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

Jean-Marc Burniaux,
John P. Martin,
Giuseppe Nicoletti,
Joaquim Oliveira Martins

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Resource Allocation Division

June 1991

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ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

No. 104: GREEN -- A MULTI-REGION DYNAMIC GENERAL EQUILIBRIUM MODEL FOR QUANTIFYING THE COSTS OF CURBING CO_2 EMISSIONS: A TECHNICAL MANUAL

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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 **G**ene**R**al **E**quilibrium **EN**vironments 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 May 1991. Work is continuing to extend GREEN in several different directions to make the model more policy relevant, and a revised version of the technical manual will be issued in due course.

* * *

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 "**G**ene**R**al **E**quilibruim **EN**vironmental 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 mai 1991. Le développement du modèle se poursuit actuellement dans plusieurs directions différentes de manière à en améliorer les aspects de politique économique ; une version mise à jour de ce manuel technique sera publiée en temps voulu.

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I. INTRODUCTION

The OECD Economics and Statistics Department has developed a global applied general equilibrium (AGE) model, covering three OECD regions and several non-OECD regions, with the objective of quantifying the 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 provides technical documentation on the version of the model that was operational by May 1991. Work is continuing to extend the regional and temporal dimensions of GREEN and to modify its specification in ways that will make it more policy relevant. These revisions, once implemented, will be written up in a revised version of the technical manual which will be issued in due course. A companion paper by Burniaux, Martin, Nicoletti and Oliveira Martins (1991) presents some initial simulation results from three scenarios of alternative international agreements to curb CO_2 emissions.

Both in its regional and inter-sectoral structure, GREEN retains many of the features of WALRAS, the AGE model developed by the OECD to evaluate the economy-wide effects of agricultural subsidies[1]. But there are a number of significant differences between the two models, due to the specific features of the CO_2 issue. Since the main man-made source of CO_2 emissions arises from the burning of fossil fuels, GREEN pays particular attention to modelling the energy sector and the supply of fossil fuels. CO_2 emissions are a worldwide phenomenon, which is linked to global climate changes through the accumulation over time of CO_2 and other greenhouse gases (CFCs, methane, nitrous oxide) in the atmosphere. It is natural, therefore, that the main differences between WALRAS and GREEN are in regional coverage and treatment of dynamics. In particular, GREEN embodies an explicit, albeit simple, intertemporal structure. Other important differences concern sectoral coverage, the specification of production and market rigidities. Finally, GREEN concentrates on government excise taxes -- so-called "carbon taxes" -- aimed at reducing the level of CO_2 emissions over time.

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 six regional sub-models: three

[1] See Burniaux *et al.* (1990) for a technical manual on WALRAS, as well as the papers contained in the Special Issue of *OECD Economic Studies* on "Modelling the Effects of Agricultural Policies" (No. 13, Winter 1989-90).

OECD regions -- North America, Europe and the Pacific -- and three non-OECD regions -- USSR, China and energy-exporting LDCs (mainly OPEC). In addition, there is a residual aggregate for 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 -- which includes hydroelectric, nuclear and other carbon-free sources of energy -- are distinguished. 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. At this stage, 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 1985-2020 period, in seven steps of five-year intervals. In each region, the base model is calibrated on exogenous growth rates of GDP 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 eight 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 energy. The remaining three -- agriculture, energy-intensive industries and non-energy intensive industries and services -- relate to the production of goods and services.

In each sector, gross output is produced using five energy inputs, a fixed factor (land,

[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.

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 energy and intermediate inputs can be obtained either from domestic or foreign suppliers.

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 carbon-free resource, 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 serves two purposes: it is a proxy for time-to-build adjustment costs in the nuclear sector and may also be used to proxy the effects of so-called "backstop technologies", i.e. new carbon-free energy sources such as photovoltaic (solar) energy. Natural gas is assumed to become sensitive to its price only when potential supply (whose determination is described below) exceeds demand. In this latter case, the supply curve for gas accounts for pressures due to extraction costs. Finally, the elasticity of coal to its price is assumed to be finite but large.

Over time, the 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 supply or, alternatively, of ultimate resources.

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[4]. 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 the five different energy sources distinguished in the model. Fifth, the mix between capital and the fixed factor is determined. Finally, demand for intermediate and energy inputs is allocated among domestic supply and imports.

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[3]Fossil and non-fossil fixed factors correspond to available resources of coal, natural gas, crude oil and the carbon-free energy source. 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]Production technology has a nested CES structure, which implies separability among subsets of different input bundles.

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 fossil fuels (coal, crude oil, natural gas) and petroleum products.

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 the assumption that the beginning-of-period capital stock is partially mobile across sectors[5].

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[6]. 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 except crude

[5]These costs can also be proxied by a putty-clay production technology. The putty-clay technology implies that, in all sectors where substitution among primary inputs is allowed, it concerns only capital that is installed in the current period i.e. the new vintage of capital. Capital inherited from the past, and which is not supplied in second-hand capital markets, can only be used in predetermined proportions with other inputs. In this case, the production structure depicted in Figure 1 would apply only to the fraction of gross output produced using the new capital vintage. Under this assumption, the way sectors adjust to relative price changes depends crucially on the relative proportions of new and old vintages in the capital stock. The current version of GREEN is based on a putty-putty techology, but it is planned to incorporate putty-clay technology in the future.

[6]A similar approach to the treatment of adjustment costs in an AGE model was used by Fullerton (1983). In simulations, the solution algorithm searches in each region for six basic rental prices of primary factors plus an additional rental price of old capital in each declining sector.

oil in the energy-exporting LDCs region. 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. In the current version of GREEN, this price is exogenous[7]. 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 oil price.

(ii) <u>Consumption</u>

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. Finally, it is assumed that consumer demand can be directed either at domestic or at foreign markets.

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[8].

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[9]. 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.

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[7]Modelling this price in the context of imperfectly competitive oil markets will be the subject of future research.

[8]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".

[9]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.

Therefore, consumers make their choices based on (i) income from labour and capital (old and new); (ii) rents from fixed factors; 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) 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 and natural gas. It is applied at the level of consumers of *primary* fuels only. In this way, distortions between domestic and imported fuels are avoided and the tax is applied prior to any indirect taxation included in the model. The distinction between a production- and a consumption-based carbon tax would affect assessments of international incidence[10].

Technically, in each region, the tax is 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.

(iv) 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. 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.

(v) Foreign trade

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 arise 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

[10]These issues are discussed in Whalley and Wigle (1990).

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[11]. 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[12]. The energy-exporting LDCs region is assumed to act as a price leader in the world oil market and the other countries are assumed to behave as price-takers. Real domestic prices of oil may vary across countries, reflecting real exchange rate changes[13]. Oil-trade flows and market shares result from the balance between domestic demand and supply of oil at given real world prices, with the energy-exporting LDCs acting as a residual supplier.

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. To satisfy the world current-account constraint, the counterpart of this net flow is reallocated exogenously among the other countries. No account is taken of international income flows associated with changes in stocks of net foreign assets.

(vi) 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 allowed 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

[11]Alternatively, a symmetric assumption of product differentiation for imports *and* for exports can be adopted. Such a specification was included in WALRAS.

[12]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.

[13]The real world price of oil is computed with respect to a weighted average of primary factor prices in the three 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 export price of other goods and services in ROW.

freely in world markets at this price[14]. 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.

(vii) Closure

In each period, the model equates gross investment to net saving. Net saving is the sum of saving by households, 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[15].

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

The time dimension of GREEN is recursive. 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[16]. Therefore, the development of the economy over time is characterised by a sequence of period-related, but intertemporally uncoordinated, flow equilibria[17]. The dynamics in GREEN originate from two sources, depletion of exhaustible resources and capital accumulation.

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[14]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.

[15]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.

[16]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).

[17]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 convergent path is not necessarily unique, since there may be several ways to calibrate the model in order to ensure convergence.

A resource depletion submodel is specified for oil and natural gas. The submodel makes potential supply dependent 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 old 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[18]; (ii) the real wage; (iii) the prices of coal, gas and the carbon-free resource; and (iv) the price of land. In counterfactual simulations, the solution algorithm computes, in addition, the carbon 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

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

is emission rights.

In simulations, model dynamics are calibrated in each region on exogenous GDP 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[19]. In counterfactual simulations, AEEI, and technical progress associated with the capital/labour/fixed factor bundle are exogenous and GDP growth rates become endogenous.

III. TECHNICAL SPECIFICATION[20]

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 export price of other goods and services in RoW. 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 units that differ from observed physical ones. Given this assumption, any difference in factor quantities across sectors corresponds to differences in **adjusted** magnitudes, which are measured in efficiency units. In making this adjustment, the implicit assumption is that observed differences in relative factor prices reflect differences in efficiencies[21].

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

[20]The following notational conventions are adopted in this section. Production sectors are indexed $i = 1,...,8$, 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 $y = f(x_1,...,x_k; z_1,...z_s)$.

[21]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:

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

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[22].

In addition, world trade equilibrium determines the world import price of each commodity except the price of crude oil, which is a crucial exogenous variable 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 exogenous real world price of oil is denoted $\overline{P}^{CO}$ [23].

Defining P = (r^{K^N}, $r_i^{K^O}$, w, r^f) and $P^{WT} = [P_j^{WT}]$ ($j \neq 3$), equilibrium producer prices in each sector (P_i) ultimately depend on prices of primary factors and imports, the carbon tax and the exogenous world price of crude oil:

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

GREEN includes distortionary factors 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 does not include import tariffs. However, it does incorporate *ad valorem* taxes or subsidies on *non-energy* intermediate inputs. In addition, as will be explained below, the excise carbon 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 these goods (i = 1, 7, 8) can be defined as follows:

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[22]As will be explained below, the carbon tax can be interpreted as the "shadow price" of CO_2 emissions.

[23]The real world price of crude oil is defined as the price of oil, P^{CO}, deflated by a weighted average of primary factor prices in the OECD area, NUM^{OECD}, which is a more representative price index of world trade than the *numéraire* of the model:

$$\overline{P}^{CO} = \frac{P^{CO}}{NUM^{OECD}}$$

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

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

Denoting by τ_i^{FU} fuel-specific tax rates (i = 2, 3, 4, 5, 6) and by RE the (region-specific) real exchange rate, after-tax prices for fuels can be defined in a similar way[24],

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

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

with $P_i = P_i^{WT} = \overline{P}^{CO} \cdot RE$ for i = 3, reflecting the assumption that crude oil is a homogeneous good across countries[25].

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):

$$PC_j^D = \sum_{i=1,7,8} tr_{ij}^D\, PT_i^D + \sum_{k=2}^{6} tr_{kj}^D\, PF_k^D \qquad (1)$$

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

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 structure varies across the eight sectors distinguished in the model (see Table 1). In the production of fossil fuels, technology is characterised by a Leontief (fixed-coefficients) specification. In agricultural, industrial and electricity sectors, it combines

[24] In practice, there is no tax on the carbon-free source of energy in the model ($\tau_6^{FU} = 0$). In addition, τ^{FU} on imported and domestic fuels is not identical. The tax rate on domestic fuels is adjusted to neutralise the effect of own consumption of fossil fuel i in fossil-fuel sector i.

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

Leontief specifications for intermediate goods and capital/fixed factor bundles with a nested-CES specification for the other levels of production.

In fossil-fuel sector i (i = 2, 3, 4, 5), gross output Q_i is produced using labour L_i, capital K_i, a fixed factor F_i, *non-energy* intermediate inputs X_{ji} (j = 1, 7, 8) and fuels FU_{si} (s = 2, 3, 4, 5), where X_{ji} and FU_{si} represent quantities sold by sectors j or s and purchased by sector i according to the transaction matrix of the input-output table. 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.

Indicating by lower-case letters the ratios of inputs to sectoral gross output, the production function for fossil-fuel sector i can be expressed as follows,

$$Q_i = \min\{(\frac{X_{1i}}{x_{1i}}, \frac{X_{7i}}{x_{7i}}, \frac{X_{8i}}{x_{8i}}), (\frac{FU_{2i}}{fu_{2i}}, ..., \frac{FU_{6i}}{fu_{6i}}), \frac{L_i}{l_i}, \frac{K_i}{k_i}, \frac{F_i}{f_i}\} \quad (3)$$

with $F_i = 0$ for i = 5.

In agriculture, energy-intensive industries, other industries and services as well as in the electricity sector, *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. In this case, the fixed factors are land for agriculture (F_1) and the carbon-free resource for the electric sector (F_6), while no fixed factors are assumed to be used in the industrial sectors (i = 7, 8).

In these sectors, the production technology allows for substitution across labour, capital and fuels through a nested-CES specification. Nesting is obtained by assuming weak separability between subsets of primary inputs. The nesting hierarchy bundles in the innermost nest the various kinds of fuels -- FU_{si} (s = 2,..., 6) -- 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.

Description of this nested-CES technology 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

(ρ_{si}<0);

α^j_{si} = 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[26]:

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

Using this notation, the mixed CES-Leontief production function for Q_i can be written as follows,

$$Q_i = \min\{(\frac{X_{1i}}{x_{1i}}, \frac{X_{7i}}{x_{7i}}, \frac{X_{8i}}{x_{8i}}), \frac{KLEF_i}{klef_i}\} \tag{4}$$

$$KLEF_i = CES\{L_i, KEF_i, \lambda_i^L; \rho_{1i}, \alpha_{1i}^1, \alpha_{1i}^2\} \tag{5}$$

$$KEF_i = CES\{E_i, KF_i, \lambda_i^E; \rho_{2i}, \alpha_{2i}^1, \alpha_{2i}^2\} \tag{6}$$

$$E_i = CES\{FU_{2i},..., FU_{6i}; \rho_{3i}, \alpha_{3i}^2,..., \alpha_{3i}^6\} \tag{7}$$

$$KF_i = \min\{\frac{\lambda_i K_i}{a_i^K}, \frac{\lambda_i F_i}{a_i^F}\} \tag{8}$$

where the parameters $klef_i = k_i + l_i + f_i + \sum_{s=2}^6 fu_{si}$, $a_i^K = \frac{\lambda_i K_i}{KF_i}$ and $a_i^F = \frac{\lambda_i F_i}{KF_i}$ are fixed

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

at their benchmark-year values[27].

Producers are assumed to minimise their after-tax costs of production, given the technology described by equations (4)-(8). 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 fuel s by PF_s and the unit costs of the bundles KEF, E and KF by c^{KEF}, c^{E} and c^{KF}, respectively, the following first-order conditions characterise the optimum for sector i:

$$\frac{w}{c_i^{KEF}} = \frac{\alpha_{1i}^{1}}{\alpha_{1i}^{2}} \left(\frac{L_i}{KEF_i}\right)^{\frac{1}{\rho_{1i}}} \tag{9}$$

$$\frac{c_i^{KF}}{c_i^{E}} = \frac{\alpha_{2i}^{1}}{\alpha_{2i}^{2}} \left(\frac{KF_i}{E_i}\right)^{\frac{1}{\rho_{2i}}} \tag{10}$$

$$\frac{PF_s}{PF_r} = \frac{\alpha_{3i}^{s}}{\alpha_{3i}^{r}} \left(\frac{FU_{si}}{FU_{ri}}\right)^{\frac{1}{\rho_{3i}}} \tag{11}$$

with r,s = 2, 3, 4, 5, 6 and r ≠ s.

The unit costs c^{KEF}, c^{E}, c^{KF} -- as well as the unit cost of the composite input KLEF -- are the duals of production functions (5)-(8) above:

$$c_i^{KLEF} = UC\{w, c_i^{KEF}, \lambda_i^{L}; \rho_{1i}, \alpha_{1i}^{1}, \alpha_{1i}^{2}\} \tag{12}$$

$$c_i^{KEF} = UC\{c_i^{E}, c_i^{KF}, \lambda_i^{E}; \rho_{2i}, \alpha_{2i}^{1}, \alpha_{2i}^{2}\} \tag{13}$$

$$c_i^{E} = UC\{PF_2, ..., PF_6; \rho_{3i}, \alpha_{3i}^{2}, ..., \alpha_{3i}^{6}\} \tag{14}$$

[27]Note that technical progress is associated with at most 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.

$$c_i^{KF} = a_i^{K^N} r^{K^N} + a_i^F P_i^f \tag{15}$$

Substituting the first-order conditions (9)-(11) into equations (5)-(7) and using the unit costs definitions (12)-(15), it is possible to derive the producer's optimal demands for the composite inputs at each stage of the production process:

$$l_i = klef_i \, (c_i^{KLEF})^{-\rho_{1i}} \, (\frac{w}{\alpha_{1i}^1})^{\rho_{1i}} \tag{16}$$

$$kef_i = klef_i \, (c_i^{KLEF})^{-\rho_{1i}} \, (\frac{c_i^{KEF}}{\alpha_{1i}^2})^{\rho_{1i}} \tag{17}$$

$$kf_i = kef_i \, (c_i^{KEF})^{-\rho_{2i}} \, (\frac{c_i^{KF}}{\alpha_{2i}^2})^{\rho_{2i}} \tag{18}$$

$$e_i = kef_i \, (c_i^{KEF})^{-\rho_{2i}} \, (\frac{c_i^{E}}{\alpha_{2i}^1})^{\rho_{2i}} \tag{19}$$

$$a_{si}^{fu} = e_i \, (c_i^{E})^{-\rho_{3i}} \, (\frac{PF_s}{\alpha_{3i}^s})^{\rho_{3i}} \tag{20}$$

where $l_i = \frac{L_i}{Q_i}$, $kef_i = \frac{KEF_i}{Q_i}$, $kf_i = \frac{KF_i}{KEF_i}$, $e_i = \frac{E_i}{KEF_i}$ and $a_{si}^{fu} = \frac{FU_{si}}{E_i}$.

Equations (17)-(20) 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 demand for fuels (fu_{si}):

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

$$f_i = kef_i \cdot kf_i \cdot a_i^F \tag{21}$$

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

for s = 2, 3, 4, 5, 6.

Given the technical coefficients (21) 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 -- K_i^O and K_i^N, respectively -- given the assumption of homogeneity in demand of these types of capital 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. 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} (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:

$$x_{ji} = CES\{x_{ji}^D, x_{ji}^I; \rho_{4i}, \alpha_{4ji}^D, \alpha_{4ji}^I\} \tag{22}$$

$$fu_{si} = CES\{fu_{si}^D, fu_{si}^I; \rho_{5i}, \alpha_{5si}^D, \alpha_{5si}^I\} \tag{23}$$

It is assumed that, for each intermediate input, the domestic and imported shares are identical across sectors, i.e. $\alpha_{4ji}^D=\alpha_{4jk}^D$, $\alpha_{4ji}^I=\alpha_{4jk}^I$, $\alpha_{5si}^D=\alpha_{5sk}^D$, $\alpha_{5si}^I=\alpha_{5sk}^I$ for i ≠ k. Therefore, given prices for after-tax domestic and imported intermediate goods and fuels, cost-minimisation by producers, subject to equations (22)-(23), yields the following optimal input-output coefficients:

$$x_{ji}^D = x_{ji} \, (PT_j)^{-\rho_{4j}} \, (\frac{PT_j^D}{\alpha_{4j}^D})^{\rho_{4j}} \tag{24}$$

$$x_{ji}^I = x_{ji} \, (PT_j)^{-\rho_{4j}} \, (\frac{PT_j^I}{\alpha_{4j}^I})^{\rho_{4j}} \tag{25}$$

for j = 1, 7, 8; and,

$$fu_{si}^{D} = fu_{si}\,(PF_s)^{-\rho_{5s}}\,(\frac{PF_s^D}{\alpha_{5s}^D})^{\rho_{5s}} \quad (26)$$

$$fu_{si}^{I} = fu_{si}\,(PF_s)^{-\rho_{5s}}\,(\frac{PF_s^I}{\alpha_{5s}^I})^{\rho_{5s}} \quad (27)$$

for s = 2, 4, 5, 6.

In equations (24)-(27), the composite prices of intermediate goods and fuels, PT_j and PF_s, are defined as CES aggregates of the prices of domestic and imported goods and fuels, according to the CES dual-cost aggregator defined above:

$$PT_j = UC\{PT_j^D,\ PT_j^I;\ \rho_{4j},\ \alpha_{4j}^D,\ \alpha_{4j}^I\}$$

$$PF_s = UC\{PF_s^D,\ PF_s^I;\ \rho_{5s},\ \alpha_{5s}^D,\ \alpha_{5s}^I\}$$

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 (8 x 8) 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,

$$A^D = [x_{ji}^D,\ fu_{si}^D] \quad \text{with } j = 1, 7, 8;\ s = 2,\dots, 6;\ i = 1,\dots,8;$$

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

$$A^I = [x_{ji}^I,\ fu_{si}^I] \quad \text{with } j = 1, 7, 8;\ s = 2,\dots, 6;\ i = 1,\dots,8;$$

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

$$A^F = [k_i,\ l_i,\ \hat{f}_{ii}] \quad \text{with } \hat{f}_{ii} = diag[f_{ii}],\ i = 1,\dots,8,$$

yielding a (10 x 8) matrix with $f_{ii} = 0$ for i = 5, 7, 8.

Given the (8 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:

$$\begin{matrix} L \\ K \\ F_1 \\ F_2 \\ F_3 \\ F_4 \\ F_6 \end{matrix} = A^F \cdot Q \ , \qquad X^I = A^I \cdot Q \tag{28}$$

On the other hand, given the assumption of constant returns to scale in all sectors, the vector of gross outputs is determined by the (8 x 1) vector of final demands $Y = [Y_i]$, using the inverse of the domestic input-output matrix:

$$Q = [I - A^D]^{-1} \ Y \tag{29}$$

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 disposahle 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):

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

where v 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 -- less depreciation of the existing capital stock. Indexing by j expanding sectors and by n declining sectors, and denoting by $(1 - \delta_i)$ depreciation rates by sector, personal income can be defined as follows:

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

$$- r^{K^N} \cdot \sum_j (1 - \delta_j) \cdot K_j - \sum_n (1 - \delta_n) \cdot r_n^{K^O} \cdot K_n$$

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 three-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 fuel and power and transport and communication, they choose an optimal consumption-mix of fuels. Third, they allocate their consumption among imported and domestic goods. 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[28].

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[29]. 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.

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[28]The ELES was first proposed by Lluch (1973). Both Cobb-Douglas and CES demand systems impose unit income elasticities across goods, a property that finds little empirical support. Other demand models, such as the translog or AIDS, are more flexible than the ELES but are difficult to implement in AGE models, given their lack of *global* well-behaved properties.

[29]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.

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 subsistence quantity of the i-th consumer good by γ_i and defining $C^* = [C_1,..., C_4, \sigma]$, the utility function is defined as,

$$U(C^*) = \sum_{i=1}^{4} \beta_i \ln(C_i - \gamma_i) + \beta_5 \ln(\sigma) \tag{30}$$

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

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

$$Y^D = \sum_{i=1}^{4} PC_i \cdot C_i + S \tag{31}$$

Maximisation of (30) subject to (31) and the given price system yields the following demand system in expenditure form[30],

$$PC_i \cdot C_i = PC_i \cdot \gamma_i + \beta_i(Y^D - \sum_{j=1}^{4} PC_j \cdot \gamma_j) \qquad i = 1,..., 4 \tag{32}$$

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

In equation (32), 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.

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:

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

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

[30]See Howe (1975).

important implication of this atemporal specification of consumer behaviour is that no consistent index of intertemporal welfare can be derived[31].

Once the (4 x 1) vector of consumption demands, $C = [C_i]$ (i = 1,..., 4), has been determined, it is translated into a (8 x 1) vector of consumer demands for intermediate goods, $X_C = [X_{1C}, FU_{2C},..., FU_{6C}, X_{7C}, X_{8C}]$, through a (8 x 4) transition matrix, $TR = [tr_{ij}]$:

$$X_C = TR \cdot C$$

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:

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

$$tr_{ij} = \frac{FU_{ijC}}{C_j}, \qquad i = 2,..., 6$$

with $\sum_i tr_{ij} = 1$ for j = 1,..., 4; $\sum_j tr_{ij} \cdot C_j = X_{iC}$ for i = 1, 7, 8; and $\sum_j tr_{ij} \cdot C_j = FU_{iC}$ for i = 2,...,6.

It is assumed that consumers take the transition matrix as a technical datum for all consumer goods except fuel and power and transport and communication (j = 2, 3)[32]. In the case of these latter goods, consumers are allowed to choose an optimal mix of fuels within the given unit energy requirements (e_{jC}), defined as the ratio of total energy used in consumption of good j (E_{jC}) to the consumption of this good:

$$e_{jC} = \frac{E_{jC}}{C_j}.$$

Consumers are assumed to minimize the cost of total energy expenditure in consuming each good j (j = 2, 3), given a CES transformation function defined over the different kinds of fuels:

$$E_{jC} = CES\{FU_{2C},..., FU_{6C}; \rho^C_{1j}, \alpha^2_{Cj},..., \alpha^6_{Cj}\} \qquad (33)$$

[31]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.

[32]In practice, in the base-year, household demand for transport and communication included only petroleum products as a source of energy.

Given the (composite) fuel prices, PF_i, and defining the unit cost of energy in consumption of good j, c_{jC}^{E}, as the dual of equation (33),

$$c_{jC}^{E} = UC\{PF_2,..., PF_6; \rho_{1j}^{C}, \alpha_{Cj}^{2},..., \alpha_{Cj}^{6}\}$$

the optimal unit requirement of fuel s for each unit of energy used in the consumption of good j, denoted $a_{sj}^{fu^C}$, can be derived following the same steps as in sub-section III.B.:

$$a_{sj}^{fu^C} = e_{jC} \, (c_{jC}^{E})^{-\rho_{1j}^{C}} \, (\frac{PF_s}{\alpha_{Cj}^{s}})^{\rho_{1j}^{C}}$$

Finally, the corresponding optimal entry in the transition matrix (i.e. the unit requirement of fuel s for consumer good j) can be obtained as

$$tr_{sj} = e_{jC} \cdot a_{sj}^{fu^C}$$

The final stage of consumer optimisation concerns the choice between domestic and imported goods, given the assumption of imperfect substitutability among these 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. $\rho_{2j}^{C} = \rho_{2k}^{C}$, $\alpha_{Cij}^{D} = \alpha_{Cik}^{D}$, $\alpha_{Cij}^{I} = \alpha_{Cik}^{I}$ for $j \neq k$:

$$tr_{ij} = CES\{tr_{ij}^{D}, tr_{ij}^{I}; \rho_2^{C}, \alpha_{Ci}^{D}, \alpha_{Ci}^{I}\}$$

Denoting the composite consumption prices of intermediate goods and fuels by PT_i^C and PF_i^C, 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:

$$tr_{ij}^{D} = tr_{ij}\ (PT_i^C)^{-\rho_2^C}\ (\frac{PT_i^D}{\alpha_{Ci}^D})^{\rho_2^C} \tag{34}$$

$$tr_{ij}^{I} = tr_{ij}\ (PT_i^C)^{-\rho_2^C}\ (\frac{PT_i^I}{\alpha_{Ci}^I})^{\rho_2^C} \tag{35}$$

for i = 1, 7, 8; and,

$$tr_{ij}^{D} = tr_{ij}\ (PF_i^C)^{-\rho_2^C}\ (\frac{PF_i^D}{\alpha_{Ci}^D})^{\rho_2^C} \tag{36}$$

$$tr_{ij}^{I} = tr_{ij}\ (PF_i^C)^{-\rho_2^C}\ (\frac{PF_i^I}{\alpha_{Ci}^I})^{\rho_2^C} \tag{37}$$

for i = 2, 4, 5, 6.

Note that no equations such as (34)-(37) exist for crude oil, given the assumption that this commodity is perfectly homogeneous across countries.

In equations (34)-(37), PT_i^C and PF_i^C are defined as CES aggregates of the prices of domestic and imported goods and fuels, according to the CES dual cost aggregator:

$$PT_i^C = UC\{PT_i^D,\ PT_i^I;\ \rho_2^C,\ \alpha_{Ci}^D,\ \alpha_{Ci}^I\}$$

$$PF_i^C = UC\{PF_i^D,\ PF_i^I;\ \rho_2^C,\ \alpha_{Ci}^D,\ \alpha_{Ci}^I\}$$

Using these definitions and the coefficients tr_{ij}, 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 (8 x 1) vectors of the domestic and foreign components of household consumption demand for intermediate goods -- denoted $X_C^D = [X_{iC}^D]$, $X_C^I = [X_{iC}^I]$, respectively -- can be derived as follows:

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

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

(ii) Investment and change in stocks

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 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 (FU_{sI}). 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,

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

$$E_I = CES\{FU_{2I},..., FU_{6I}; \rho_I, \alpha_I^2,..., \alpha_I^6\}$$

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 -- denoted fu_{sI} (s = 2,..., 6) -- are determined through a cost minimisation procedure subject to the CES specification of the energy bundle E_I. Denoting the unit cost of the energy bundle by c^{E_I}, the expression for the optimal technical coefficients for fuels is:

$$fu_{sI} = e_I \, (c^{E_I})^{-\rho_I} \, (\frac{PF_s}{\alpha_I^s})^{\rho_I}$$

where,

$$c^{E_I} = UC\{PF_2,..., PF_6; \rho_I, \alpha_I^2,..., \alpha_I^6\}$$

Finally, it is assumed that the demands for intermediate goods used in the production of the investment good are allocated across domestic supplies and imports according to a CES transformation function, as in equations (22)-(23) above, with elasticity of substitution ρ_2^I and CES distribution parameters α_I^D, α_I^I. Using the resulting optimal technical coefficients for domestic and imported intermediate goods (denoted ι_i^D, fu_{sI}^D and ι_i^I, fu_{sI}^I, respectively), it is possible to derive investment demands for domestic (I_i^D) and imported goods (I_i^I):

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

$$I_s^D = fu_{sI}^D \cdot INV, \qquad I_s^I = fu_{sI}^I \cdot INV \qquad i = 2,\dots, 6$$

with $\sum_{i=1,7,8} (\iota_i^D + \iota_i^I) + \sum_{s=2}^{6} (fu_{sI}^D + fu_{sI}^I) = 1$.

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, a fixed-coefficients specification applies to both non-energy intermediate goods and fuels. Denoting fixed coefficients in stockbuilding by ξ_i and stockbuilding of good i by ST_i, the aggregate change in inventories is expressed as

$$STB = \min\{\frac{ST_1}{\xi_1},\dots, \frac{ST_8}{\xi_8}\}$$

where $\xi_i = \dfrac{ST_i}{STB}$.

On the other hand, the allocation of stockbuilding demand across domestic and imported components -- denoted ST_i^D and ST_i^I, respectively -- is determined as in equations (22)-(23), with elasticity of substitution ρ_2^{ST} and CES distribution parameters α_{ST}^D, α_{ST}^I. Given the resulting optimal technical coefficients ξ_i^D, ξ_i^I, the following stockbuilding demands are obtained:

$$ST_i^D = \xi_i^D \cdot STB, \qquad ST_i^I = \xi_i^I \cdot STB \qquad i = 1,\dots, 8$$

with $\sum_{i=1}^{8} (\xi_i^D + \xi_i^I) = 1$.

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

(iii) <u>Government</u>

The government is assumed to levy an excise tax on carbon emissions, 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 of sales of emission rights. Therefore, denoting carbon-tax revenues by R^C and revenues from the sale of emission rights by R^E, total government revenues can be expressed as:

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

A crucial component of government revenues is the carbon tax T^C, which is expressed as a fixed amount of US$ per ton of CO_2 emissions. While its determination will be discussed below, it is useful at this stage to determine how this revenue is generated and how the tax 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,..., 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[33]. Given the overall carbon tax T^C, it is then possible to derive government revenues from this tax by summing over the demands for the different fossil fuels:

$$R^C = T^C \cdot \sum_{s=2}^{5} \epsilon_s \cdot \phi_s \cdot \sum_{i=1}^{8} FU_{si} = T^C \cdot \sum_{s=2}^{5} \epsilon_s \cdot \phi_s \cdot FU_s = T^C \cdot \sum_{s=2}^{5} \epsilon_s \cdot FU_s^{TJ}$$

where FU_s^{TJ} is total demand for fuel s 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 of each kind of fossil-fuel s (T_s^{TJ}),

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

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

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

Finally, denoting total exports of fuel s by EX_s, its *ad valorem* tax rate is computed as the

[33] One Terajoule (TJ) is equal to 10^{12} Joules (J). The Joule is a unit of measurement of energy, approximately equivalent to a quarter of a Calory.

ratio of government fuel-specific revenues to the total value of domestic absorption of the fuel[34]:

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

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[35].

Denoting the unit cost of government non-transfer expenditures by c^G and the composite price of government purchases of XG by PG, 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:

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

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

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

[34]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 II.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 introduction of the carbon tax.

[35]It is assumed that the government does not "consume" any fixed factor.

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

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

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

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

and P^G is a weighted average of the after-tax prices of intermediate goods:

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

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,

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

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

with $\sum_i (\psi_i^D + \psi_i^I) = 1$.

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, according to a CES specification, with elasticity of substitution ρ_2^G and CES distribution parameters α_{2G}^s (s = 2,..., 6). 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. For each producer good i, total imports by region r (r = 1,..., 7) -- denoted M_{ir} -- are the sum of imports of good i for use in production (X_i^I), household and government consumption (X_{iC}^I and X_{iG}^I, respectively) or for investment (I_i^I) and stockbuilding (ST_i^I) purposes:

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

Except for crude oil, which is assumed to be a homogeneous commodity, 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 transformation 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 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}:

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

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

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

Net imports of crude oil (s = 3) by region r are determined as the difference between total production and total demand by the region, given the exogenous real world price of oil $\overline{P}^{CO}$:

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

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 ≠ r):

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

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

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

The specification of the RoW region is restricted to a set of simple import demand functions, which express imports as a function of the ratio between world import prices and the export price of other goods and services in RoW (i.e. the *numéraire* of the model). Imports from RoW are derived as a residual from the world trade block.

(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, a single emission constraint is imposed at the world level and 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, it is immediately obvious that, 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 II.C.(iii), it is assumed that, in each region, the proceeds from the sale of emission rights accrue to the government. 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, new capital and crude oil are predetermined at the beginning of each period, the supply of the other primary factors is assumed to be sensitive to own contemporaneous 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, supply of natural gas is assumed to depend on its price only when its production is below potential. Own-price sensitivity of factor supplies (F_f^S) is modelled according to the following simple constant-elasticity specification:

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

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

(ii) Mobility of old capital across sectors

Given the dynamic nature of GREEN, 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 surplus, stockbuilding and net foreign capital inflows in each region r[36]:

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

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 price of crude oil. In each region, equilibrium is defined as a price vector P = (r^{K^N}, $r_i^{K^O}$, w, r^f; f = 1, 2, 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:

$$K_i^O = \delta_i \cdot K_i - \Delta_i \qquad \textbf{(38)}$$

-- 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:

$$\sum_i K_i^N + K_G^N = I + \Delta \qquad \textbf{(39)}$$

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

$$F_f = F_f^S \qquad \textbf{(40)}$$

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

---

[36]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.

$$L + L_G = L^S \qquad (41)$$

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

$$P_i \cdot Q_i = \{\textstyle\sum_{j=1,7,8} (PT_j^D \cdot a_{ji}^D + PT_j^I \cdot a_{ji}^I) + \sum_{s=2}^{6} (PF_s^D \cdot fu_{si}^D + PF_s^I \cdot fu_{si}^I)\} \cdot Q_i$$
$$+ r^{K^N} \cdot K_i^N + r_i^{K^O} \cdot K_i^O + w \cdot L_i + r^i \cdot F_i \qquad (42)$$

where $K_i^N = 0$ in declining sectors, $r^{K^N} = r_i^{K^O}$ in expanding sectors and $F_i = 0$ for i = 5, 7, 8.

Equation (38) determines the rental rates of old capital in declining sectors, equation (39) determines the rental rate of new (and old) capital in expanding sectors, equation (40) determines the rental rates of fixed factors, equation (41) determines the real wage rate and equation (42) determines producer prices. 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), which can be interpreted as the shadow price 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 the tax applies to the consumption of each fossil fuel s expressed in Terajoules (FU_{sr}^{TJ}), the carbon tax is determined in each region by the following material balance constraint:

$$\textstyle\sum_{s=2}^{5} \epsilon_s \cdot FU_{sr}^{TJ} \leq \overline{CE_r} \qquad (43)$$

When emissions are constrained at the world level and trade in emission rights is allowed, a single constraint such as (43) determines the world carbon 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:

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

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:

$$Y_{ir} = X^D_{irC} + X^D_{irG} + I^I_{ir} + ST^D_{ir} + EX_{ir}$$

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

$$\sum_{r=1}^{7} CA_r = 0$$

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. The sequence of static equilibria described above is period-related through these equations, but the time path of the economy is not intertemporally coordinated as it would be in a perfect foresight model. Current decisions of agents affect future economic developments through the accumulation or decumulation of stocks, but are not affected by expectations regarding future economic outcomes.

(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 δ_t, this accumulation function can be expressed as follows:

$$K_t = \delta_{t-1} \cdot K_{t-1} + I_{t-1} \qquad \textbf{(44)}$$

Sectoral capital stocks evolve in a similar way, but embody the additional assumption that the depreciated capital stock could be scrapped at a rate which exceeds the (constant) sector-specific depreciation rates δ_i. This second-hand capital is then supplied to other sectors according to the disinvestment functions Δ_t 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:

$$K_{it} = \delta_i \cdot K_{it-1} + I_{it-1} - \Delta_{it} \qquad \textbf{(45)}$$

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 (45) over sectors:

$$\sum_i K_{it} = \sum_i \delta_i \cdot K_{it-1} + \sum_i I_{it-1} - \sum_i \Delta_{it} = \delta_{t-1} \cdot K_{t-1} + I_{t-1} = K_t \tag{46}$$

Equation (46) 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) Resource depletion sub-model

The resource depletion sub-model is implemented only for crude oil and natural gas. Coal is assumed to be in infinite supply. 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[37]. Given this estimate, the supply path is determined by two technological parameters: (i) the rate of discovery of new reserves -- hereafter called the "conversion rate"[38]; 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.

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:

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

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

$$Q_{i,t} = r_i \cdot RES_{i,t} \tag{47}$$

$$NRES_{i,t} = d_i \cdot YTFR_{i,t} \tag{48}$$

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

$$RES_{i,t} = RES_{i,t-1} + NRES_{i,t-1} - Q_{i,t-1} \tag{49}$$

Substituting equations (47)-(48) into (49), 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:

$$\frac{RES_{i,n}}{RES_{i,0}} = (1 - r_i)^{n} \cdot + d_i \cdot L(d_i, r_i; n) \cdot \frac{1}{\Pi_{i,0}} \tag{50}$$

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 (50) 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 (50) 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 (47) and the "conversion" equation (48). 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.

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

The assumption that the depletion parameters (r_i and d_i) 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, except for the production of crude oil in the energy-exporting LDCs region, 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 for both crude oil and natural gas is sensitive to world oil prices.

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, and the associated constant terms by Ω_i and Υ_i, the following specifications were assumed:

$$d_i(\bar{P}^{co}) = \Omega_i \cdot (\bar{P}^{co})^{\omega_i} \tag{51}$$

$$YTFR_i(\bar{P}^{co}) = \Upsilon_i \cdot (\bar{P}^{co})^{\upsilon_i} \tag{52}$$

Equations (51) and (52) are mutually exclusive since the calibration procedure for the resource depletion sub-model only has one degree of freedom (see Sectiön 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 specification. 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 yet-to-find reserves, inducing an upward shift in the production path relative to the reference case.

H. Solution algorithm

Static equilibria of GREEN are obtained following an iterative solution procedure similar to that used for WALRAS. The solution method is a *tâtonnement* procedure based on the Gauss-Siedel algorithm[39]. 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 three 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).

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[39]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.

-- 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 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[40]. The USSR and China were treated as separate regions in view of their potential importance as sources of CO_2 emissions over the simulation period[41].

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, as well as the corresponding items in the I-O tables of the benchmark data set. Consistency between sectoral outputs and I-O figures is ensured by an iterative bi-proportional adjustment process for material balances[42].

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*

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[40]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).

[41]I-O tables for the USSR and China are based on domestic price structures that can be expected to involve large distortions, especially in energy sectors. This appears to be particularly true in the Soviet Union.

[42]This adjustment process is operated by a RAS subroutine.

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 -- this is 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.

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 crude oil and natural gas intermediate demand 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[43]. 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[44].

[43]An additional problem was created by an apparent anomaly in the I-O table for the USSR, 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.

[44]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.

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, i.e. the elasticity of substitution between labour and the capital/energy/fixed factor bundle in each sector (ρ_{1i}), the elasticity of substitution between energy and the capital/fixed factor bundle in each sector (ρ_{2i}) and the inter-energy elasticity of substitution in each sector (ρ_{3i});

(b) the inter-energy elasticities of substitution in the production of the investment good (ρ_I), in consumer demand for each good (ρ_{1j}^C) and in government demand for intermediate goods (ρ_2^G);

(c) the elasticities of substitution between domestic and imported intermediate goods (ρ_{4i}) and fuels (ρ_{5i}) in each production sector, in household consumption (ρ_2^C), in the production of the investment good (ρ_2^I), in the demand for stockbuilding (ρ_2^{ST}) and in government demand for intermediate goods (ρ_3^G);

(d) the elasticities of substitution between government inputs (ρ_G);

(e) 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});

(f) the income elasticities of household consumption demand for different goods (β_i);

(g) the own-price supply elasticities of fixed factors (η^f);

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

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

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

(k) 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 relied on Secretariat estimates 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[45]. 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[46].

[45]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).

[46]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:

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

The current version of GREEN runs over a 35-year time horizon using time units of 5 years, which can be viewed as a sequence of *medium-term* temporary equilibria. It is planned, however, to introduce a putty-clay production structure in the next version of GREEN, in which only long-run elasticities are of interest. Therefore, the survey concentrated on long-run elasticity estimates and generally downplayed complementarity results, unless these had a firm empirical basis in a dynamic context.

(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 according to the regions in GREEN.

The estimates reported in Table 7 indicate that capital (K) and labour (L) inputs are generally found to be 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 would be required in GREEN. However, the estimates of labour-energy elasticities reported in Table 8 indicate that these inputs are often found to be substitutable to the same extent as capital and labour[47]. 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. A glance at the table suggests that the most important influence on the sign of the estimated elasticities is the nature of the data.

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[47]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.

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[48]. 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[49]. 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[50].

Given the uncertainty surrounding the capital-energy debate and the wide range of estimates presented in Tables 9 and 10, a value of 0.3 was assumed for the elasticity between capital and energy in GREEN. On the other hand, this uncertainty strongly supports the 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.

(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

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

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

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

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)][51]. 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[52].

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 a plausible base-case

[51]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.

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

elasticity for GREEN simulations would lie between 1 and 1 1/2, given that the simulation horizon is the medium term[53].

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[54]. 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 (1990) 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[55].

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 argued 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, 1990). 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 (1990) arbitrarily set this elasticity to unity, citing the lack of compelling econometric evidence on this topic. 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

[53]Furthermore, given the assumed CES technology, additional nesting levels in the production structure of GREEN could be needed in future work, in order to account for the possible lower substitutability between subsets of the energy inputs -- such as gas and coal.

[54]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.

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

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[56]. 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)-(j) of GREEN. CO_2-emission coefficients (k) 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, 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)[57].

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[58]. 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 infinite for oil, almost infinite for coal and finite for natural gas in each period. The low upward elasticity of the carbon-free resource reflects the important

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[56]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.

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

[58]On the lack of empirical estimates of energy supply elasticities, see also Whalley and Wigle (1990).

costs associated with the extension of existing non-fossil energy supply (e.g. nuclear power). This parameter can also be interpreted as measuring the ease of introducing backstop technologies. Finally, Table 17 reports the parameters of the resource-base sub-model, which are assumed to be equal to their base-year observed values[59].

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)-(k). 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 price of crude oil ($\overline{P}^{CO}$); (ii) the production targets for crude oil and natural gas in each region and in specific periods; (iii) real output growth in each region; and (iv) Harrod-neutral energy-augmenting technical progress in each sector i and region r (λ_{ir}^{E}) -- the so-called "autonomous energy efficiency improvement" (AEEI). Given these exogenous variables, a sequence of temporary equilibria is computed from 1985 to 2020, under two crucial assumptions: (i) the economy was in equilibrium in 1985; and (ii) the growth path from 1985 to 2020 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.

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[59]Data for the computation of these parameters was drawn from Masters, Root and Attanasi (1990). The ratios of proven to yet-to-find reserves correspond to the mean uncertainty percentiles.

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^j_{1i}, α^j_{2i}, α^j_{3i}, α^D_{4j}, α^I_{4j}, α^D_{5s}, α^I_{5s}), consumers (α^s_{Cj}, α^D_{Ci}, α^I_{Ci}), government (α^j_G, α^s_{2G}, α^D_G, α^I_G) and with the Armington specification of international trade (α^{jWT}_{ir}), the production of the investment good (α^s_I, α^D_I, α^I_I) and stockbuilding (α^D_{ST}, α^I_{ST});

(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 and the *ad valorem* tax rates on domestic and imported *non-energy* intermediate goods (τ^D_i, 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^L_i 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 (50) 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, $\overline{P}^{CO}_{ref}$. 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 ($Q^{ref}_{i,t}$), the level of reserves implied by this production target ($RES^{ref}_{i,t}$) is given by equation (47) of Section III. Therefore, in principle, it is possible to derive the reference value of the conversion rate d^{ref}_i by solving this equation with respect to d_i. Denoting by $RES_{i,0}$ base-year reserves of fuel i, the equation can be rearranged to yield:

$$d_i = \frac{(RES^{ref}_{i,t}/RES_{i,0}) - (1-r_i)^t}{L(d_i;r_i,t)} \cdot \Pi_{i,0} \tag{53}$$

The conversion rate can be derived as the fixed point of equation (53) 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[60].

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. 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:

$$\omega^d_i = \frac{Log\, d^{low}_i - Log\, d^{ref}_i}{Log\,\overline{P}^{CO}_{low} - Log\,\overline{P}^{CO}_{ref}} \tag{54}$$

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 (53) 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).

Table 19 reports the values of the exogenous variables. Growth rates of the real world price of oil and 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

[60] 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 $YTFR_i$.

surrounding this key exogenous variable. 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 one percent 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[61]. Similarly, an important role can be played by GDP growth rates, which affect the growth of energy demand.

[61]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.

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TABLE 1

Sectors of production in GREEN :

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

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).

(b) US dollars per Terajoule.

(c) Thousands of Terajoule.

(d) Millions 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 :

OECD Europe (a)	Nth. America	Pacific	Energy-Exporting LDCs			Separate Regions
Austria	Canada	Australia	OPEC	non-OPEC		China
Belgium	United States	Japan				
Denmark		New Zealand	Algeria	Angola	COAL	USSR
Finland			Ecuador	Benin		
France			Gabon	Brunei	South Africa	ROW
Germany F. R.			Indonesia	Cameroon		
Greece			Iran	Colombia	GAS	
Ireland			Iraq	Congo		
Italy			Kuwait	Malaysia	Bolivia	
Netherlands			Lybia	Mexico		
Norway			Nigeria	Oman		
Portugal			Qatar	Peru		
Spain			Saudi Arabia	Trinidad & T.		
Sweden			Utd. Arab Em.	Tunisia		
Switzerland			Venezuela	Egypt		
United Kingdom						

a. Turkey is included with ROW.

Table 5. Sectoral definitions and input-output correspondences in GREEN.

Sectors :	ISIC	SITC	Input - Output Tables								
			EEC	Japan	USA (2 dig.)	Canada (4)	Finland	Norway	Australia	USSR	China
1) Agriculture	11 - 13	00 + 034 + 036 (041 to 045) + 054 + 057 + 07 (2 - 25 - 266 - 27 - 28	010	01 to 05	1 to 4	1 to 3	1 to 3	23001 + 23002 + 23003	0101 + 0102 + 0103 + 0104 + 0105 + 0106 + 0200 + 0300 + 400	16	1 to 4
2) Coal mining	210	322 + 323	030 (3)	06	7	5 and 9 (5)	5 (6)	23005 (7)	1200 (8)	03 and 04 (9)	7
3) Crude oil	220	333	071	1301	8	5 and 10 (5)	5 (6)	23004	1200 (8)	02	8
4) Natural gas	220	341	075	1302	8	5 and 11 (5)	5 (6)	23004	1200 (8)	02	8
5) Refined oil	353 + 354	334 + 335	050 + 073	35 + 36	31	25	15	23019	2708	07 (10)	9
6) Electricity, gas, water (1)	4	35	095 to 098	54 + 55 + 56	68	31	23 and 24	23030	3601 + 3602 + 3701	01	6
7) Energy intensive Industries(2)	341 + 351 + 352 + 371 + 372	(25 + 64) + 5 + 67 + 68	130 + 170 + 471	24 + (29 to 34) + (38 to 41)	(24 + 25) + (27 to 30) + (37 + 38)	17 + 19 + 26	12 + 14 + 18	23012 + 23013 23014 + 23016 23018 + 23022	2601 + 2701 to 2707 + 2901 + 2902	05 + 06 + 07 (10) + 09	5 + 10 + 11 + 18
8) Other ind. and services	230+290+rest of 3+ 5 to 9	1+2+4+(6 to 9)-(64+67+68)	rest of the economy	rest of the economy	rest of the economy	rest of the economy	rest of the economy	rest of the economy	rest of the economy	rest of the economy	rest of the economy

(1) Includes hydro-electricity, electricity produced by nuclear power and by other "non-greenhouse" 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).

(3) Assuming that the transformation of lignite into briquettes is done entirely at mining sites.

(4) In terms of the M (medium) aggregation which is the most disaggregated one to be published on the input side.

(5) The second number refers to the branch number on the output side.

(6) Group 'Other mining' includes coal, crude oil and natural gas.

(7) Coal mining is aggregated in group 'mining.'

(8) Coal mining and oil and gas extraction are included in the same commodity group.

(9) Coal mining also includes item 'Other fuels.'

(10) Chemicals and petrochemicals are grouped under the same item.

Table 6: Estimation of intermediate demand 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 7

Survey of interfactor and interenergy elasticities of substitution Econometric estimates: capital-labour substitutability (a) North America									
Author	INTER LINK(b) (1987)	GSD (1990)	Carrere & Devezeaux (1988)		Chung (1987)	Pindyck (1979)	Berndt & Hesse (1986)(c)	Delorme & Lester (1986)	
Country								(d)	(e)
USA	0.74	1.35	1.55	0 45	1.23	1.41	0.45		
CAN	0 64	1.01	1.21	0.47		1.43	0.48	-0 74	1.12
								3.15	1.03
Model	[KE]L CES	KL CES	KLE Translog	KLE Translog	KLEM Translog	KL[PCGEI]M Translog	KLEINEI Translog	KsKeLEMI Translog	
Data	Agg TS 60-83	Agg TS 60-89	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		Provisional						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

Survey of interfactor and interenergy elasticities of substitution Econometric estimates: capital-labour substitutability (a) Pacific							
Author	INTER LINK(b) (1987)	GSD (1990)	Macro models (c)	Carrere & Devezeaux (1988)		Turnovsky et al (1982)	Pindyck (1979)
Country							
JAP	0.32	0.5		0 78	0 54		0.7
ASL	0.42		0.5			2	
NZD	0 44		0 69				
Model	[KE]L CES	KL CES	KL CES	KLE Translog	KLE Translog	KL[PCGEI]M Translog	KL[PCGEI]M Translog
Data	Agg.TS 60-83	Agg TS 60-89	Agg.TS (a)	Agg TS 60-84	Agg.CC-TS 60-84	Man.TS 46-75	Agg CC-TS 59-73
Comment		Provisional				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 7 (cont.)

Survey of interfactor and interenergy elasticities of substitution
Econometric estimates: capital labour substitutability (a)
Europe

Author	INTER LINK(b) (1987)	GSD (1990)	Macro models (c)	Carrere & Devezeaux (1988)		Ilmakunnas & Torma (1989)	Pindyck (1979)	Berndt & Hesse (1986)(d)	Hesse & Tarka (1986)
Country									
GER	0.73	0.33		0.33	0.51		0.71	0.74	0.8
FRA	0.72	0.2		0.83	0.4		0.72	0.23	0.83
UKM	0.77	0.55		2.57	0.21		0.64	0.5	0.77
ITA	0.64	0.48		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	KL CES	KLE Translog	KLE Translog	KLEINEIM Gen.Leont.	KL[PCGEI]M Translog	KLEINEI Translog	KLEINEIM Translog
Data	Agg.TS 60-83	Agg.TS 60-89	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		Provisional				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 8

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					

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 8 (cont.)

Survey of interfactor and interenergy elasticities of substitution Econometric estimates: labour-energy substitutability (a) Europe							
Author	Carrere & Deveneaux (1988)		Ilmakunnas & Torma (1989)		Pindyck (1979)	Hesse & Tarka (1986)	
Elasticity	σ_{LE}		σ_{LEL}	σ_{LNE}	σ_{LE}	σ_{LEL}	σ_{LNE}
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 elasticites in manufacturing in the major seven OECD countries

Author	Country	Factors	Data	Prod. Function	Capital-energy elasticity
Bernot and Wood (1975)	USA	KLEM	TS (47-71)	translog	-3.22 (1965)
Hudson and Jorgenson (1974)	USA	(KE) (LM)	TS (47-71)	trg-Cobb-D	-0.31 (1971)
Hudson and Jorgenson (1977)	USA	KLEM	TS (47-71)	translog	-1.39
Griffin and Gregory (1976)	USA	KLE	CS-TS	translog	+1.07 (1965)
Oztalay _et al_. (1979)	USA	KLEM	CS-TS	translog	+1.22
Artus-Peyroux (1981)	USA	KLE	TS (63-78)	translog	-0.78 (1978)
Khaled (1978)	USA	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
Bernot 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_. (1975)	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)	UK	KLEM	CS-TS	translog	1.04 (1965)
Artus-Peyroux (1981)	UK	KLE	TS	translog	0.13
Hunt (1984)	UK	KLE	TS	translog	-1.64 (3)

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

Source: Carrere and Devezeaux (1988)

Table 10

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

Elasticity	σ_{KE}								σ_{EIK}		σ_{NEIK}	
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)

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

	σ_{KE}					σ_{EIK}	σ_{NEIK}
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).

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

Elasticity	σ_{KE}				σ_{EIK}		σ_{NEIK}	
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 11

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_{OC}	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.

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 11 (cont.)

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_{ENE}	σ_{ENE}	σ_{PG}	σ_{PC}	σ_{CO}
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 (1990)	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 (1990)	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 (1990)		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 (1990)	1.0

iii) Inter-fuel elasticity of substitution in final demand

Whalley and Wigle (1990)	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	2	3	4	5	6	7	8	Government
Labour/KEF(ρ_{1i})	-0.6	0.0	0.0	0.0	0.0	0.0	-0.6	-0 6	
E/KF(ρ_{2i})	-0.3	0.0	0.0	0.0	0.0	-0.3	-0.3	-0.3	
Interenergy (ρ_{3i}) (1)	-1.2	0.0	0.0	0.0	0.0	-1.2	-1.2	-1 2	
Domestic/imported ($\rho_{4i} \cdot \rho_{5i}$) (2)	-3 0	-4.0	∞	-4.0	-4.0	-4.0	-2.0	-2.0	
Government inputs (ρ_G)									-0.75
World trade (ρ_{ir}^{WT})	-4.0	-5.0	∞	-5.0	-3.0	-0.5	-3.0	-3.0	

1. An interenergy elasticity of 1.2 is also assumed for consumer (ρ^{C}_{1j}) and government (ρ^{G}_{2}) demand and in the production of the typical investment good (ρ_I).

2. 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}) demand.

Table 15: **ELES Income elasticities (β_i)**

Region : Elasticity of demand for:	North America	Europe	Pacific	Energy Exporting LDCs	USSR	China
Food and beverages	0.5	0.5	0.5	0.6	0.6	0.7
Fuel and power	0.5	0.5	0.5	0.6	0.6	0 8
Transport and communications	0.8	0.8	0.8	0.9	0.9	1.2
Other goods and services	1.1	1.1	1.1	1.2	1.2	1.5

Table 16· **Own-price elasticities of fixed factors (η^f)**

Region : / Factor (1) :	North America	Europe	Pacific	Energy Exporting LDCs	USSR	China
Land	2.0 0.5	1.0 0.5	1.0 0.5	3.0 0.5	3.0 0.5	3.0 0.5
Coal	4.0 ∞	4.0 ∞	4 0 ∞	4.0 ∞	5 0 ∞	5 0 ∞
Oil	∞ ∞	∞ ∞	∞ ∞	∞ ∞	∞ ∞	∞ ∞
Natural gas	0 0 3.0	0 0 3.0	0 0 3 0	∞ ∞	0.0 4 0	0 0 4 0
Carbon-free	0 2 ∞	0.2 ∞	0.2 ∞	0.2 ∞	0.2 ∞	0 2 ∞

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

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

Region : Resource:	North America	Europe	Pacific	USSR	China
Crude oil·					
Extraction rate (r) (1)	0 063	0.052	0.083	0.056	0 045
Ratio of proven to yet-to-find reserves (2)	0.676	1.034	0.48	0.796	0 458
Natural gas·					
Extraction rate (r) (1)	0.055	0.027	0.017	0.019	0 017
Ratio of proven to yet-to-find reserves (2)	0.478	1.13	0.4	0.916	0.115

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 These ratios correspond to the mean uncertainty percentiles of Masters, Root and Attanasi (1990).

Table 18 **Other parameters (all sectors)**

Region : / Parameter	North America	Europe	Pacific	Energy Exporting LDCs (1)	USSR	China
Disinvestment elasticity	0.7	0.7	0.7	0.7	0.7	0.7
Depreciation rate	0.027	0.017	0.028	0.023	0.032	0.013

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 South Africa when a carbon tax is introduced

Table 19: Exogenous variables in GREEN

Regions			North America			Europe			Pacific			Energy-Exporting LDCs (1)	USSR			China		
				Production targets (3)			Production targets (3)			Production targets (3)				Production targets (3)			Production targets (3)	
Variables	Real world price of crude oil (2)	AEEI (%)	GDP (2)	Crude oil	Natural gas	GDP (2)	Crude oil	Natural gas	GDP (2)	Crude oil	Natural gas	GDP (2)	GDP (2)	Crude oil	Natural gas	GDP (2)	Crude oil	Natural gas
Periods																		
1989-1990	2.43	1	2.5			2.2			3.7			3.8	2.5			4.5		
1990-2000	2.43	1	2.5			2.1			3.6			3.8	2.5			4.5		
2000-2010	1.95	1	2.0	0.7 (4)	1.3 (5)	1.6	0.92 (4)	1.21 (5)	2.6	0.65 (4)	2.05 (5)	3.3	2.0			4.0	1.61 (4)	7.83 (7)
2010-2020	1.63	1	2.0			1.6			2.6			3.3	2.0	1.94 (6)	1.71 (7)	4.0		

1. Potential supply of oil and gas in energy-exporting LDCs is assumed to be infinite.
2. Percentage growth rates.
3. Index (1985 = 1.00 reference price scenario).
4. IEA production targets in 2005.

Figure 1: **Structure of production in GREEN**

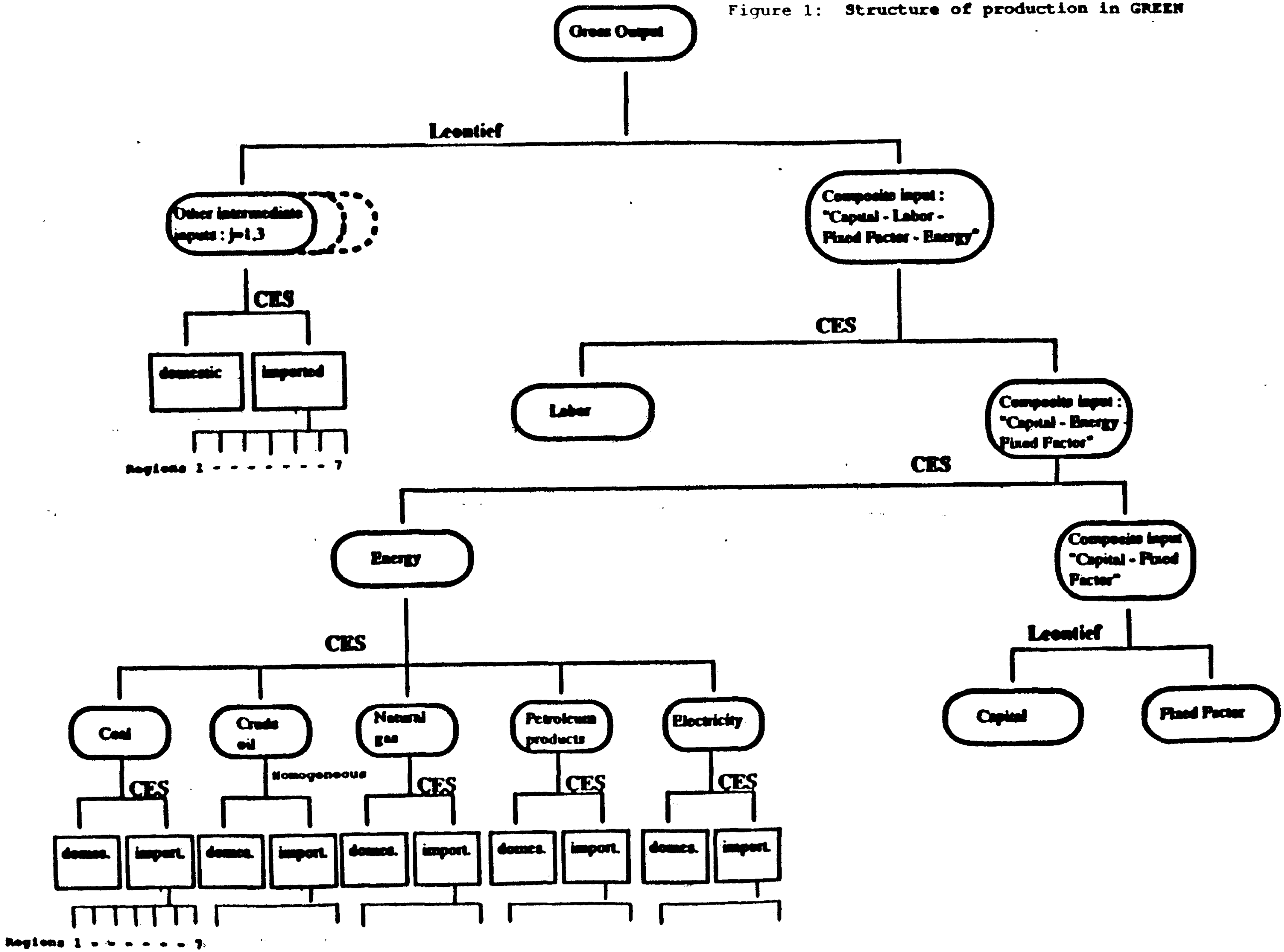


Figure 2: Structure of the household demand in GREEN

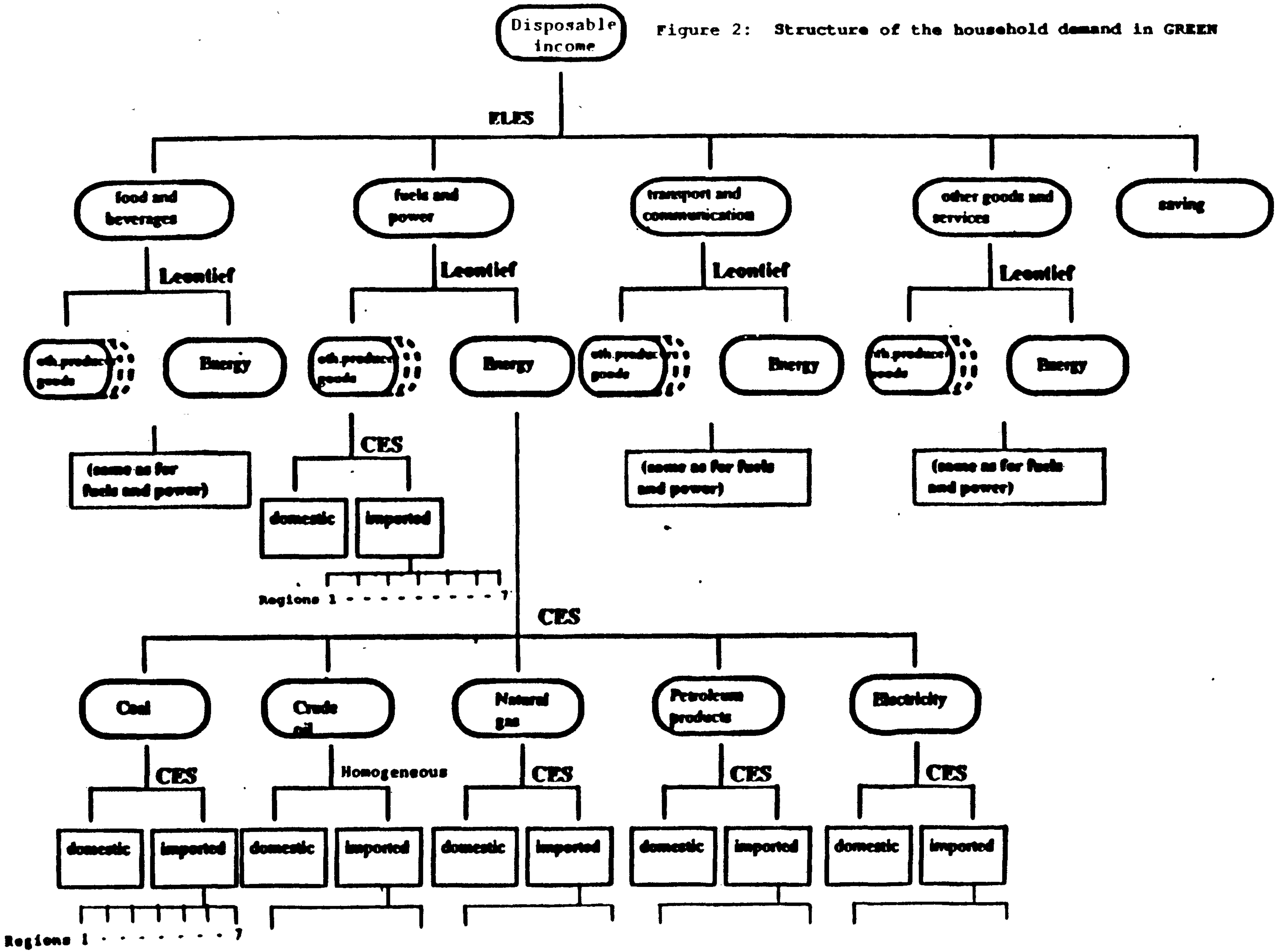
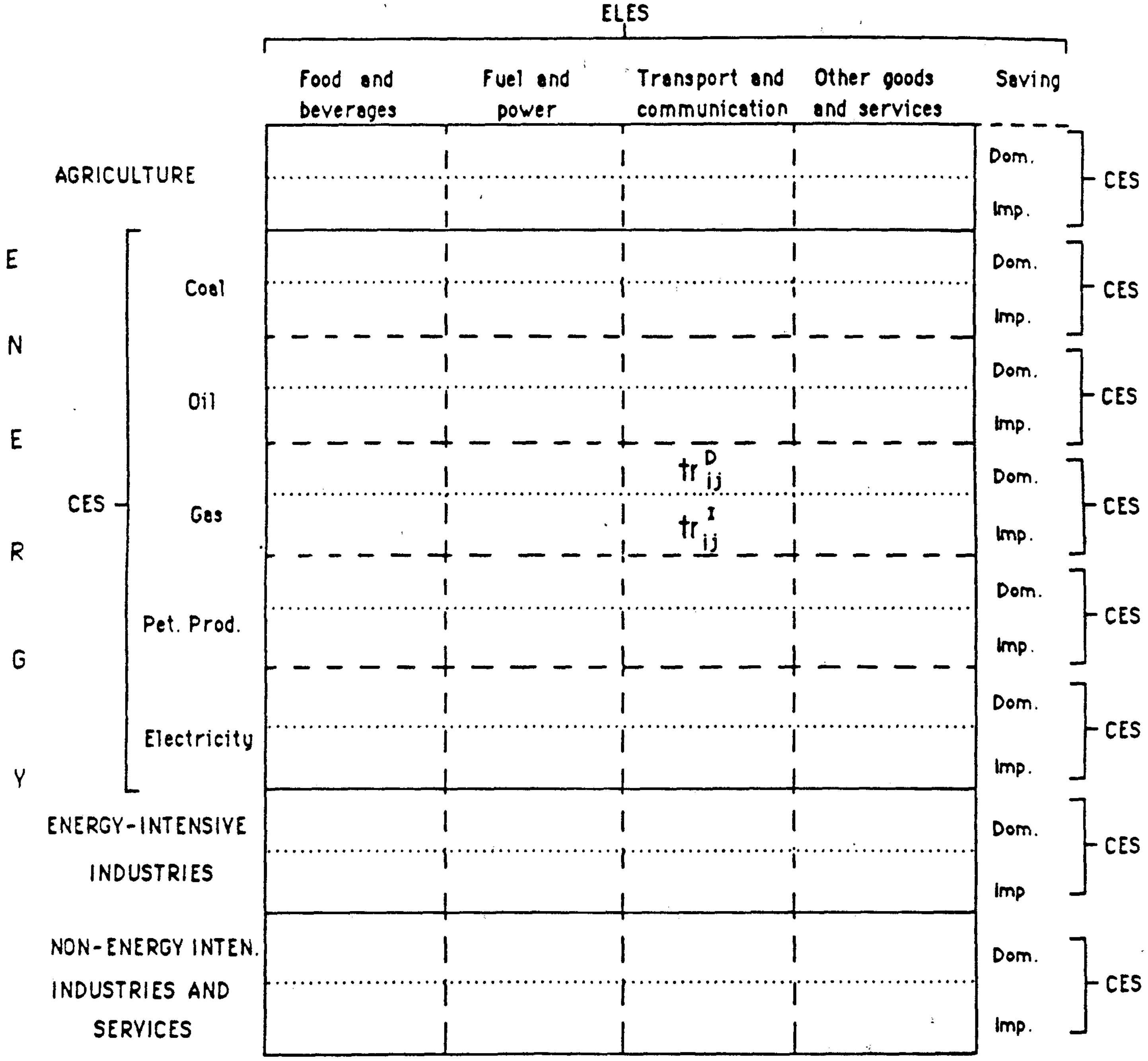


Figure 3: **Structure of household demand**



Transition Matrix

Figure 4: **Data structure of GREEN**

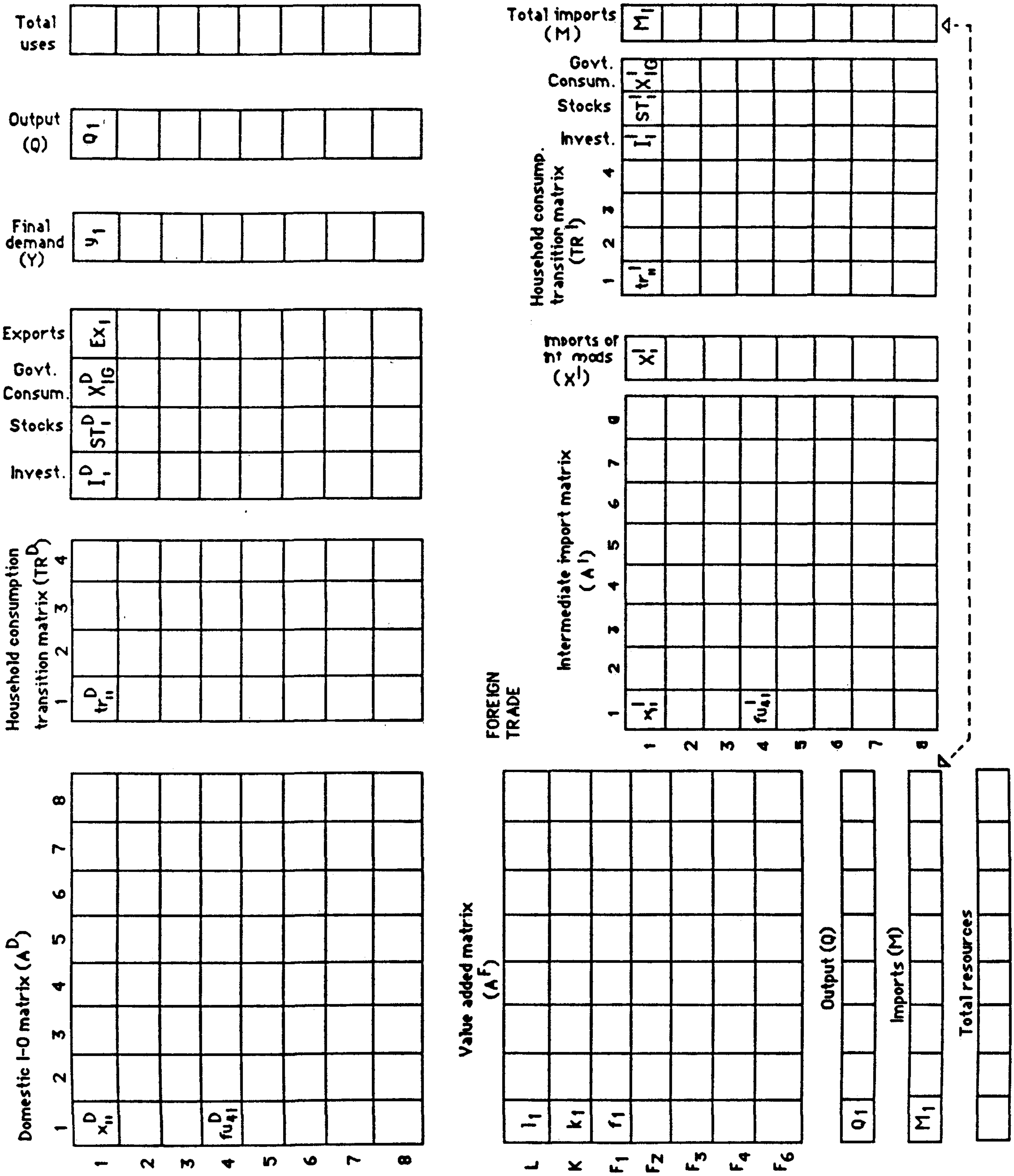
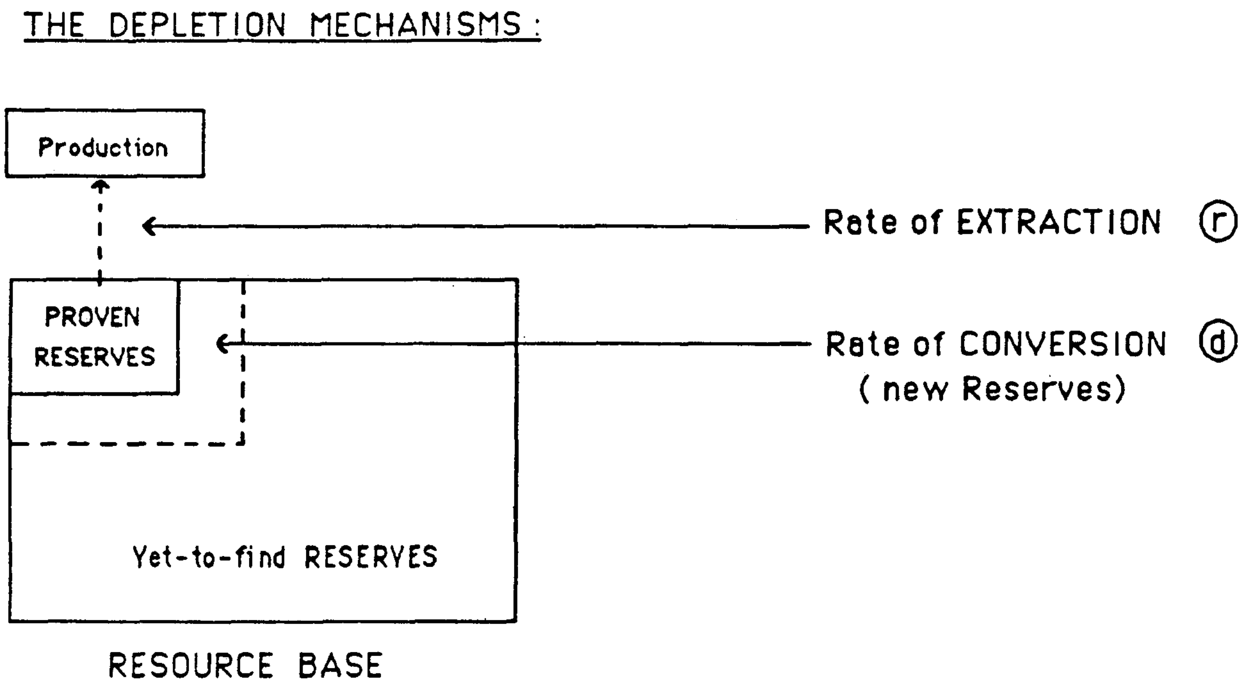


Figure 5: **Resource depletion models**



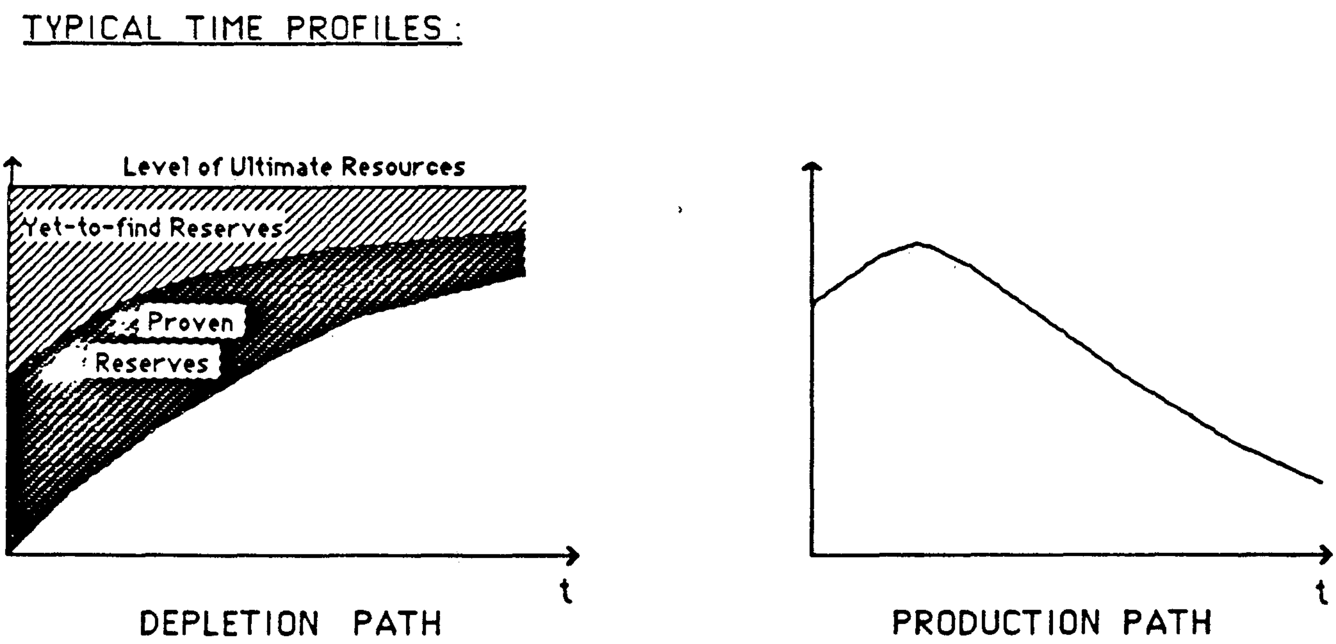
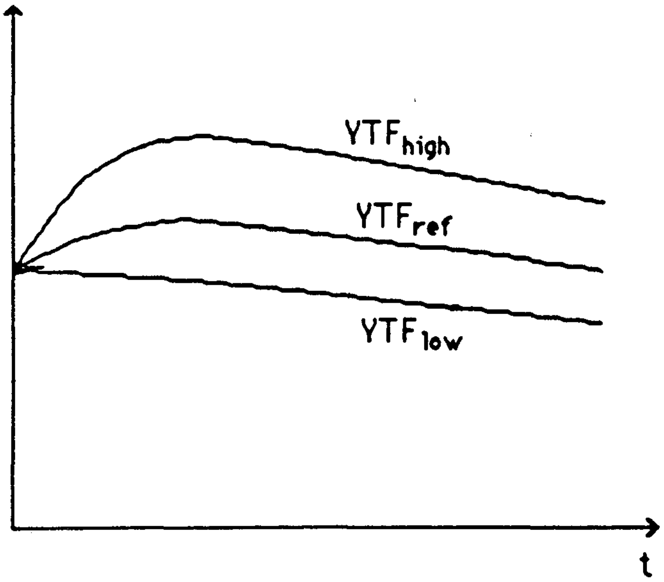


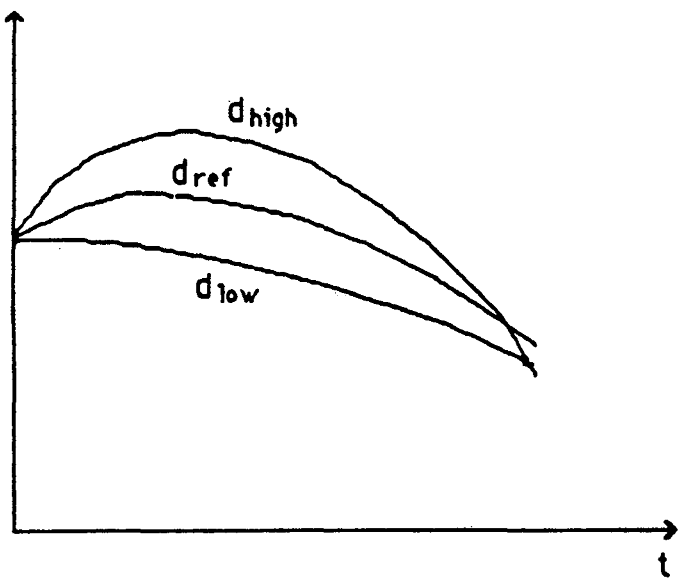
Figure 6: **Price sensitivity**

a) Resource base (YTFR) Price Sensitive:



$YTLF_L < YTF_{ref} < YTF_H$

b) Conversion Factor (d) Price Sensitive:



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

Annex 1

- 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.

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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 crude oil output value and a $0.5 billion natural gas output value. 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 70 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 1 : TOTAL INTERMEDIATE DEMAND

	AGRICUL	COAL MIN.	CRUDE OIL	NATUR. GAZ	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.GAZ	0	0		54 [16]c	0	488 [16]e	0		
REFINED O	179 [16]b			0	0 [16]b	54 [16b]	941 [16]b		
ELECTRI.	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. GAZ	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 [1,6]	494 [1,6]	1049 [4]b	637 [1]	855 [1]a	34178	67254 [2]
OUTPUT	22739 [8]	0	13500.34 [6]	541.9547 [6]	5901 [4]b	1309	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

[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

continued

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
b = based on the IO table for the US.

[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 $/toe
	- output	2647 000 toe	- output	0 000 toe	- output	0 000 t
	- value	493 mill.$	- 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

TABLE 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.GAZ	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]a	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]

[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)

total domestic demand	11259.2				
					dom.prices (see Energy prices and taxes, IEA, OECD, 1989)
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 : In		
					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 : In		
	-				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)

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