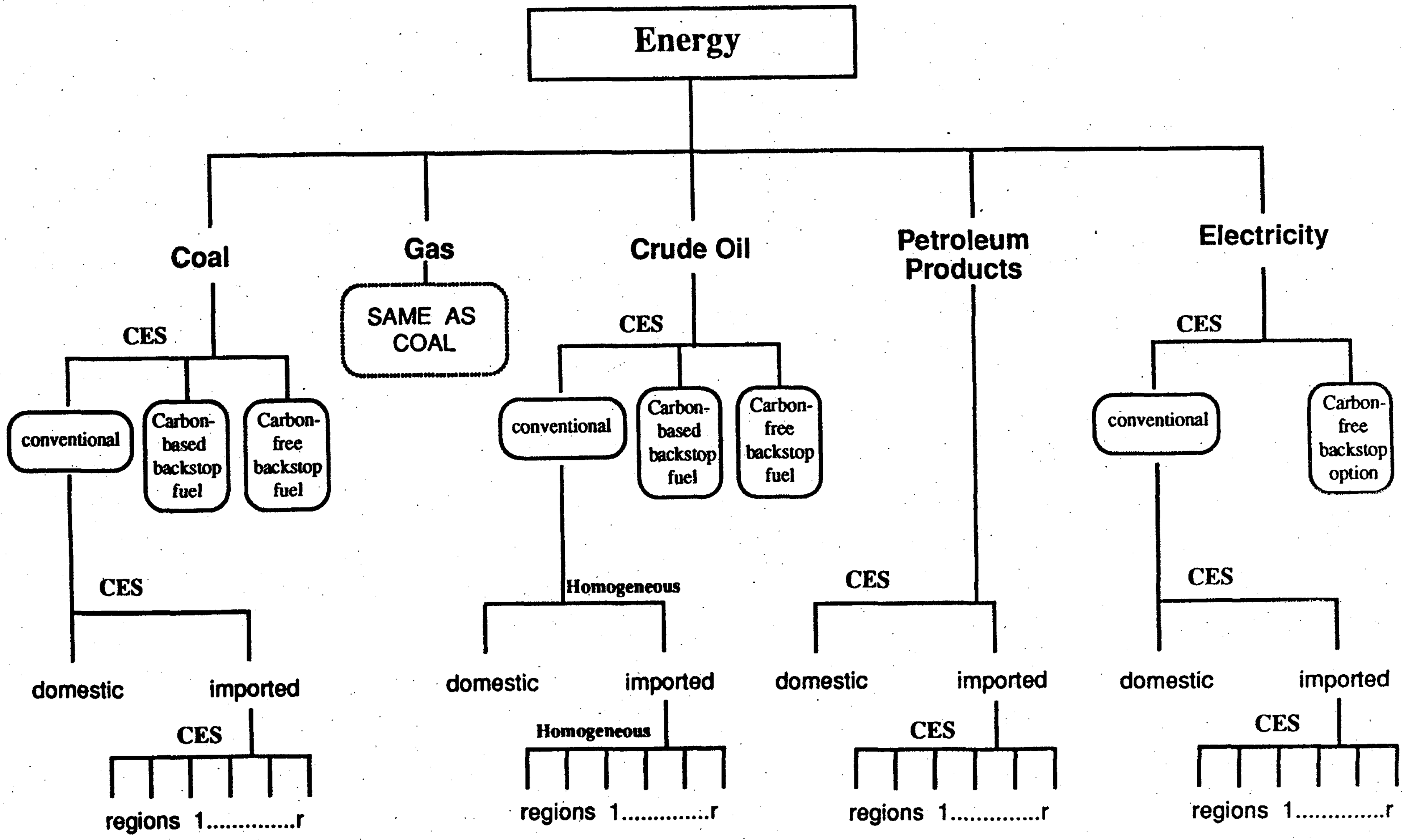


Figure 2. Structure of household demand in GREEN

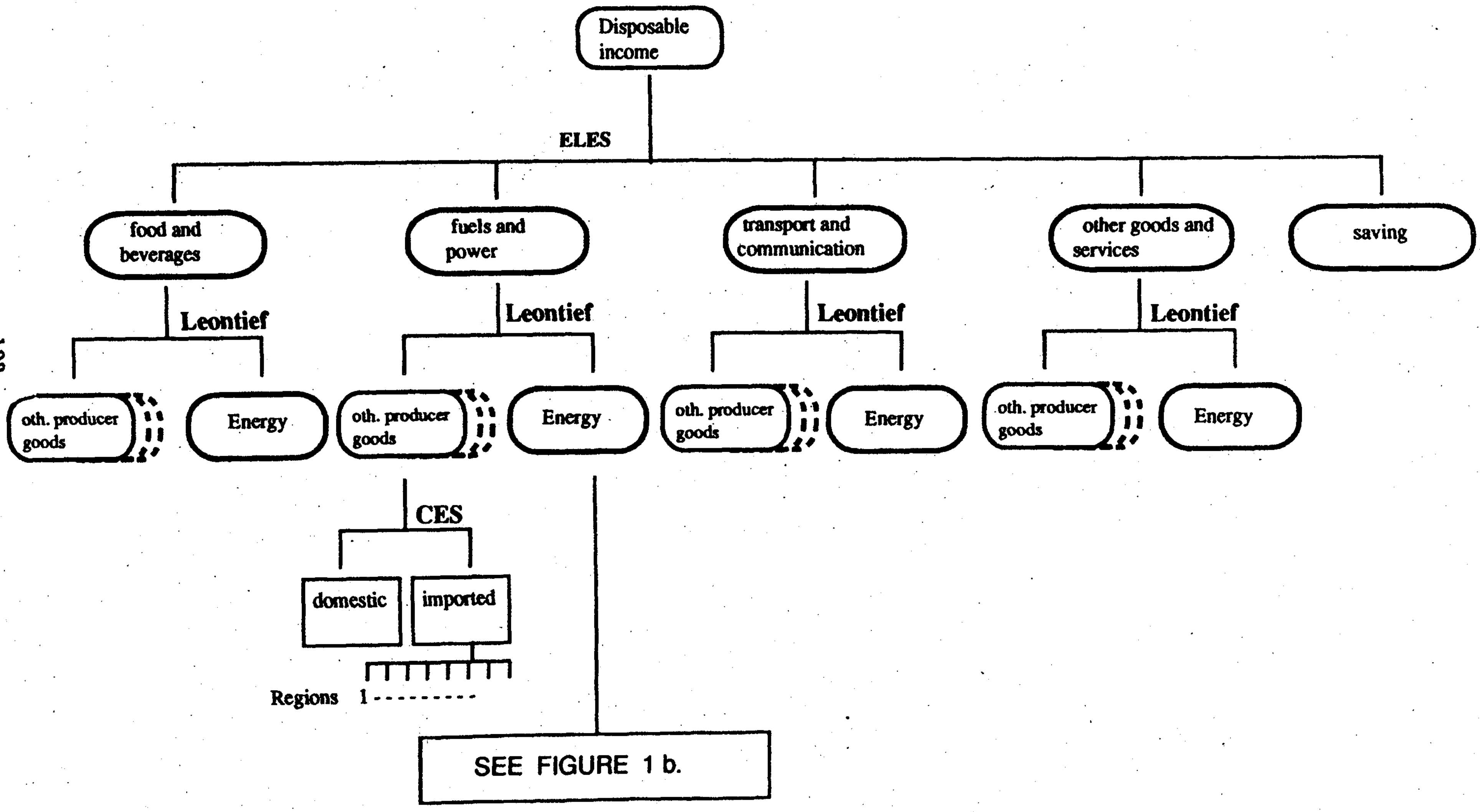


Figure 3 : Structure of household demand

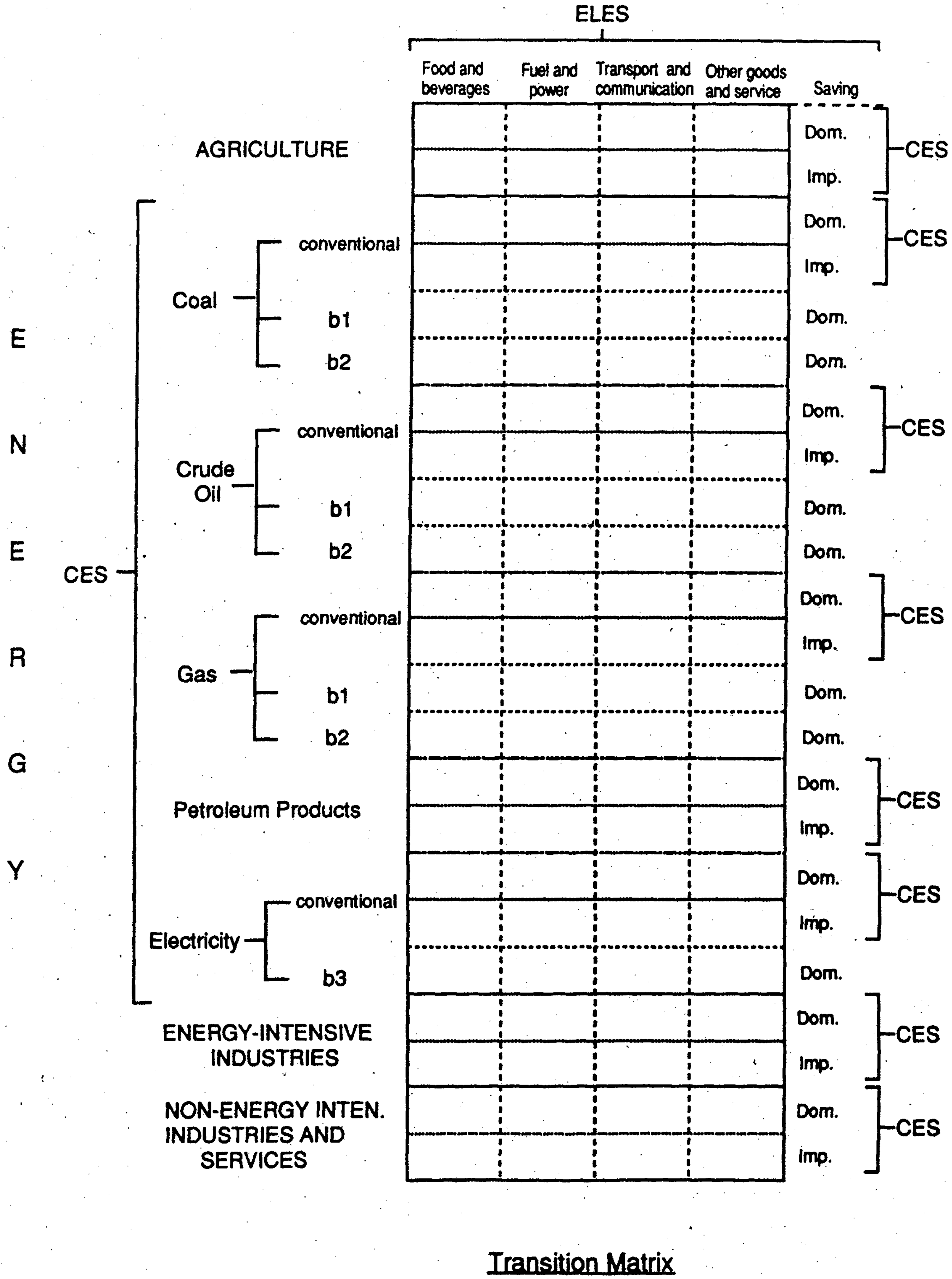


Figure 4. Data structure of GREEN

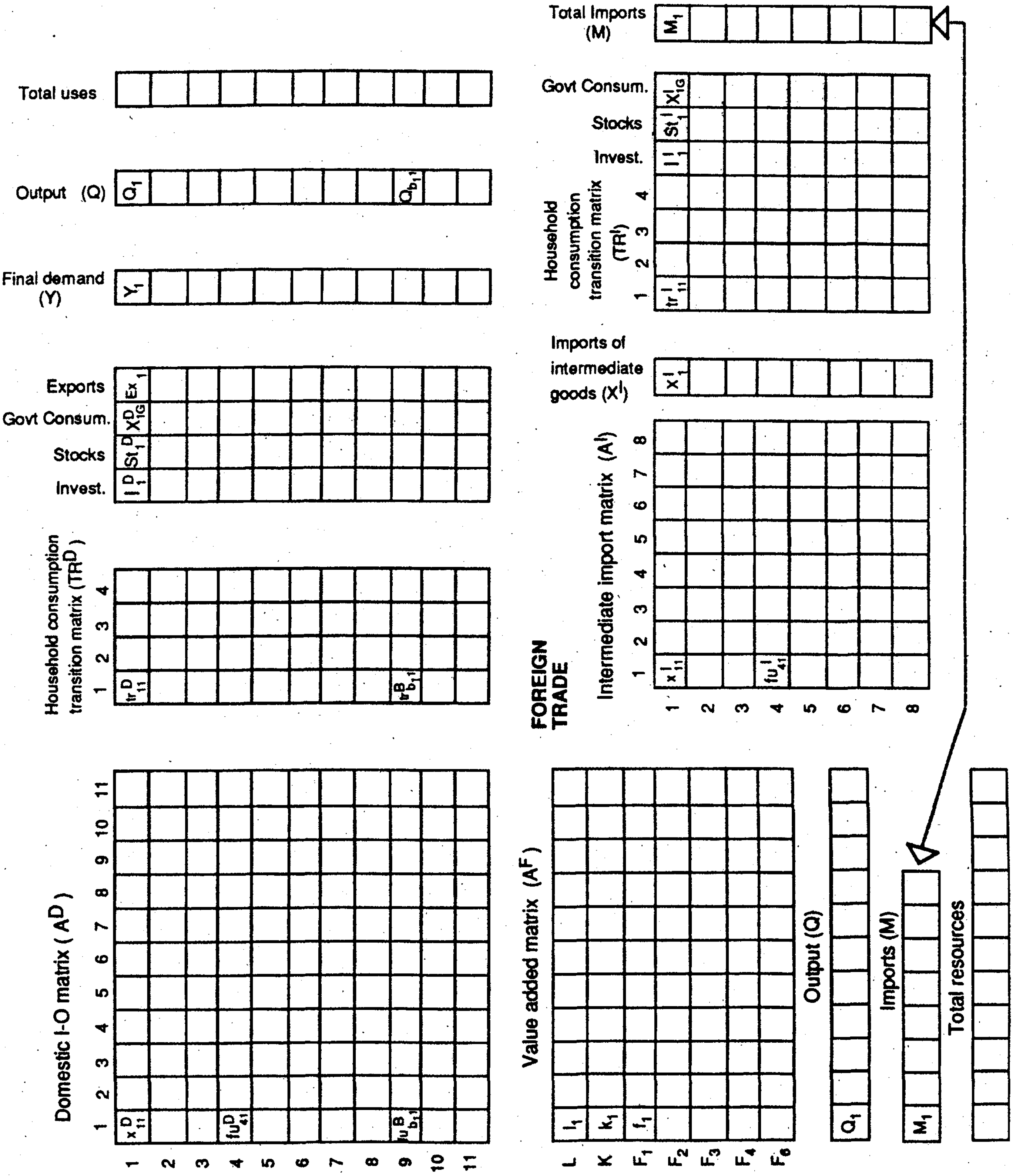


Figure 5: Short- and long-term price elasticities with the putty/semi-putty model: old vintage elasticities are set equal to 0,25, 0,5 and 0,75.

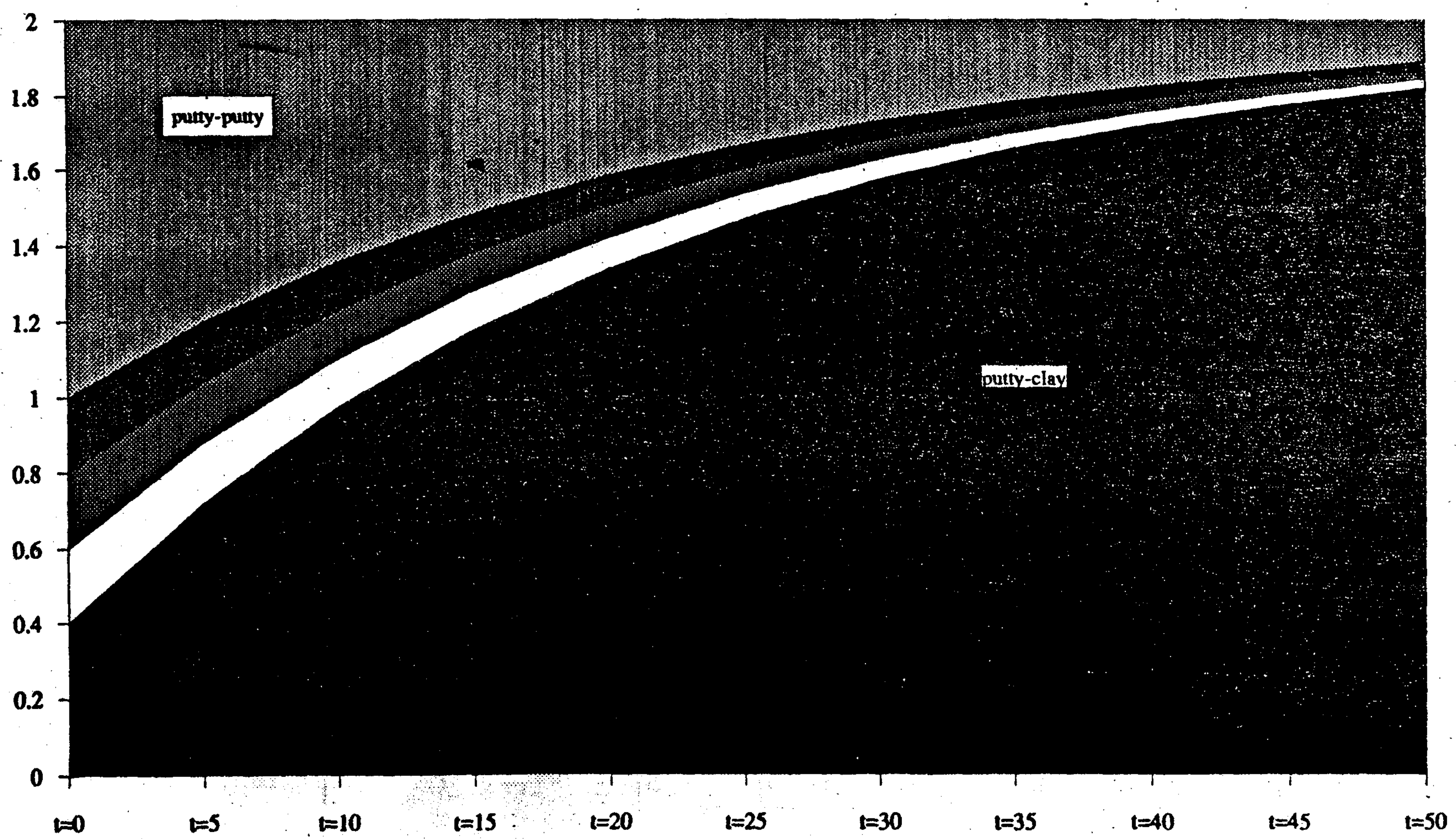
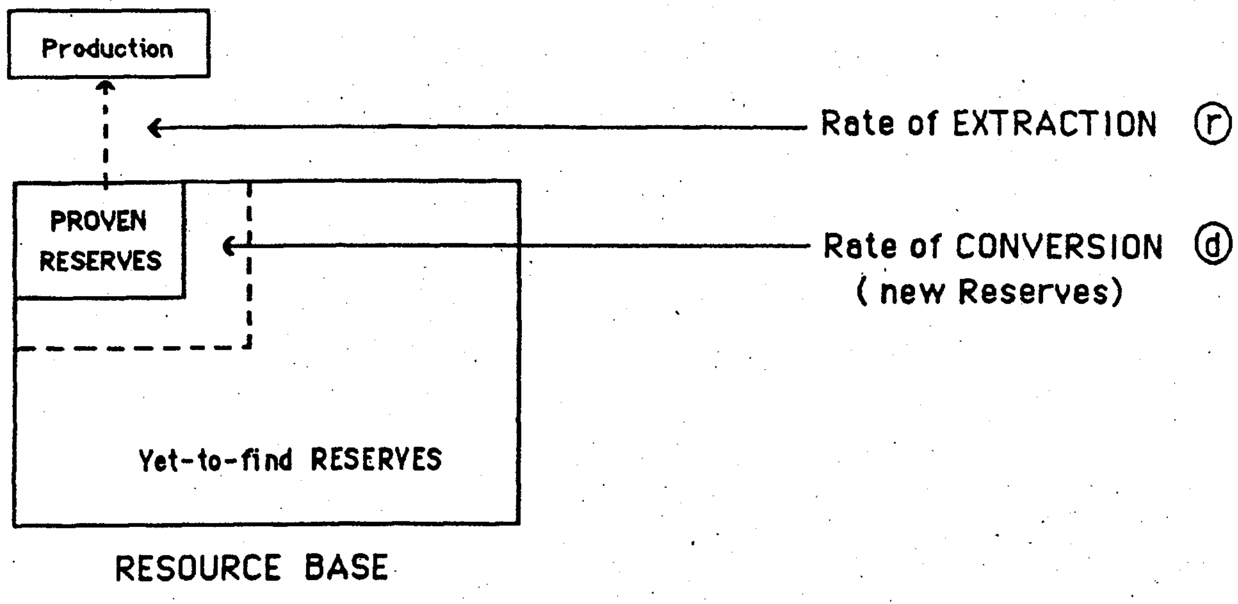


FIGURE 6: **Resource Depletion Models**

THE DEPLETION MECHANISMS:



TYPICAL TIME PROFILES:

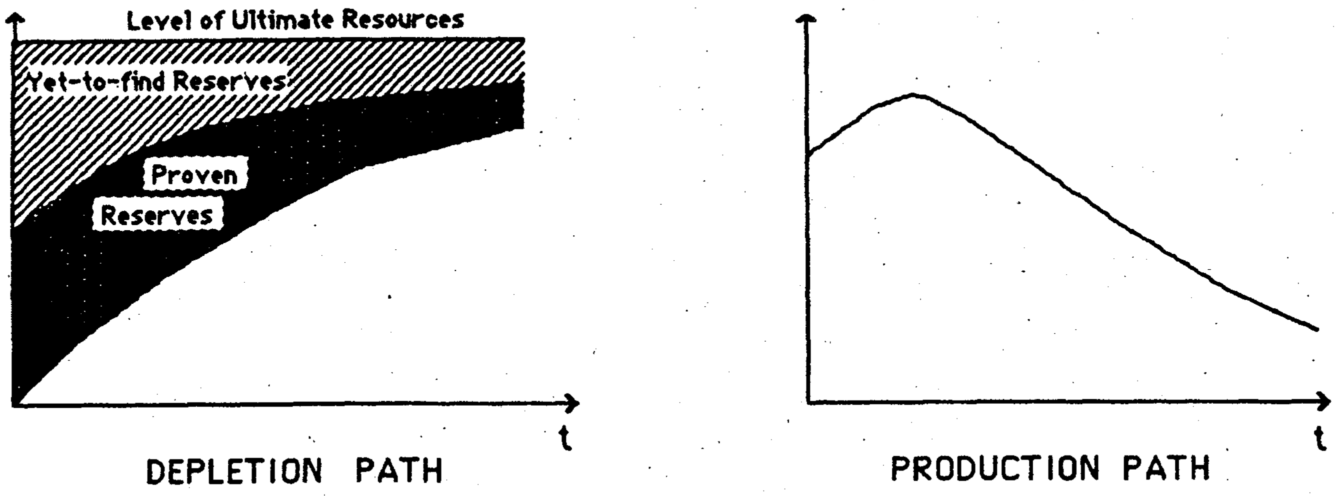
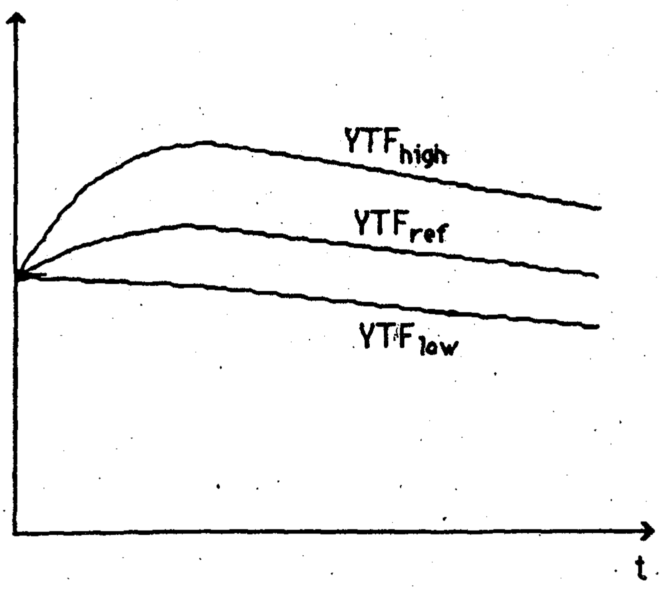


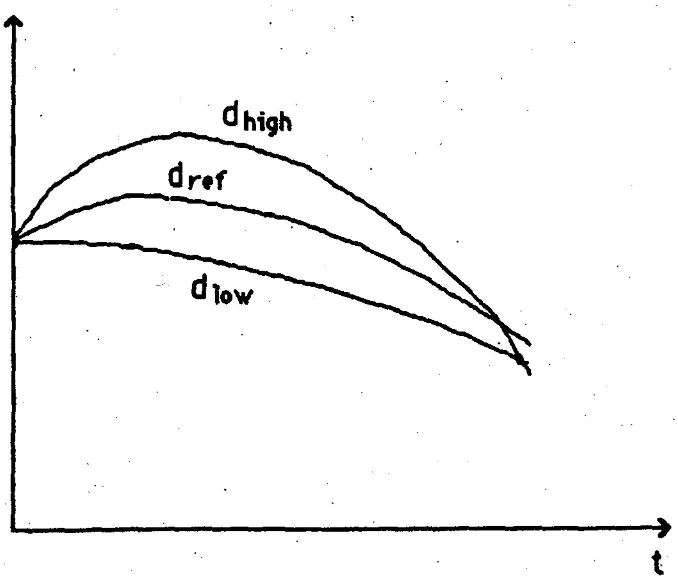
FIGURE 7: **Price Sensitivity**

a) Resource base (YTFR) Price Sensitive:



$YTLF_L < YTF_{ref} < YTF_H$

b) Conversion Factor (d) Price Sensitive:



$d_{Low} < d_{ref} < d_{high}$

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